

Security in WiFi networks

Security Protocols (bmevihim132)

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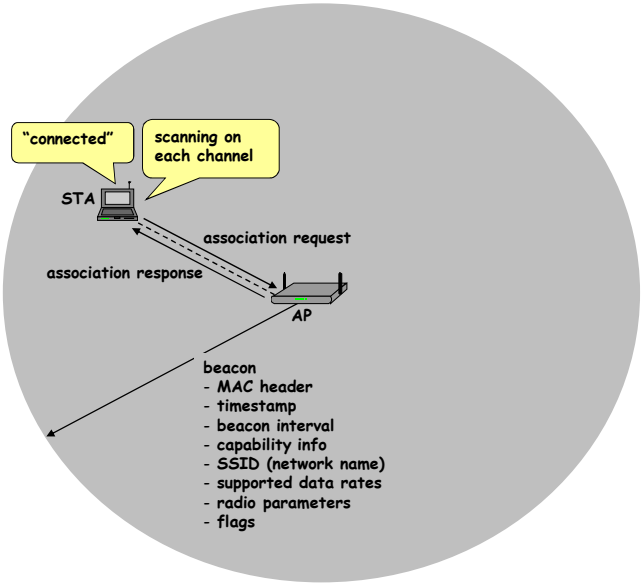
Outline

- reminder on the operation of WiFi networks
- MAC address filtering and SSID based access control
- WEP – operation and **attacks**
- 802.11i (WPA/TKIP, WPA2/AES-CCMP)

Brief reminder on WiFi networks



SSID-based access control

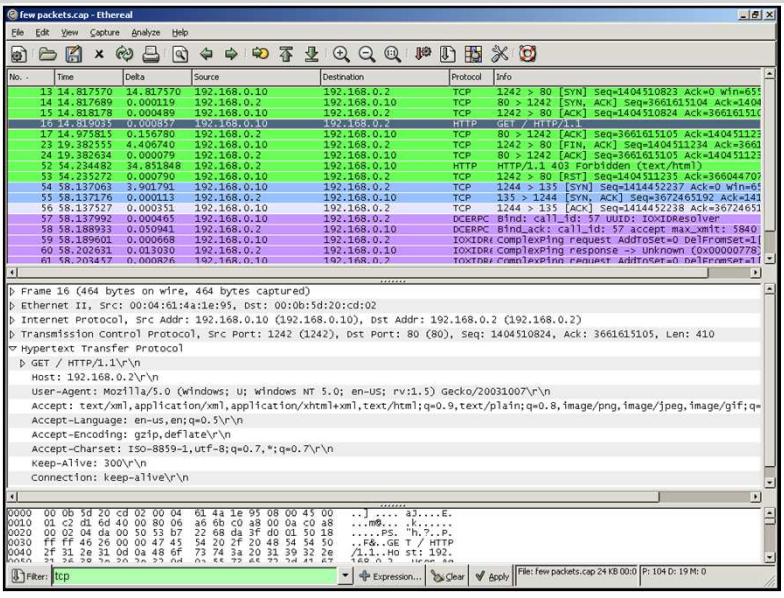
- SSID = Service Set IDentifier (network name)
  - a 32-character unique identifier (differentiates one WLAN from another)
  - found in the header of packets and acts as a "password" when a mobile device tries to connect to the WLAN
- unfortunately, the SSID can be sniffed, and hence, this mechanism does not provide really secure access control

MAC filtering based access control

- MAC address filtering
  - only devices with certain MAC addresses are allowed to associate
  - needs pre-registration of all allowed devices at the AP

- unfortunately, MAC addresses can be sniffed and forged
  - sniffing
    - MAC address is sent in clear in each packet
    - put your WLAN adapter card in promiscuous mode (accepts all packets)
    - eavesdrop the traffic and find out which MAC addresses are accepted
  - forging
    - MAC address of certain WLAN adapter cards can be set by the user
    - example: `# ifconfig ath0 hw ether <mac address of C>`

Eavesdropping with Wireshark



Security problems in wireless

- no inherent physical protection
  - physical connections between devices are replaced by logical associations
  - sending and receiving messages do not need physical access to the network infrastructure (cables, hubs, routers, etc.)
- broadcast communications
  - wireless usually means radio, which has a broadcast nature
  - transmissions can be overheard by anyone in range
  - anyone can generate transmissions,
    - which will be received by other devices in range
    - which will interfere with other nearby transmissions and may prevent their correct reception (jamming)

- eavesdropping is easy
- injecting bogus messages into the network is easy
- replaying previously recorded messages is easy
- illegitimate access to the network and its services is easy
- denial of service is easily achieved by jamming

Wireless com sec requirements

- confidentiality
  - messages sent over wireless links must be encrypted
- authenticity
  - origin of messages received over wireless links must be verified
- replay detection
  - freshness of messages received over wireless links must be checked
- integrity
  - modifying messages on-the-fly (during radio transmission) is not so easy, but possible
  - integrity of messages received over wireless links must be verified
- access control
  - access to the network services should be provided only to legitimate entities
  - access control should be permanent
    - it is not enough to check the legitimacy of an entity only when it joins the network and its logical associations are established, because logical associations can be hijacked
- protection against jamming

WEP – Wired Equivalent Privacy

- part of the original IEEE 802.11 specification
- goal
  - make the WiFi network *at least as secure as a wired LAN* (that has no particular protection mechanisms)
  - WEP has never intended to achieve strong security
  - at the end, it has achieved no security at all
- services
  - access control to the network
  - message confidentiality
  - message authenticity/integrity

WEP – Access control

- before association, the STA needs to authenticate itself to the AP
- authentication is based on a simple challenge-response protocol:

  STA → AP: authenticate request

  AP → STA: authenticate challenge (r) // r is 128 bits long

  STA → AP: authenticate response ($e_K(r)$)

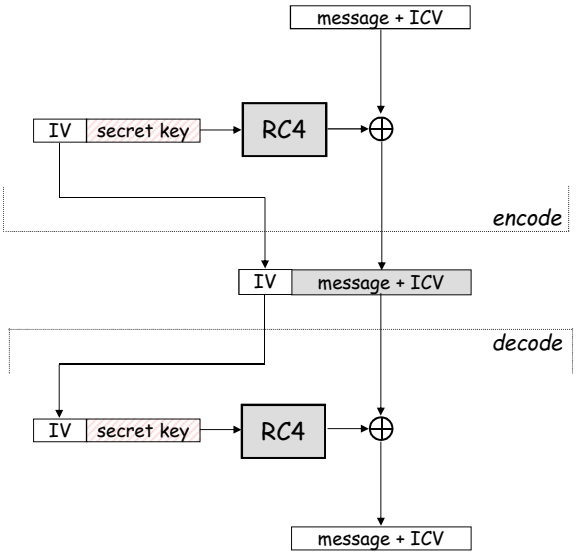
  AP → STA: authenticate success/failure
- once authenticated, the STA can send an association request, and the AP will respond with an association response
- if authentication fails, no association is possible

WEP – Message conf and integrity

- WEP encryption is based on the RC4 stream cipher
  - it is essential that each message is encrypted with a different key stream
  - the RC4 cipher is initialized with a shared secret key and an IV (initial value)
    - shared secret key (40 or 104 bits) remains unchanged
    - 24-bit IV is changed for every message sent
  - RC4 produces a pseudo-random byte sequence (key stream), which is XORed to the message
  - reception is analogous

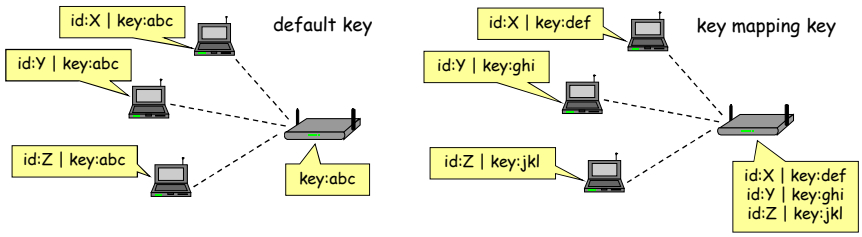
- WEP integrity protection is based on an encrypted CRC value
  - ICV (integrity check value) is computed and appended to the message
  - the message and the ICV are encrypted together as described above

WEP – Message conf and integrity



WEP – Keys

- two kinds of keys are allowed by the standard
  - default key (also called shared key, group key, multicast key, broadcast key, key)
  - key mapping keys (also called individual key, per-station key, unique key)

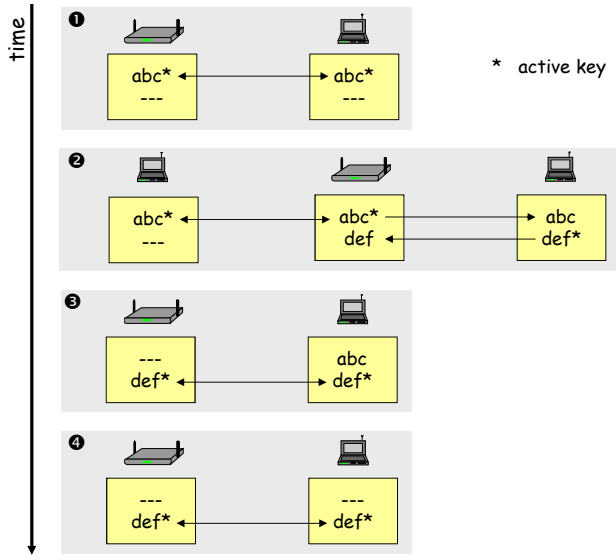


- in practice, often only default keys are supported
  - the default key is manually installed in every STA and the AP
  - each STA uses the same shared secret key → in principle, STAs can decrypt each other's messages

WEP – Management of default keys

- the default key is a group key, and group keys need to be changed when a member leaves the group
  - e.g., when someone leaves the company and shouldn't have access to the network anymore
- it is practically impossible to change the default key in every device simultaneously
- hence, WEP supports multiple default keys to help the smooth change of keys
  - one of the keys is called the active key
  - the active key is used to encrypt messages
  - any key can be used to decrypt messages
  - the message header contains a key ID that allows the receiver to find out which key should be used to decrypt the message

WEP – The key change process



WEP flaws – Auth and access control

- authentication is one-way only
  - AP is not authenticated to STA
  - STA may associate to a rogue AP which can perform a Man-in-the-Middle attack
- the same shared secret key is used for authentication and encryption
  - weaknesses in any of the two protocol can be used to break the key
  - different keys for different functions are desirable
- no session key is established during authentication
  - access control is not continuous
  - once a STA has authenticated and associated to the AP, an attacker can send messages using the MAC address of STA
  - correctly encrypted messages cannot be produced by the attacker, but replay of STA messages is still possible
- STA can be impersonated
  - … next slide

WEP flaws – Auth and access control

- recall that authentication is based on a challenge-response protocol:

  …
  AP → STA: r
  STA → AP: IV | r ⊕K
  …
  where K is a 128 bit RC4 output on IV and the shared secret

- an attacker can compute r ⊕(r ⊕K) = K

- she can use K (and the same IV) to impersonate STA later:

  …
  AP → attacker: r'
  attacker → AP: IV | r' ⊕K
  …

WEP flaws – Integrity and replay

- there's no replay protection at all
  - IV is not mandated to be incremented after each message
  - receiver is not mandated to check the freshness of received IVs

- attacker can manipulate messages despite the ICV mechanism and encryption
  - CRC is a linear function wrt to XOR:

    $$CRC(X \oplus Y) = CRC(X) \oplus CRC(Y)$$

  - attacker observes (M | CRC(M)) ⊕K where K is the RC4 output
  - for any ΔM, the attacker can compute CRC(ΔM)
  - hence, the attacker can compute:

    $$((M \mid CRC(M)) \oplus K) \oplus (\Delta M \mid CRC(\Delta M)) =$$
    $$((M \oplus \Delta M) \mid (CRC(M) \oplus CRC(\Delta M))) \oplus K =$$
    $$((M \oplus \Delta M) \mid CRC(M \oplus \Delta M)) \oplus K$$

WEP flaws – Confidentiality

- IV reuse
  - IV space is too small
    - IV size is only 24 bits → there are 16,777,216 possible IVs
    - after around 17 million messages, IVs are reused
    - a busy AP at 11 Mbps is capable for transmitting 700 packets per second → IV space is used up in around 7 hours
  - in many implementations IVs are initialized with 0 on startup and then incremented by one after each message
    - if several devices are switched on nearly at the same time, they all use the same sequence of IVs
    - if they all use the same default key (which is the common case), then IV collisions are readily available to an attacker
- exploiting weaknesses in the RC4 cipher
  - see next slides …

Operation of RC4

- initialization:

```
for i = 0 to 255 do
  S[i] = i
end

j = 0
for i = 0 to 255 do
  j = j+S[i]+K[i mod len(K)] mod 256
  swap(S, i, j)
end

i = 0
j = 0
```

- generation:

```
i = i+1 mod 256
j = j+S[i] mod 256
swap(S, i, j)
return S[ S[i]+S[j] mod 256 ]
```

FMS (Fluhrer-Mantin-Shamir) attack

- notation:
  - (S_k, i_k, j_k) is the state after the k-th step of the initialization algorithm
  - $(S_{256}, i_{256}=0, j_{256}=0)$ is the state before the generation starts
- in WEP, the attacker knows the first 3 bytes of K (K[0..2] = IV)
- the attacker can simulate the execution of the RC4 initialization for the first three steps, and hence, knows S_3 and j_3
- in the next step ($i_4 = 3$):

  $j_4 = j_3 + S_3[3] + K[3]$

  $S_4[3] = S_3[j_4] = S_3[j_3 + S_3[3] + K[3]]$
- since S is a permutation, S[a] = b implies $S^{-1}[b] = a$
- thus, we have:

  $K[3] = S_3^{-1}[S_4[3]] - j_3 - S_3[3]$
- if we knew $S_4[3]$, we would be able to compute K[3] (first byte of the key)

FMS attack

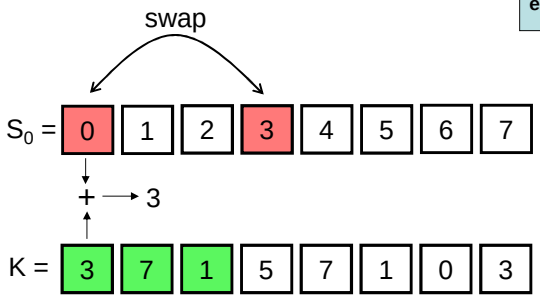
- let's assume that
  - $S_{256}[1] = S_3[1]$, $S_{256}[S_{256}[1]] = S_3[S_3[1]]$, and $S_{256}[3] = S_4[3]$
    (i.e., S[1], S[S[1]], and S[3] do not participate in any more swaps in the rest of the initialization procedure)
  - $S_3[1] < 3$, $S_3[1] + S_3[S_3[1]] = 3$
    (note that these can be tested, because S_3 is known to the attacker)
- let's compute the first key stream byte:
  - $i = 1$, $j = S_{256}[1]$
  - swap $S_{256}[1]$ and $S_{256}[S_{256}[1]]$
    - their sum is still $S_{256}[1] + S_{256}[S_{256}[1]] = S_3[1] + S_3[S_3[1]] = 3$
  - output $X = S_{256}[3] = S_4[3]$
- hence the first key stream byte will give us $S_4[3]$, which reveals K[3]

FMS attack

- what is the probability that S[1], S[S[1]], and S[3] do not participate in any swaps in the remaining 253 steps of the initialization?
  - note that $S_3[1] < 3$ (by assumption), and $i > 3$ (we passed the first 3 steps)
  - S[1], S[S[1]], and S[3] may be swapped only if j takes the value 1, S[1], or 3, respectively (i will not take these values anymore)
  - if we assume that j changes randomly, then it takes any value with probability 1/256
  - hence, we get $(253/256)^{253} \sim 0.0584$
- if the conditions $S_3[1] < 3$ and $S_3[1] + S_3[S_3[1]] = 3$ are satisfied, then we compute the correct value of K[3] with probability 0.0584
- otherwise the value that we compute for K[3] can be any value with probability 1/255 ~ 0.004
- if we repeat this experiment, then the most frequent value that we compute for K[3] is the correct value!

Example: RC4 initialization

```
for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
    swap (S, i, j)
end
```

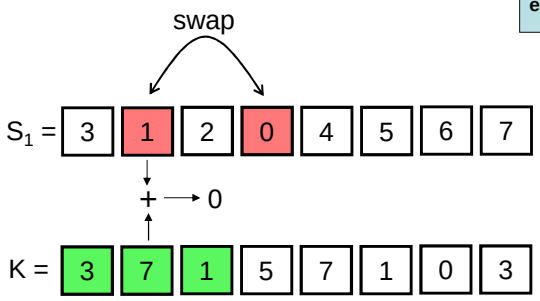


j = 0

i = 0 $j_1 = 3$

Example: RC4 initialization

```
for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
    swap (S, i, j)
end
```



j = 0

i = 0 $j_1 = 3$

i = 1 $j_2 = 3$

Example: RC4 initialization

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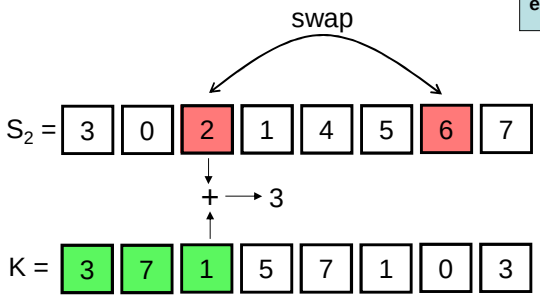


j = 0

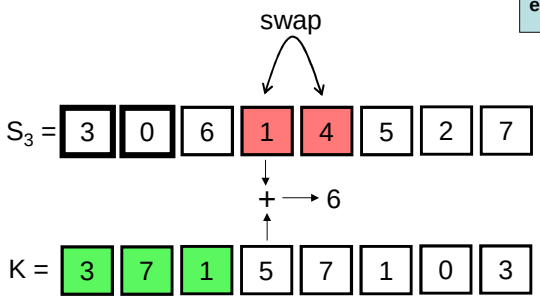
i = 0 $j_1 = 3$

i = 1 $j_2 = 3$

i = 2 $j_3 = 6$

Example: RC4 initialization

```
for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
    swap (S, i, j)
end
```



j = 0

i = 0	$j_1 = 3$
i = 1	$j_2 = 3$
i = 2	$j_3 = 6$
i = 3	$j_4 = 4$

Example: RC4 initialization

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for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
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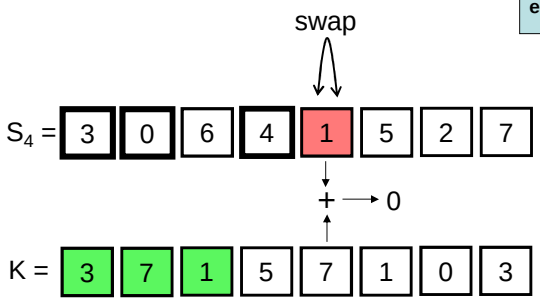
end
```



j = 0

i = 0	$j_1 = 3$
i = 1	$j_2 = 3$
i = 2	$j_3 = 6$
i = 3	$j_4 = 4$
i = 4	$j_5 = 4$

Example: RC4 initialization

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for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
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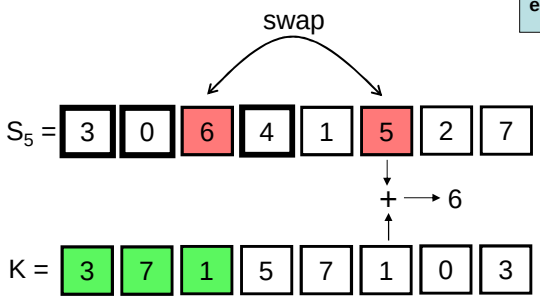
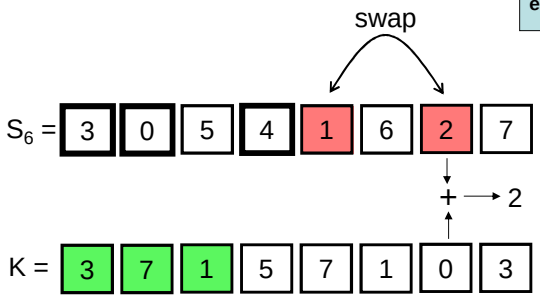
```



	j = 0
i = 0	$j_1 = 3$
i = 1	$j_2 = 3$
i = 2	$j_3 = 6$
i = 3	$j_4 = 4$
i = 4	$j_5 = 4$
i = 5	$j_6 = 2$

Example: RC4 initialization

```
for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
    swap (S, i, j)
end
```



	j = 0
i = 0	$j_1 = 3$
i = 1	$j_2 = 3$
i = 2	$j_3 = 6$
i = 3	$j_4 = 4$
i = 4	$j_5 = 4$
i = 5	$j_6 = 2$
i = 6	$j_7 = 4$

Example: RC4 initialization

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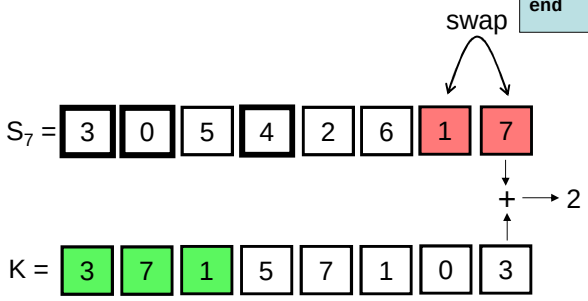
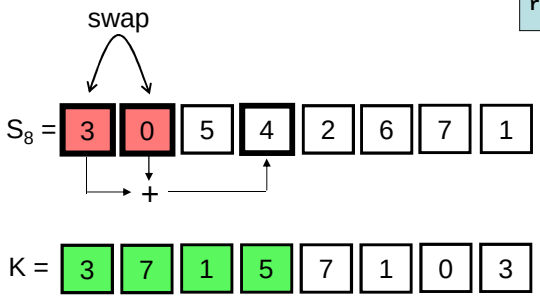
for i = 0 to 7 do
    j = j + S[i] + K[i] mod 8
    swap (S, i, j)
end
```



	j = 0
i = 0	$j_1 = 3$
i = 1	$j_2 = 3$
i = 2	$j_3 = 6$
i = 3	$j_4 = 4$
i = 4	$j_5 = 4$
i = 5	$j_6 = 2$
i = 6	$j_7 = 4$
i = 7	j = 6

Example: RC4 generation

```
i = i+1 mod 8
j = j + S[i] mod 8
swap (S, i, j)
return S[ S[i]+S[j] mod 8 ]
```



i = 0	j = 0
i = 1	j = 0

output X = 4

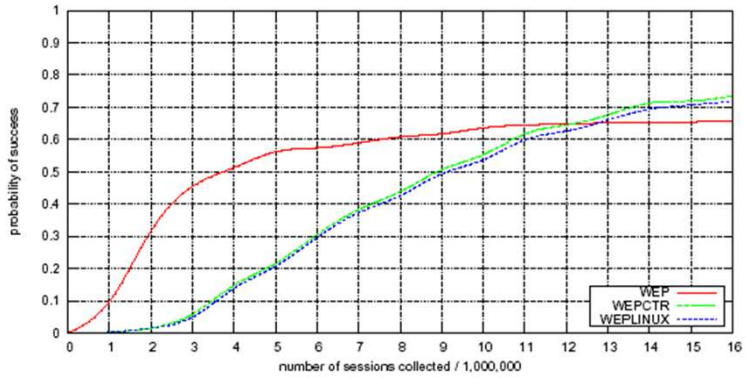
K[3] = $S_3^{-1}[X] - j_3 - S_3[3]$ = 4 – 6 – 1 = 5

FMS attack – the full monty

- assume that we know K[0..c]
- observe the traffic and pick messages for which the FMS conditions ($S_c[1] < c$, $S_c[1] + S_c[S_c[1]] = c$) hold
- for each message, guess the first byte of the message (and hence the first byte X of the key stream used for encrypting the message)
- compute a candidate value for K[c] as $S_c^{-1}[X] – j_c – S_c[c]$
- select the most frequent candidate → K[c]
- increment c and repeat

- when you have a full K, try it by decrypting the eavesdropped messages
- if it does not work, then go back and select the second most frequent candidate for K[c] in the last step
- …

FMS attack – success rate



source: Erik Tews, Attacks on the WEP protocol, Diploma Thesis, TU Darmstadt, 2007

Chopchop attack (KoreK)

- allows an attacker to interactively decrypt the last m bytes of plaintext of a WEP encrypted packet by sending 128m crafted packets on average to the network, and observing if they are accepted or not (ICV is correct or not)
- does not reveal the root key!
- not based on any special properties of the RC4 stream cipher (protocol flaw!)

Chopchop attack – background

- CRC verification mechanism:
  - (message, ICV) is represented as a binary polynomial P
  - if P mod $R_{CRC} = P_{ONE}$, then the message is accepted, where
    - R_{CRC} is the given CRC polynomial
    - P_{ONE} is polynomial with all coefficients equal to one
- we can write P as $Qx^8 + L$, where
  - Q represents the one byte shortened packet
  - L represents the last byte
- if P verifies correctly then how do we need to modify Q such that it verifies correctly too?

$$P \bmod R_{CRC} = P_{ONE}$$
$$Qx^8 \bmod R_{CRC} = P_{ONE} + L \bmod R_{CRC}$$
$$Q \bmod R_{CRC} = (P_{ONE} + L)(x^8)^{-1} \bmod R_{CRC}$$
$$\Delta Q \leftarrow P_{ONE} + (P_{ONE} + L)(x^8)^{-1}$$

Chopchop attack – background

- Q+ΔQ verifies correctly and ΔQ depends only on L

  $Q+\Delta Q \bmod R_{CRC} = Q + P_{ONE} + (P_{ONE} + L)(x^8)^{-1} \bmod R_{CRC} = P_{ONE}$
  because $Q + (P_{ONE} + L)(x^8)^{-1} \bmod R_{CRC} = 0$

- due to RC4 stream ciphering, anything can be added to an encrypted packet without knowing the encryption key

Chopchop attack – the full monty

- eavesdrop a WEP encrypted packet P + K
  - we know that P verifies correctly, but we don't know P
- guess the last byte L of P
  - there are only 256 possibilities!
- chop the last byte of the encrypted packet and XOR in ΔQ to get (Q + K') + ΔQ = (Q + ΔQ) + K'
- send (Q + ΔQ) + K' to the AP and observe if it is accepted
  - send the packet from a station not yet associated to the AP
  - if the packet is correct, the AP will send a message telling the station that it needs to rejoin the network, otherwise the packet is discarded
- if unsuccessful, try another candidate for L
  - on average, after 128 trials you have the correct value for L
- repeat the procedure by chopping Q + ΔQ …

Tools

- there are many available on the web
- look at http://www.aircrack-ng.org for a comprehensive cracking toolbox

WEP – Lessons learnt

1. engineering security protocols is a **very** risky business
   - you may combine otherwise strong building blocks in a wrong way and obtain an insecure system at the end
     - example:
       - stream ciphers alone are OK
       - challenge-response protocols for entity authentication are OK
       - but they shouldn't be combined in a way done in WEP
     - example:
       - encrypting a message digest to obtain an ICV is acceptable
       - but it doesn't work if the message digest function is linear wrt to the encryption function
   - using an expert in the design phase pays out (fixing the system after deployment will be much more expensive)
     - experts will not guarantee that your system is 100% secure
     - but at least they know many pitfalls that you don't
     - they know the details of crypto algorithms better than you do
2. avoid the use of WEP (as much as possible)

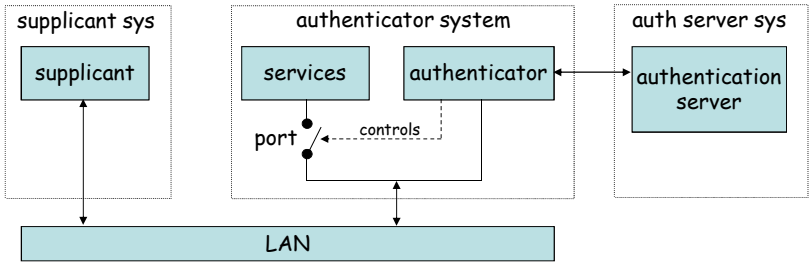
Overview of 802.11i

- after the collapse of WEP, IEEE started to develop a new security architecture → 802.11i (now integrated in 802.11)
- main novelties in 802.11i wrt to WEP
  - access control model is based on 802.1X
  - flexible authentication framework (based on EAP)
  - authentication can be based on strong protocols (e.g., TLS)
  - authentication process results in a shared session key (which prevents session hijacking)
  - different functions (encryption, integrity) use different keys derived from the session key using a one-way function
  - integrity protection is improved
  - replay protection is added
  - encryption function is improved

802.11i, WPA, and WPA2

- WPA (WiFi protected access)
  - industrial name for 802.11i TKIP (Temporal Key Integrity Protocol)
  - integrity protection is based on Michael
  - encryption is based on RC4, but WEP's problems have been avoided
  - ugly solution, but runs on old hardware (after software upgrade)
- WPA2
  - industrial name for 802.11i AES-CCMP (Counter mode and CBC-MAC Protocol)
  - integrity protection and encryption is based on AES (in CCMP mode)
  - nice solution, but needs new hardware

802.1X authentication model



- the supplicant requests access to the services (wants to connect to the network)
- the authenticator controls access to the services (controls the state of a port)
- the authentication server authorizes access to the services
  - the supplicant authenticates itself to the authentication server
  - if the authentication is successful, the authentication server instructs the authenticator to switch the port on
  - the authentication server informs the supplicant that access is allowed

Mapping the 802.1X model to WiFi

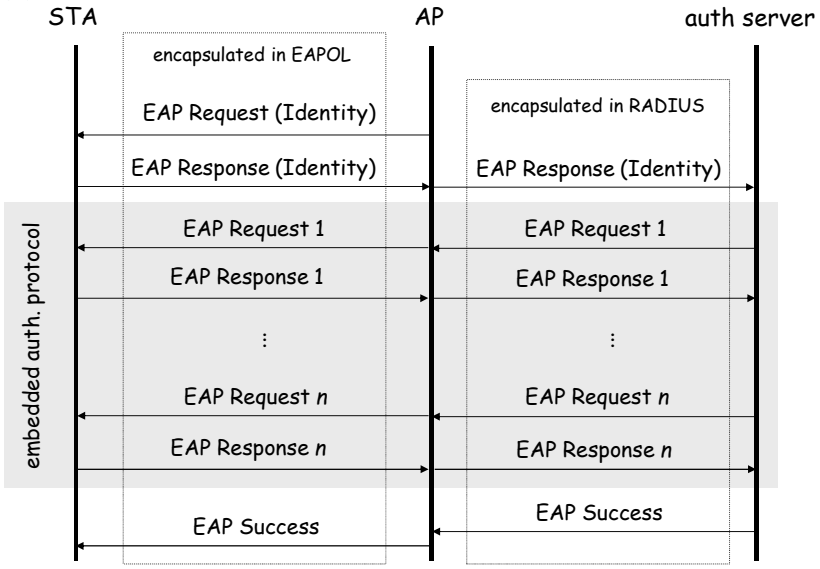
- supplicant → mobile device (STA)
- authenticator → access point (AP)
- authentication server → server application running on the AP or on a dedicated machine
- port → logical state implemented in software in the AP

- one more thing is added to the basic 802.1X model in 802.11i:
  - successful authentication results not only in switching the port on, but also in a session key between the mobile device and the authentication server
  - the session key is sent to the AP in a secure way
    - this assumes a shared key between the AP and the auth server
    - this key is usually set up manually

Protocols: EAP, EAPOL, RADIUS

- EAP (Extensible Authentication Protocol) [RFC 3748]
  - carrier protocol designed to transport the messages of “real” authentication protocols (e.g., TLS)
  - very simple, four types of messages:
    - EAP request – carries messages from the authentication server to the supplicant
    - EAP response – carries messages from the supplicant to the authentication server
    - EAP success – signals successful authentication
    - EAP failure – signals authentication failure
  - authenticator doesn’t understand what is inside the EAP messages, it recognizes only EAP success and failure
- EAPOL (EAP over LAN) [802.1X]
  - used to encapsulate EAP messages into LAN protocols (e.g., Ethernet)
  - EAPOL is used to carry EAP messages between the STA and the AP
- RADIUS (Remote Access Dial-In User Service) [RFC 2865-2869, RFC 2548]
  - used to carry EAP messages between the AP and the auth server
  - MS-MPPE-Recv-Key attribute is used to transport the session key from the auth server to the AP
  - RADIUS is mandated by WPA and optional for WPA2

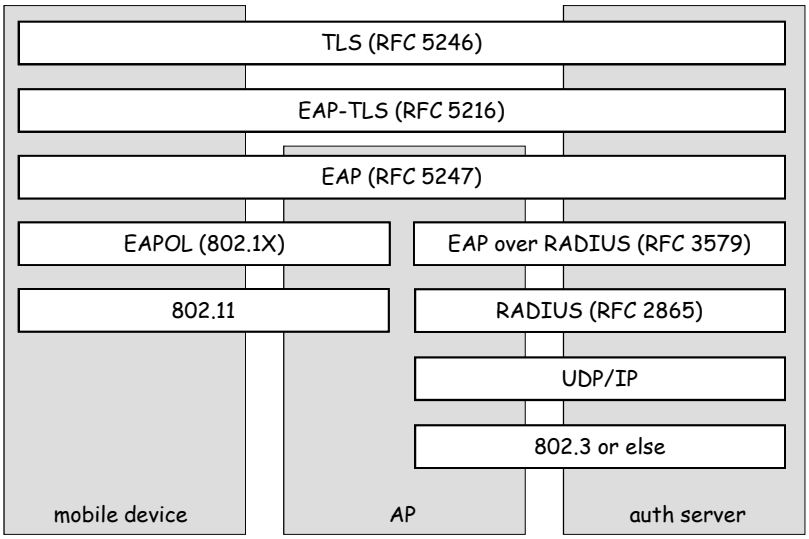
EAP in action



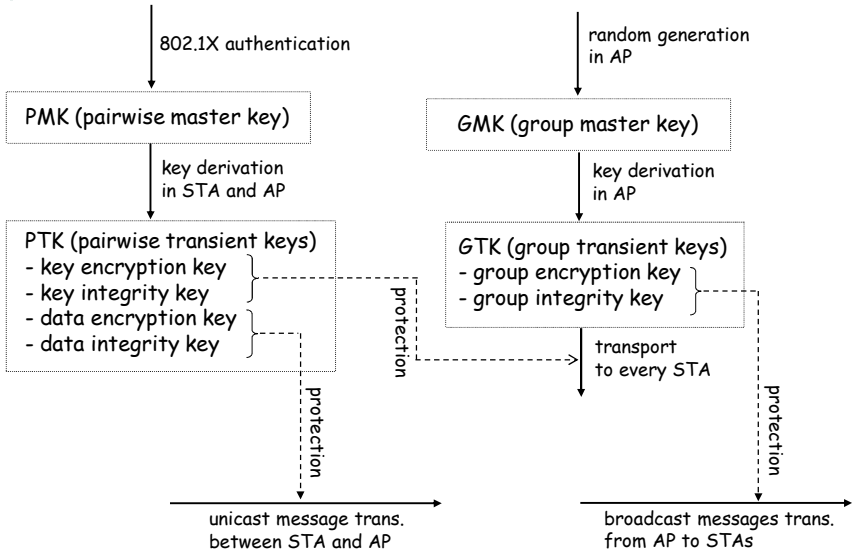
Protocols: EAP-TLS, EAP-TTLS, …

- EAP-TLS (TLS over EAP) [RFC 5216]
  - only the TLS Handshake Protocol is used
  - server and client authentication, generation of master secret
  - TLS maser secret becomes the session key
  - mandated by WPA, optional in WPA2
- EAP-TTLS (Tunneled TLS over EAP) [RFC 5281]
  - phase 1: TLS Handshake possibly without client authentication
  - phase 2: legacy client authentication (e.g., password based) protected by the secure tunnel established in phase 1
    - eavesdropping and man-in-the-middle attacks are prevented
    - privacy is improved (user name is also encrypted)
- EAP-PSK, EAP-FAST, EAP-PEAP, EAP-SIM, EAP-AKA, …

Protocol architecture



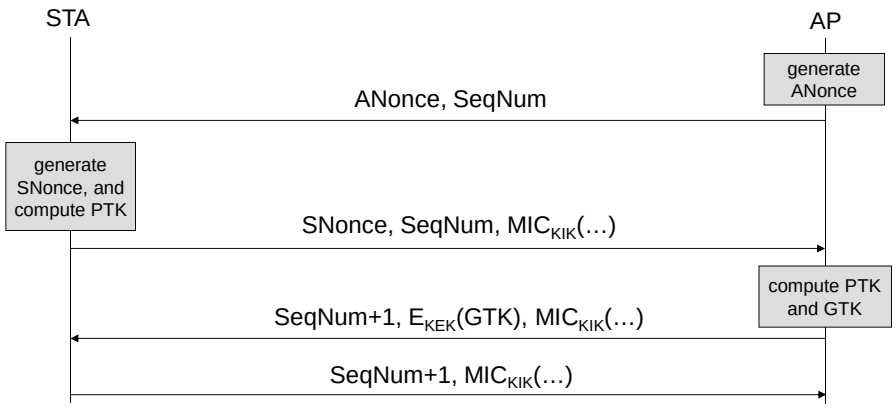
Key hierarchy overview



Four way handshake (simplified)

objective:

- prove that AP also knows the PMK (result of the authentication between STA and Auth Server)
- exchange random values to be used in the generation of PTK



MIC() and E(): HMAC-MD5 and RC4 or HMAC-SHA and AES

PTK and GTK computation for TKIP

PRF-512(PMK,
"Pairwise key expansion",
MAC1 | MAC2 | Nonce1 | Nonce2) =
= KEK | KIK | DEK | DIK

PRF-256(GMK,
"Group key expansion",
MAC | GNonce) =
= GEK | GIK

see TLS slides for the definition of PRF …

PTK and GTK comp for AES-CCMP

PRF-384(PMK,
"Pairwise key expansion",
MAC1 | MAC2 | Nonce1 | Nonce2) =
= KEK | KIK | DE&IK

PRF-128(GMK,
"Group key expansion",
MAC | GNonce) =
= GE&IK

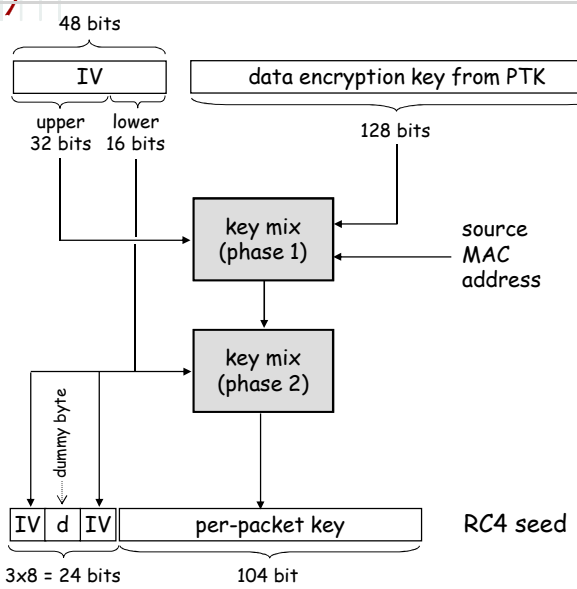
TKIP

- runs on old hardware (supporting RC4), but …
- WEP weaknesses are corrected
  - new message integrity protection mechanism called Michael
    - old CRC based ICV is still there
  - IV is used as replay counter too
  - IV length is increased to 48 bits in order to prevent IV reuse
  - per-packet keys are used to prevent attacks similar to that of the FMS attack

TKIP – Michael

- severe design constraints
  - microprocessor inside most Wi-Fi cards is not powerful enough for strong cryptographic operations
  - moving the MIC computation from the hardware into software (device driver) is an option, but APs do not have powerful CPUs → MIC function should still be simple
- design decisions
  - Michael operates at SDU level (before message is fragmented into PDUs)
    - can be implemented in the device driver (software update)
    - reduced overhead (no MIC computation for each and every PDU)
  - Michael uses simple operations (substitution, rotation, XOR)
    - fits in existing APs
  - Michael is not very strong (equivalent to 20-bit security), hence, vulnerable to brute force attacks
    - if a MIC failure is detected, then a MIC failure report frame is sent
    - if two MIC failures are detected within less than 60 seconds, the communication is shut down, and keys are renegotiated after a 60 second penalty period

TKIP – RC4 seed generation



- how to fit 48+128 bits into a 128 bit RC4 seed supported by the hardware?
- a crypto hash function would be two expensive → special mix function (based on simple operations)
- two phases for efficiency reasons
  - result of the first phase can be used for 2^{16} packets
- MAC address
  - same IV may be used by another device with no problem
- dummy byte
  - repeat of the first byte, except that bit 5 is forced to 1 and bit 4 is forced to 0
  - prevents the generation of the major class of weak RC4 keys

Attacks on TKIP

- in a recent paper (ACM WiSec, Zurich, March 16-18 2009), Beck and Tews published a chopcop attack against WPA
- background
  - Michael is not a one-way function: given a (message, MIC) pair, it is not difficult to recover the MIC key → encryption of the MIC in WPA is essential
  - old CRC-based ICV mechanism is still used
    - last 12 bytes of a plaintext packet is the 8-byte MIC and the 4-byte CRC
    - if ICV is not correct, the packet is discarded silently
    - if ICV is correct, but MIC verification fails, a MIC failure report is sent
    - IV value is not incremented in any of these cases

    → stations can be used as CRC oracles !
- attacker can break the MIC key and recover a key stream (RC4 output) for some IV (not chosen by the attacker)

BT attack on WPA – details

- assumptions:
  - IPv4 is used, and the attacker knows most bytes of the used IP range (e.g., 192.168.0.X)
  - TKIP re-keying period is sufficiently long
- attacker observes an encrypted ARP packet (sent by the AP)
  - can identify ARP packets from their characteristic length
  - ARP requests are sent to the broadcast address

  note that attacker knows large part of the plaintext; what she does not know is the last byte of the IP addresses, and the MIC and the ICV values (12 bytes)
- attacker chops the last byte, and using a guess for the last plaintext byte, modifies the chopped packet like in the KoreK chopchop attack against WEP
- modified packet is sent to the station, and response is observed
  - no response means wrong guess (CRC is incorrect)
  - MIC failure means right guess
- repeat until last byte is figured out (no need to wait between trials !)

BT attack on WPA – details

- wait 1 minute after the MIC failure, and repeat the procedure with the remaining (chopped) packet

  → this gives the last 12 bytes (MIC and ICV)
- missing parts of the IP addresses are guessed
  - each candidate is verified against the known CRC
- at this point, the entire ARP packet, the MIC, and the CRC are recovered → this gives the key stream
- from the (message, MIC) pair, the attacker can also recover the MIC key
- now, the attacker can craft a message, compute its MIC and ICV, encrypt it with the key stream, and send it to the station (with the previously observed IV)
  - however, key stream is IV specific, which functions as a sequence counter
  - therefore, the attacker must prevent the station from receiving the original ARP packet and any other packet during the attack (e.g., by constant jamming)

AES-CCMP

- CCMP means CTR mode and CBC-MAC Protocol
  - authenticated encryption mode
  - integrity protection is based on CBC-MAC (using AES)
  - encryption is based on CTR mode (using AES)
- CBC-MAC
  - computed over the MAC header, CCMP header, and the MPDU (fragmented data)
  - mutable fields are set to zero
  - input is padded with zeros if length is not multiple of 128 (bits)
  - CBC-MAC initial block:
    - flag (8)
    - priority (8)
    - source address (48)
    - packet number (48)
    - data length (16)
  - final 128-bit block of CBC encryption is truncated to (upper) 64 bits to get the CBC-MAC value
- CTR mode encryption
  - MPDU and CBC-MAC value is encrypted, MAC and CCMP headers are not
  - format of the counter is similar to the CBC-MAC initial block
    - "data length" is replaced by "counter"
    - counter is initialized with 1 and incremented after each encrypted block

Summary

- security has always been considered important for WiFi
- early solution was based on WEP
  - seriously flawed !
  - not recommended to use anymore
- the new security standard for WiFi is 802.11i (WPA and WPA2)
  - access control model is based on 802.1X
  - flexible authentication based on EAP and upper layer authentication protocols (e.g., TLS, GSM authentication)
  - improved key management
  - WPA (TKIP)
    - uses RC4 → runs on old hardware, but corrects (most of) WEP's flaws
    - WPA has been recently broken ! (paper at ACM WiSec 2009, March 16-18)
  - AES-CCMP
    - uses AES in CCMP mode (an authenticated encryption mode)
    - needs new hardware that supports AES

Recommended readings

- **J. Edney, W. Arbaugh. *Real 802.11 Security: WiFi Protected Access and 802.11i*. Addison-Wesley, 2004.**
- N. Borisov, I. Goldberg, D. Wagner. Intercepting mobile communications: the insecurity of 802.11. *Proceedings of the 7th ACM Conference on Mobile Computing and Networking*, 2001.
- S. Fluhrer, I. Mantin, A. Shamir. Weaknesses in the key scheduling algorithm of RC4. *Proceedings of the 8th Workshop on Selected Areas in Cryptography*. 2001.
- E. Tews, Attacks on the WEP protocol, Diploma Thesis, TU Darmstadt, 2007.
- M. Beck, E. Tews, Practical attacks against WEP and WPA, *Proceedings of the ACM Conference on Wireless Network Security*, March 16-18, 2009.