Communications Services and Security **Wireless Networks**

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Contents

Wireless Ethernet

Introduction

- WLAN (Wireless Local Area Network) rises as an alternative to wired networks
- Two main motivations:
  - Sometimes, wired is not possible
  - Equipment mobility requirements
- To employ radio frequency
- Range station determined by radio equipment power
- At 1.990 IEEE starts the 802.11 working group

WLAN Technologies

Two main transmission techniques

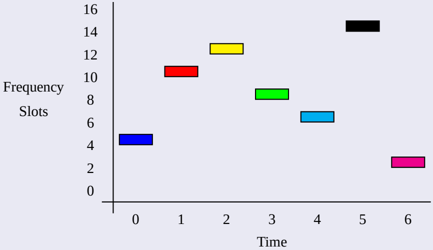
- Narrow Band
  - A frequency band is assigned to each client
  - Frequency assignment such that **no interferences** among clients
- Broad Band
  - Clients physically interfere among them
  - **Spread spectrum** techniques recover interfering situation
  - So, more immunity to external interfering sources

WLAN Technologies

Two main Spread Spectrum techniques

FHSS (Frequency-Hopping Spread Spectrum)

- The **carrier frequency** changes (hops) frequently (several times per second)
- Changing patterns known by transmitter and receiver. Synchronization required
- Any non-synchronized reception is seen as **noise**

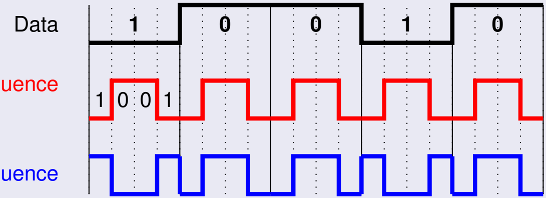


WLAN Technologies

Two main Spread Spectrum techniques

DSSS (Direct-Sequence Spread Spectrum)

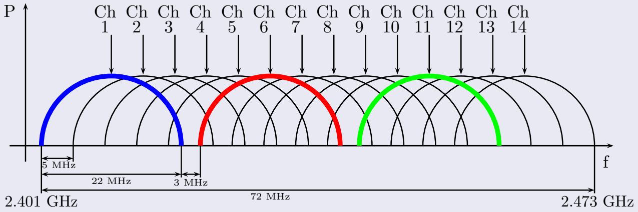
- Each information bit **XORed** by a faster bit sequence (**chips**)
- Chip sequences are **pseudo-random** and **orthogonal**
- As in frequency hopping, chip sequences are agreed by pairs (**synchronized**)
- Any non-synchronized reception is seen as **noise**



- Such a faster chip sequence makes broader the transmission band

WLAN Technologies

Chanel distribution

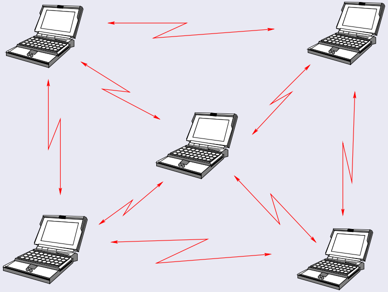


Configurations

Two type of WLAN configurations

Simple networks (*Ad-hoc*)

Client communication is allowed for stations inside the cover range

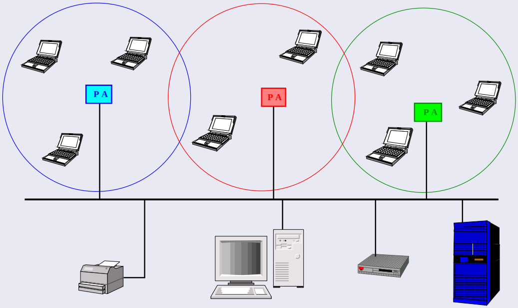


Configurations

Two type of WLAN configurations

Distributed networks (*Infrastructure*)

- A wired infrastructure exists where **Access Points** are attached
- Access points serve a set of mobile clients, giving a **cell** coverage



Medium Access Control (MAC)

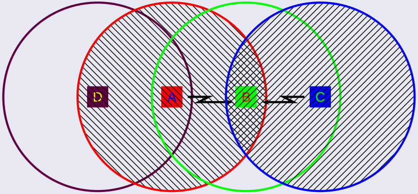
Some problems

- To employ CSMA for WLAN is **inefficient**
- Because of limited range, CSMA presents two problems:
  - **Hidden station**
  - **Exposed station**

Medium Access Control (MAC)

Hidden station problem

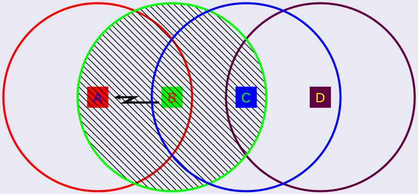
- A sends to B
- C senses the medium and detects it free (because out of range). C starts sending
- C interferes B, masking A reception



Medium Access Control (MAC)

Exposed station problem

- B sends to A
- C senses the medium busy. Can not send to D, even possible because out of range from A



Medium Access Control (MAC)

MACA protocol (Multiple Access with Collision Avoidance)

Early protocol for WLAN (Karn, 1990)
Procedure:

- When A wants to send to B, A sends a RTS (*Request To Send*) to B. The RTS frame contains the **size** of the data to be sent
- All the stations receiving RTS from A (inside A range) keep quiet until B responds
- B sends a CTS (*Clear To Send*) to A, telling its availability to receive data. CTS frame also have the data size from A
- All the stations receiving CTS from B (inside B range) keep quiet during B transmission time
- When a RTS is sent and no response is received, enters into a **exponential binary backoff** retransmission

Medium Access Control (MAC)

MACAW protocol (Multiple Access with Collision Avoidance for Wireless)

Modified MACA based (Bharghavan, 1.994). Efficiency improved

- Receiving station sends ACK when a frame has been correctly received
- To avoid initial collisions CSMA is employed for RTS frames
- Exponential binary backoff employed for each connection instead of for each station

WLAN Frames

WLAN frame types

1. Data frames: End user information frames
2. Control frames: MAC operation related frames, such as RTS, CTS, ACK, . . .
3. Management frames: Management operations related to beacons, authentication, SSID, . . .

WLAN Frames

WLAN frame structure

It is common for all WLAN frames

Preamble	PLCP Header	MAC Frame

- Preamble: two fields
  - *Sync*: 80 bits (0101...) for receiver synchronization
  - *SDF*(*Start Frame Delimiter*): 16 bits (0000 1100 1011 1101)
- PLCP Header(*Physical Layer Convergence Procedure*): Information to decode the MAC frame
  - *Signaling*: information rate (8 bits)
  - *Service*: modulation type (8 bits)
  - *Length*: frame length (16 bits)
  - *CRC*: 16 bits for error detection
- MAC Frame: Layer 2 frame

WLAN Frames: The MAC frame

Bytes	2	2	6	6	6	2	6	0 - 2312	4
	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence	Address 4	Body	CRC

MAC Frame Format

Frame control

Bits	2	2	4	1	1	1	1	1	1	1	1
	Protocol	Type	Subtype	To DS	From DS	Frag.	Retrans.	PM	PMD	WEP	Order

- Protocol: Set to 00
- Type:
  - *00*: Management (Association req/res, Probe req/res, Authentication, Beacon, . . .)
  - *01*: Control (RTS, CTS, ACK, . . .)
  - *10*: Data
- Subtype:
- To DS: Set to 1 for frames going to AP
- From DS: Set to 1 for frames coming from AP

WLAN Frames: The MAC frame

Bytes	2	2	6	6	6	2	6	0 - 2312	4
	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence	Address 4	Body	CRC

MAC Frame Format

Frame control

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- Fragmentation: indicates fragmented data
- Retransmission: set to 1 if frame has been retransmitted
- PM:(*Power Management*) tells that station is going to enter in power saving mode
- PMD: set to 1 if AP has pending data for a PM mode station
- WEP: enciphered data
- Order: for protocols DEC and LAT only

WLAN Frames: The MAC frame

Bytes	2	2	6	6	6	2	6	0 - 2312	4
	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence	Address 4	Body	CRC

MAC Frame Format

Duration / ID

Its value depends on the frame type:

- For stations in PM mode indicates the association ID (AID). So, when station wakes up, AP sends the corresponding buffered data
- Otherwise, indicates the time that channel is expected to be busy during the current transmission (in microseconds)

WLAN Frames: The MAC frame

Bytes	2	2	6	6	6	2	6	0 - 2312	4
	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence	Address 4	Body	CRC

MAC Frame Format

Addresses

Their content depends on **To DS** and **From DS** values

To DS	From DS	Address 1	Address 2	Address 3	Address 4
0	0	Destination	Source	BSSID	N / A [a]
0	1	Destination	BSSID	Source	N / A
1	0	BSSID	Source	Destination	N / A
1	1	AP_{rx}	AP_{tx}	Source	Destination [b]

[a] Ad-Hoc networks, Control and Management frames
[b] Wireless bridges

BSSID (Basic Service Set Id)

BSSID allows to differentiate WLAN in the same area.

- For infrastructure networks, BSSID is the AP MAC wired address
- For adhoc networks, BSSID is randomly generate

WLAN Frames: The MAC frame

Bytes	2	2	6	6	6	2	6	0 - 2312	4
	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence	Address 4	Body	CRC

MAC Frame Format

Addresses

Their content depends on **To DS** and **From DS** values

To DS	From DS	Address 1	Address 2	Address 3	Address 4
0	0	Destination	Source	BSSID	N / A [a]
0	1	Destination	BSSID	Source	N / A
1	0	BSSID	Source	Destination	N / A
1	1	AP_{rx}	AP_{tx}	Source	Destination [b]

[a] Ad-Hoc networks, Control and Management frames

[b] Wireless bridges

ESSID (Extended SSID) (or SSID for short)

- ESSID is a set of 32 ASCII chars. Included in management frames (beacon, . . .)
- Consists of all the BSSID of the network

WLAN Frames: The MAC frame

Bytes	2	2	6	6	6	2	6	0 - 2312	4
	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence	Address 4	Body	CRC

MAC Frame Format

Sequence

For fragmented frames indicates their sequence order

CRC

Cyclic Redundancy Check

IEEE 802.11 Extensions

- New features and specifications based on IEEE 802.11
- Higher transmission rates for WLAN
- Only physical layer is modified
- New modulation techniques to enhance throughput

IEEE 802.11 Extensions: 802.11b

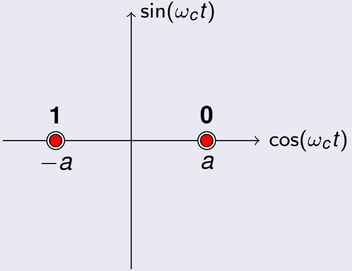
802.11b

- Operates at 2.4 GHz, ISM band (*Industrial Scientific and Medical*), known as "Wi-Fi" (*Wireless Fidelity*).
- Employs DSSS at transmission rates of 1, 2, 5.5 and 11 Mbps.
- Barker Code signal being modulated as QPSK (*Quadrature Phase Shift Keying*) at 2, 5.5 i 11 Mbps and as BPSK (*Binary Phase Shift Keying*) at 1 Mbps.
- 802.11b backward 802.11 compatible at 1 and 2 Mbps.

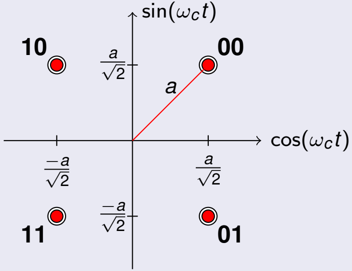
IEEE 802.11 Extensions: 802.11b

Modulations

BPSK



QAM

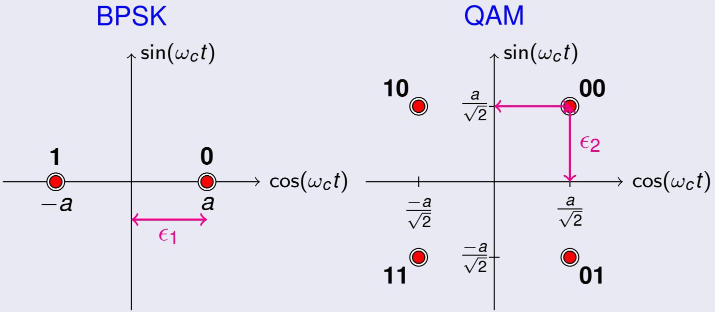


$$10_{bpsk} = \begin{cases} -a \cdot \cos(\omega_c t), & 0 \leq t < T_s, \quad (T_s = T_b) \\ a \cdot \cos(\omega_c (t - T_s)), & T_s \leq t < 2T_s \end{cases}$$

$$10_{qam} = -\frac{a}{\sqrt{2}} \cdot \cos(\omega_c t) + \frac{a}{\sqrt{2}} \cdot \sin(\omega_c t),\ 0 \leq t < T_s,\ (T_s = 2T_b)$$

IEEE 802.11 Extensions: 802.11b

Modulations

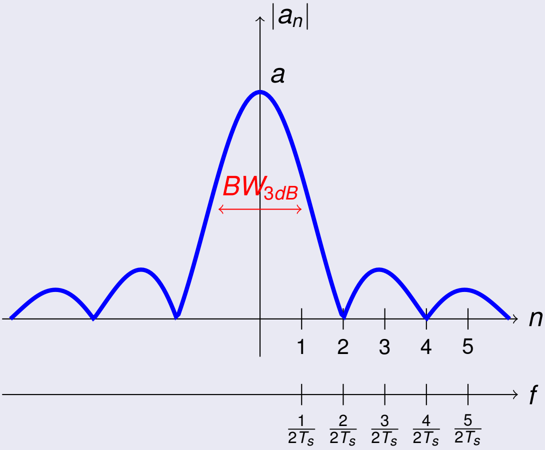


- QAM double transmission rate with the same bandwidth
- QAM more error sensitivity at the same power strength

IEEE 802.11 Extensions: 802.11b

Bandwidth for a $2T_s$ period pulse

$a_n = \frac{4a}{\pi n}\sin(\pi n/2)$

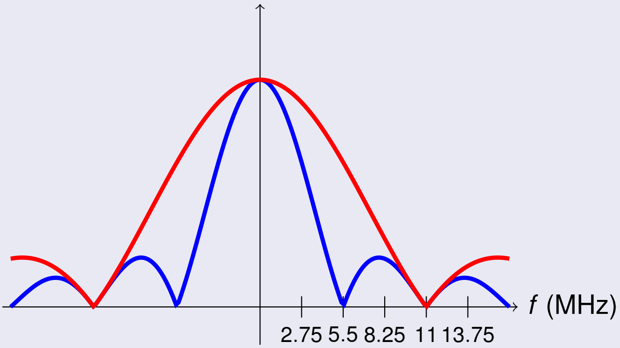


IEEE 802.11 Extensions: 802.11b

Bandwidth for a $2T_s$ period pulse

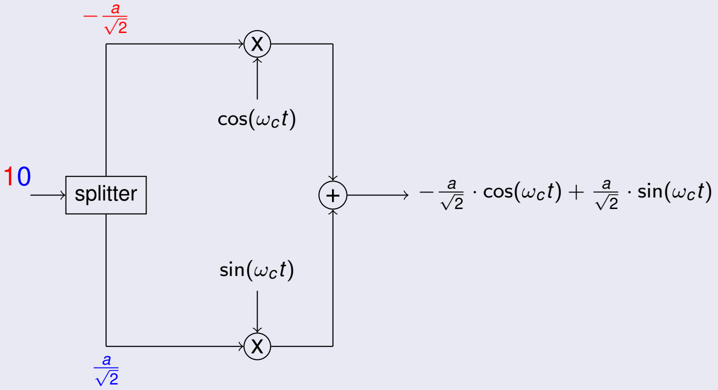
At 11 Mbps:

- QAM, $T_s = 0.18\,\mu$s
- BPSK, $T_s = 0.09\,\mu$s



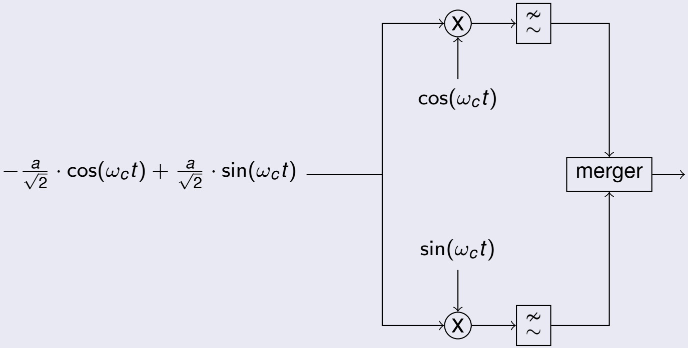
IEEE 802.11 Extensions: 802.11b

Transmission and reception outline



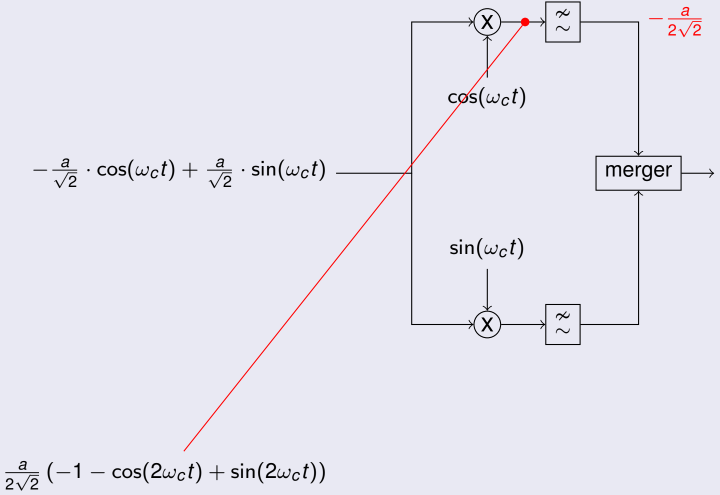
IEEE 802.11 Extensions: 802.11b

Transmission and reception outline



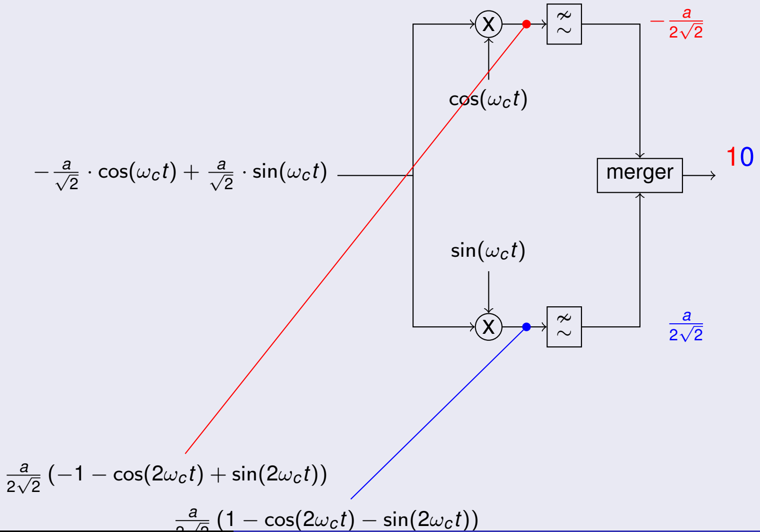
IEEE 802.11 Extensions: 802.11b

Transmission and reception outline



IEEE 802.11 Extensions: 802.11b

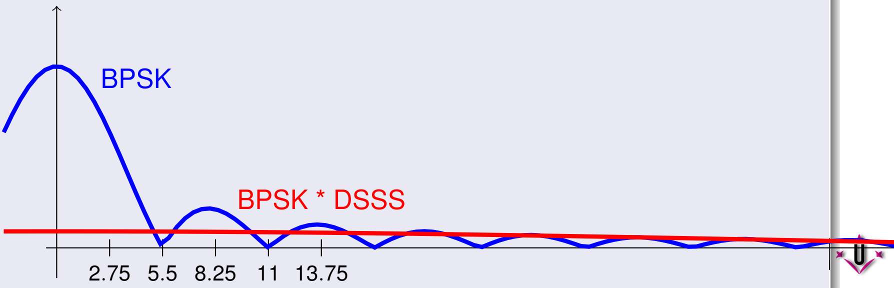
Transmission and reception outline



IEEE 802.11 Extensions: 802.11b

CDMA - DSSS

- Each information bit **XORed** with an established Barker Code
- Barker code consists on 11 chips for BPSK: + - + + - + + + - - -
- Multiple access technique as a modulation engine
- Deals better against interferences; orthogonality
- Spread Spectrum



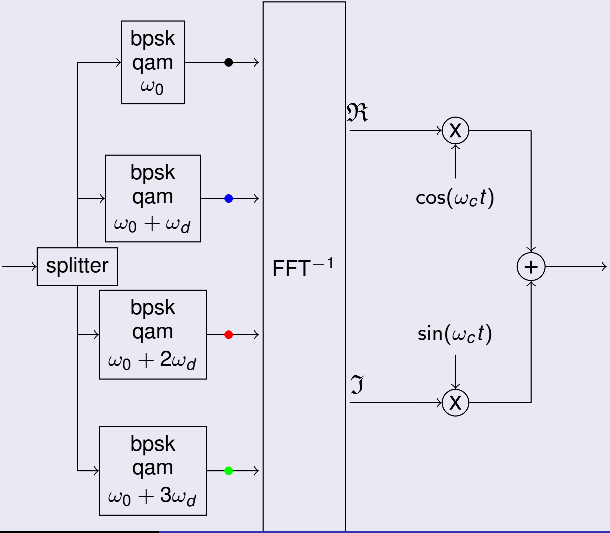
IEEE 802.11 Extensions: 802.11a

802.11a

- Working at 5 GHz (USA: 5.18 - 5.32, 5.745-5.805 GHz). UNII band (*Unlicensed National Information Infrastructure*)
- 33 channels(UNII-1 + UNII-2A + UNII-2C). 20 MHz separation
- Non compatible with the rest of wireless networks (working at 2.4 GHz.)
- Modulation OFDM (*Orthogonal Frequency Division Multiplexing*) $V_{T_{Max}}$ *54 Mbps*.
- OFDM splits a high speed carrier into 52 **orthogonal** sub-carriers, transmitting on the 52 sub-carriers at the same time
- Available rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps

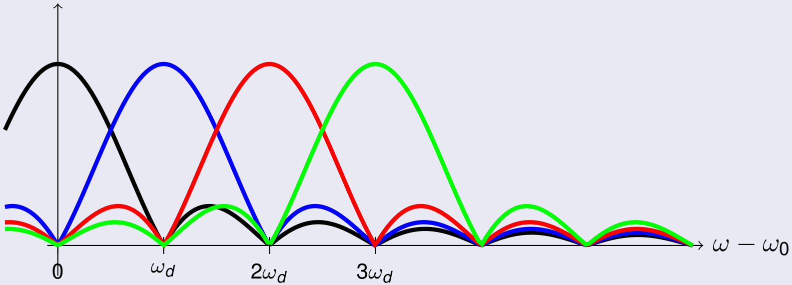
IEEE 802.11 Extensions: 802.11a

Example: 4 sub-carriers transmitter



IEEE 802.11 Extensions: 802.11a

Example: 4 sub-carriers transmitter



IEEE 802.11 Extensions

802.11g

- Same rates than 802.11a but 802.11b backward compatibility
- Operates at 2.4 GHz in ISM band
- For high transmission rates, OFDM is used, as in 802.11a
- 802.11g devices automatically change to QPSK modulation if only 802.11b compliant devices are detected

IEEE 802.11 Extensions

802.11n

- Transmission rates up to 600 Mbps
- a/b/g interoperability
- Several technologies employed
  - **Multiple Input Multiple Output** (MIMO)
  - **Channel Bonding**
  - MAC protocol enhancements

IEEE 802.11 Extensions

802.11ac

- Fifth generation wifi
- Transmission rates up to 6.9 Gbps
- Only operates at 5 GHz band
- Evolution of 802.11n
- Pushing forward 802.11n technologies (MIMO, Modulation)

IEEE 802.11 Extensions: 802.11n

MIMO

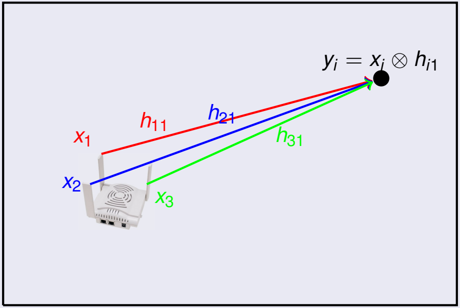
- Devices (APs and clients 802.11n) with multiple antennas

- Notation $M \times N$ indicates: M transmitting and N receiving antennas
- AP on picture may operates with the following configurations: 3×3, 3×2, 2×3, ...
- $M \geq 2$ for APs. $M \geq 1$ for clients

IEEE 802.11 Extensions: 802.11n

MIMO

- The transmitter split the information into *M* streams, being transmitted at the same time through each antenna **Spatial Multiplex**
- Each path **spatial signature** allows discrimination, determined by the **multipath** effect



IEEE 802.11 Extensions: 802.11n

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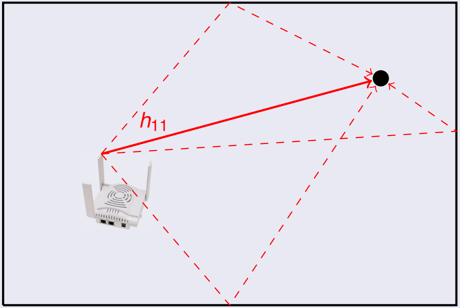

IEEE 802.11 Extensions: 802.11n

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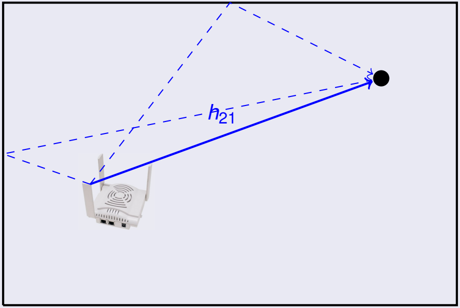

IEEE 802.11 Extensions: 802.11n

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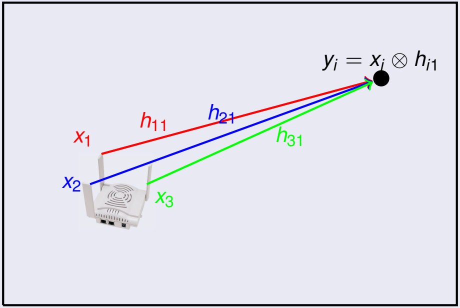


Multipath helps MIMO !

IEEE 802.11 Extensions: 802.11n

Channel Bonding

- Two channels are bonded, on each band (ISM or UNII; b/g or a)
- 20 MHz each channel
- 40 MHz total bandwidth

IEEE 802.11 Extensions: 802.11n

Modulation and Coding Scheme (MCS)

MCS	Type	*Coding rate*	SS	Mbps (20 MHz)	Mbps (40 MHz)
0	bpsk	1/2	1	6.5	13.5
1	qpsk	1/2	1	13.	27.
2	qpsk	3/4	1	19.5	40.5
...	...	...	...	......	......
7	64-qam	5/6	1	65.	135.
8	bpsk	1/2	2	13.	27.
...	...	...	...	......	......
15	64-qam	5/6	2	130.	270.
16	bpsk	1/2	3	19.5	40.5
...	...	...	...	......	......
31	64-qam	5/6	4	260.	540.

IEEE 802.11 Extensions: 802.11n

Modulation and Coding Scheme (MCS)

Modulation and coding schemes

MCS index	Spatial streams	Modulation type	Coding rate	Data rate (in Mbit/s)[a]			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15
1	1	QPSK	1/2	13	14.4	27	30
2	1	QPSK	3/4	19.5	21.7	40.5	45
3	1	16-QAM	1/2	26	28.9	54	60
4	1	16-QAM	3/4	39	43.3	81	90
5	1	64-QAM	2/3	52	57.8	108	120
6	1	64-QAM	3/4	58.5	65	121.5	135
7	1	64-QAM	5/6	65	72.2	135	150
8	2	BPSK	1/2	13	14.4	27	30
9	2	QPSK	1/2	26	28.9	54	60
10	2	QPSK	3/4	39	43.3	81	90
11	2	16-QAM	1/2	52	57.8	108	120
12	2	16-QAM	3/4	78	86.7	162	180
13	2	64-QAM	2/3	104	115.6	216	240
14	2	64-QAM	3/4	117	130	243	270
15	2	64-QAM	5/6	130	144.4	270	300
16	3	BPSK	1/2	19.5	21.7	40.5	45
17	3	QPSK	1/2	39	43.3	81	90
18	3	QPSK	3/4	58.5	65	121.5	135
19	3	16-QAM	1/2	78	86.7	162	180
20	3	16-QAM	3/4	117	130	243	270
21	3	64-QAM	2/3	156	173.3	324	360
22	3	64-QAM	3/4	175.5	195	364.5	405
23	3	64-QAM	5/6	195	216.7	405	450
24	4	BPSK	1/2	26	28.8	54	60
25	4	QPSK	1/2	52	57.6	108	120
26	4	QPSK	3/4	78	86.8	162	180
27	4	16-QAM	1/2	104	115.6	216	240
28	4	16-QAM	3/4	156	173.2	324	360
29	4	64-QAM	2/3	208	231.2	432	480
30	4	64-QAM	3/4	234	260	486	540
31	4	64-QAM	5/6	260	288.8	540	600

From wikipedia

IEEE 802.11 Extensions: 802.11n

Enhancement Factors

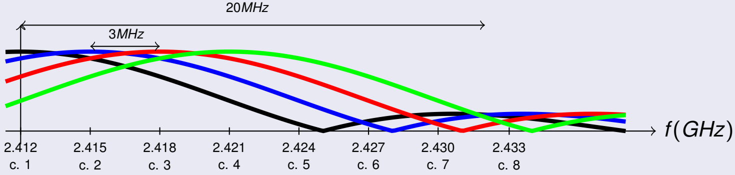
Rate	Technique
54 Mbps	OFDM conventional (48 subcarriers) As 802.11g/802.11a
65 Mbps	Up to 52 subcarriers
135 Mbps	Channel bonding (40 MHz)
$<$ 600 Mbps	Up to MIMO 4$\times$4

IEEE 802.11 Extensions: 802.11n

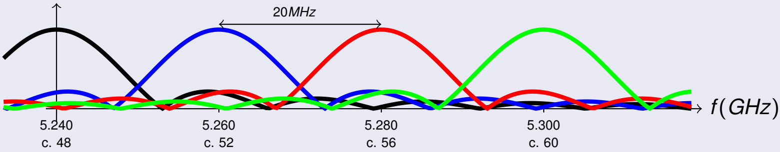
Comparing channel assignment for ISM and UNII bands

MCS=0 (bspk, 6.5 Mbps, Coding rate=1/2). Bits=101010... $T_0 = 1/6.5\mu s = 0.15\mu s$. $BW_{between\_zeros} = 26$ MHz

ISM



UNII



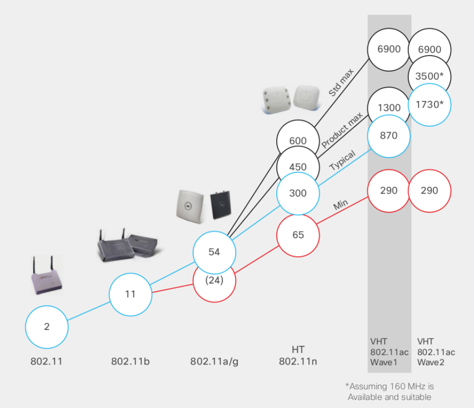
IEEE 802.11 Extensions: 802.11ac

Enhacements

- Modulations up to 256 QAM with $1/r = 5/6$
- More spatial streams, $M = 8$
- Larger bandwidths: 20, 40 , 80 and 160 MHz

IEEE 802.11 Extensions: 802.11ac

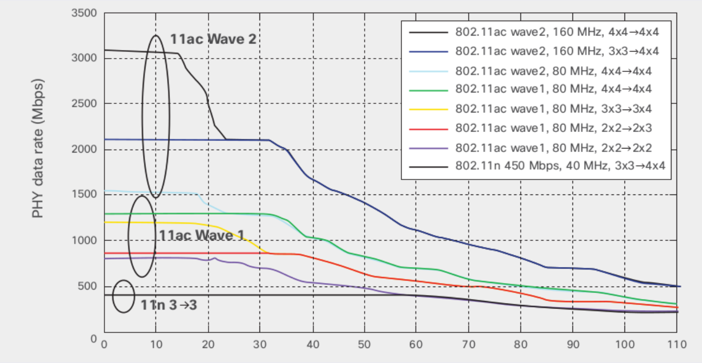
802.11 bandwidth evolution



From: 802.11ac: The Fifth Generation of Wi-Fi Technical White Paper. Cisco

IEEE 802.11 Extensions: 802.11ac

802.11 bandwidth range



From: 802.11ac: The Fifth Generation of Wi-Fi Technical White Paper. Cisco

Contents

Contents outline

- **Connection process.** Scan, authentication and association
- **Authentication**
    - Mechanisms (SSID, MAC, Captive Portal, 802.1x)
    - Protocols (PAP, CHAP, MSCHAP, EAP)
    - 802.1x (EAPOL)
- **Ciphers**
    - WEP (outdated)
    - 802.11i (WPA2)
        - TLS (Protocol for authentication and key agreement)
        - TKIP (Protocol for key interchange)

WiFi connection

Connection process phases

1. Scan
2. Authentication
3. Association

WiFi connection

Scan

- Client searches for a compatible wireless network
- **Beacon frames** employed
- Two working modes:
  - **Active scan**. Client sends **Probe Request** frames through each available channel
  - **Passive scan**. Client doesn't transmit. Expecting beacon frames

The scan scope may be limited to a given **SSID**

WiFi connection

Authentication

- Directed authentication. Clients $\rightarrow$ network
- Employed frames: Authentication Request, Authentication Response
- Two mechanisms:
  1. Open System Authentication (OSA). Default mechanism
  2. Shared Key Authentication (SKA).
     Employs **Wired Equivalent Privacy** (WEP) protocol. Both, AP and client shares a common key

  Upon both mechanisms, manufacturers use proprietary authentication methods (based on MAC address, on SSID, Captive Portal, . . .)

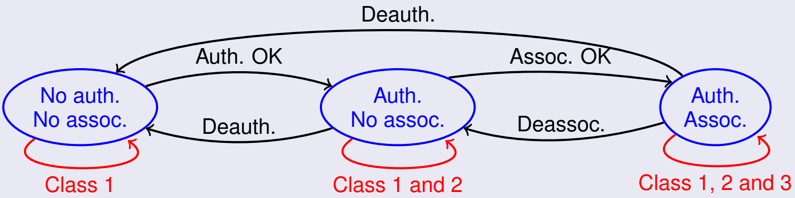
WiFi connection

Association

- Employed frames: Association Request and Association Response
- When client receives Association Response, WiFi services are operative

WiFi connection

Connection states



Class	Control	Management	Data
1	RTS CTS ACK	*Probe Request* *Probe Response* *Beacon* *Authentication* *Deauthentication* ATIM	To DS = 0 and From DS = 0
2		*Association Request/Request* *Reassociation Request/Request* *Disassociation*	
3		*Deauthentication*	To DS = 1 or From DS = 1

WiFi connection

Access Control Lists (ACL)

- ACL not included in 802.11 standard, but implemented in most APs
- It is a list of allowed MAC
- During **association**, the client MAC is checked in ACL
- If check fails, *Association Response* is sent, denying its access

Authentication

Methods

- Based on SSID (Service Set Identifier)
- Based on MAC
- Captive Portal
- 802.1x

Based on SSID

- Used on a first stage (open or protected) to allocate the clients at the corresponding subnet (corp, visitor, . . .)
- Then, proceed with the corresponding authentication method, i.e. (corp: 802.1x, visitor: Captive Portal)

Authentication

Based on MAC

- Insecure
- Suitable for light devices with few ability to authenticate (printers, scanners, . . .)
- MAC tables must be defined at APs or WiFi Controllers (centralized deployments)

Authentication

Captive Portal

- Open Authentication/Association
- Useful when changing users (hotels, visitors, . . .)
- Steps:
  1. Client associates to an open SSID. Gets IP, DNS, . . .
  2. Firewall (AP or central) allows DNS queries. Drops any other traffic
  3. Client HTTP requests are NAT-Destined to an authentication web (via https)
  4. Once authenticated, the firewall opens traffic for the client and sends a **HTTP redirect** to the client

Authentication

Authentication protocols

- PAP *(Password Authentication Protocol)*
- CHAP *(Challenge Authentication Protocol)*
- MSCHAP *(Microsoft Challenge Authentication Protocol)*
- EAP *(Extensible Authentication Protocol)*

Authentication

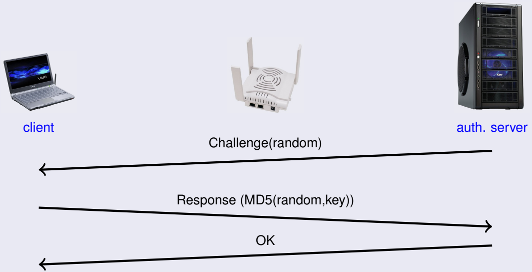
PAP *(Password Authentication Protocol)*

- The client sends `login:password` in clear text
- Insecure.

Authentication

CHAP *(Challenge Authentication Protocol)*

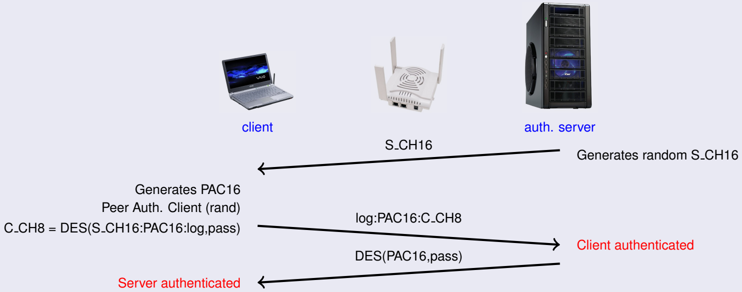
- *3-way handshake*



Authentication

MSCHAP *(Micro$oft Challenge Authentication Protocol)*

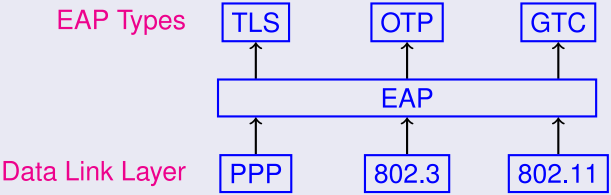
- v1. Same scheme than CHAP. DES cipher instead MD5
- v2. No backward compatibility. Authenticates server and client



Authentication: EAP

EAP *(Extensible Authentication Protocol)*

- Basis for 802.1x
- Initially thought for PPP *(Point to Point Protocol)*
- **Framework** supporting different authentication mechanisms: MD5, *One Time Password*, TLS, TTLS, LEAP, . . .



From: Wireless Networks, The Definitive Guide, O'Reilly, 2002

Authentication: EAP

EAP: Frame

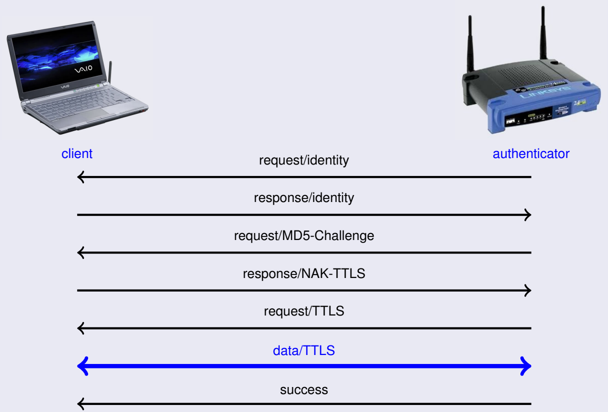
- **Code**: request (1), response (2), success(3)
- **Identifier**: It is the same for the corresponding *requests* and *responses*
- **Length**
- **Type**:
  1. Identity
  2. Notification
  3. NAK, suggests a new authentication method
  4. MD5
  5. OTP
  6. GTC

  13 TLS

  21 TTLS
- **Data**

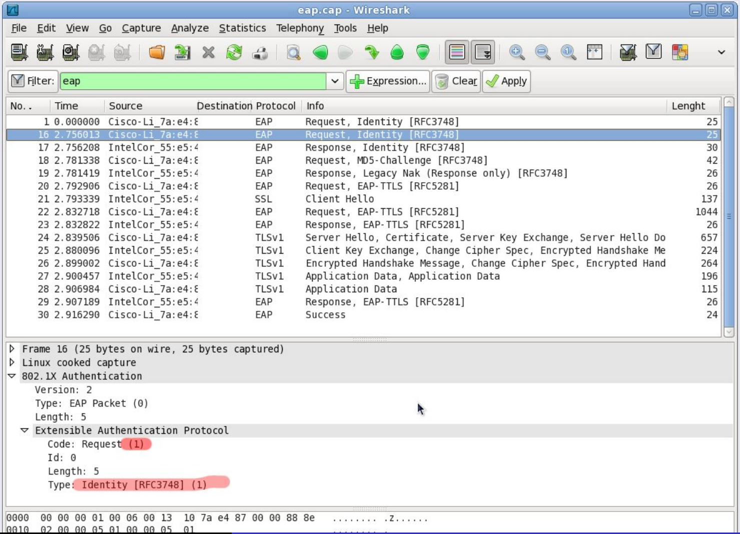
Authentication: EAP

EAP: example



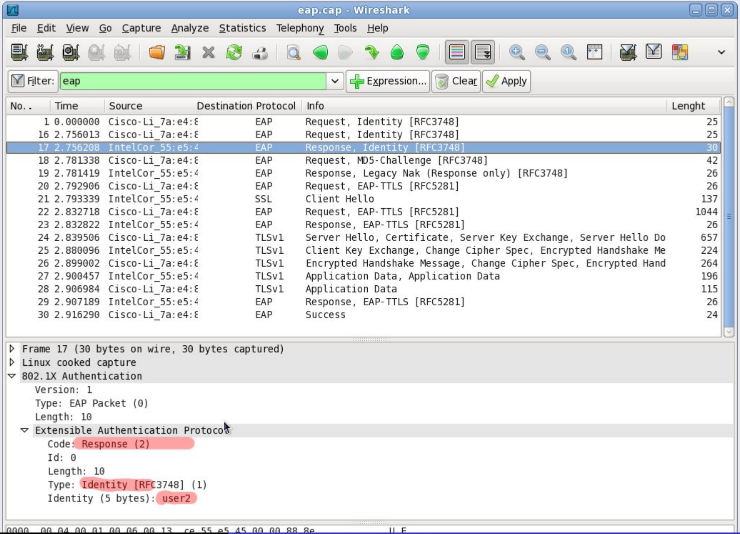
Authentication: EAP

EAP: example



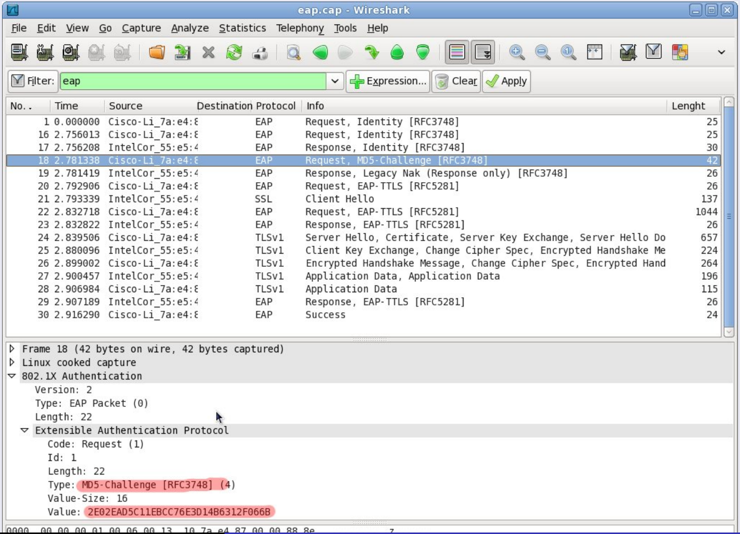
Authentication: EAP

EAP: example



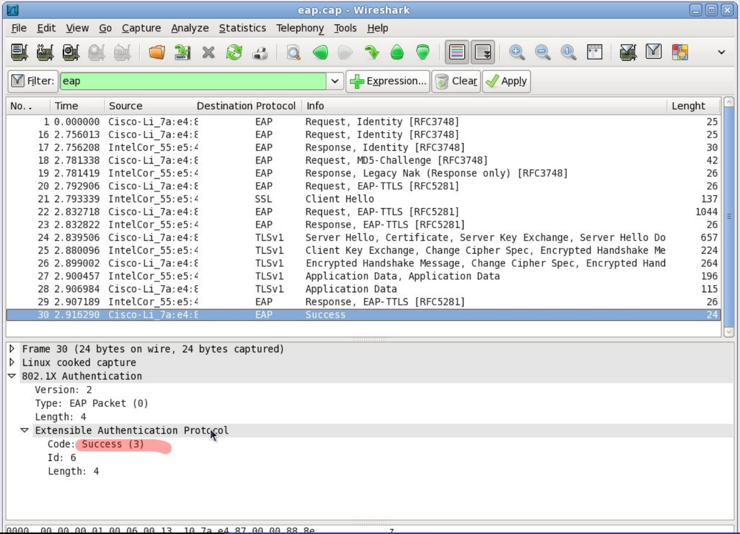
Authentication: EAP

EAP: example



Authentication: EAP

EAP: example



Authentication: 802.1x

802.1x

- Defines a **port-based** authentication method
- Initially thought for 802.3*(Ethernet)*
- Also known as EAPOL *(EAP over LAN)*
- Main parts:
  - **Supplicant**: Client
  - **Authenticator**: Can be the AP or the WiFi Controller
  - **AAA Server**: *(Accounting, Authorization and Authentication Server)*. Can be a RADIUS server

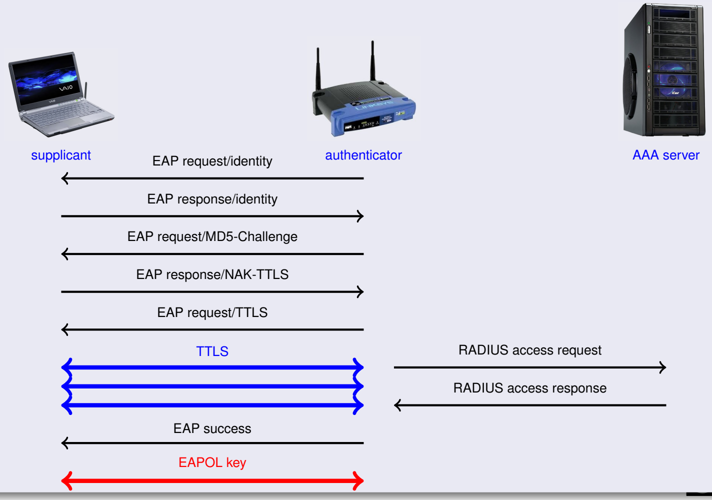
Authentication: 802.1x

Frame Format

- **MAC Header**: source and destination addresses
- **Type**: Ethernet
- **Version**: 1
- **Frame type**:
  - EAP-Packet (EAP Frames)
  - EAPOL-Start (*Supplicant* starts the process when no started by the *Authenticator*)
  - EAPOL-Logoff
  - EAPOL-Key (Crypto content for key establishment)
- **Length**
- **Frame body**

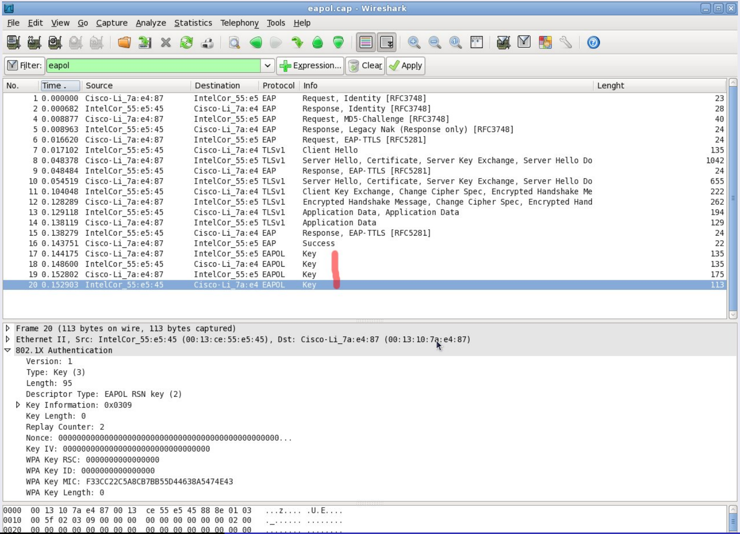
Authentication: 802.1x

Example



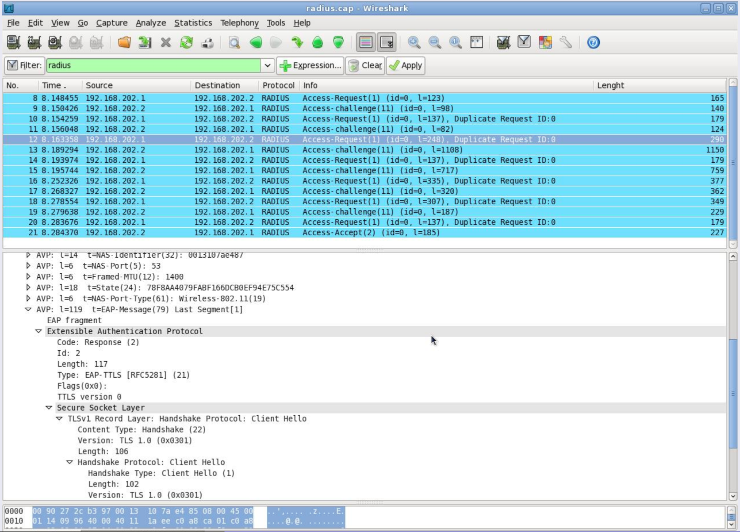
Authentication: 802.1x

EAP: example



Authentication: 802.1x

EAP: example



WEP, Wireless Enhanced Privacy

WEP facts

802.11 uses WEP as cipher algorithm

- PRNG (*Pseudo-Random Number Generator*)
- **Stream cipher** method RC4 (*Rivest Cryptosystem number 4*)
- Broken in 2000

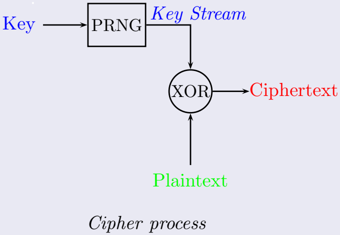
WEP Keys

- 4 keys. Only one used for cipher/decipher
- Two ways of generation:
  - *Static*: The key is written on each device
  - *Dynamic*: Generated from a **pass phrase**

WEP, Wireless Enhanced Privacy

WEP Cipher method

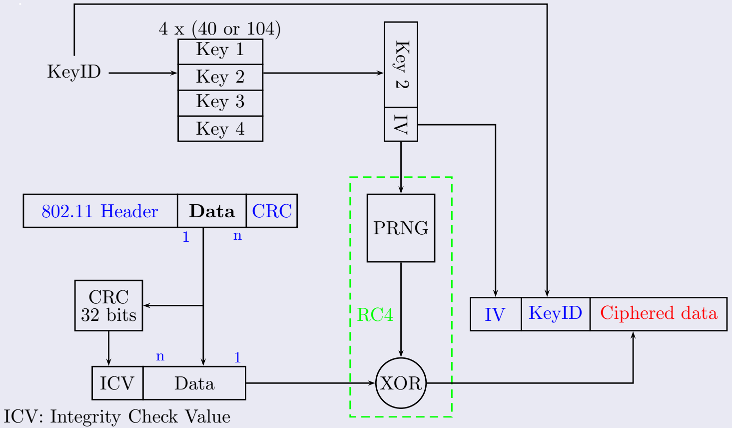
Based on RC4



WEP, Wireless Enhanced Privacy

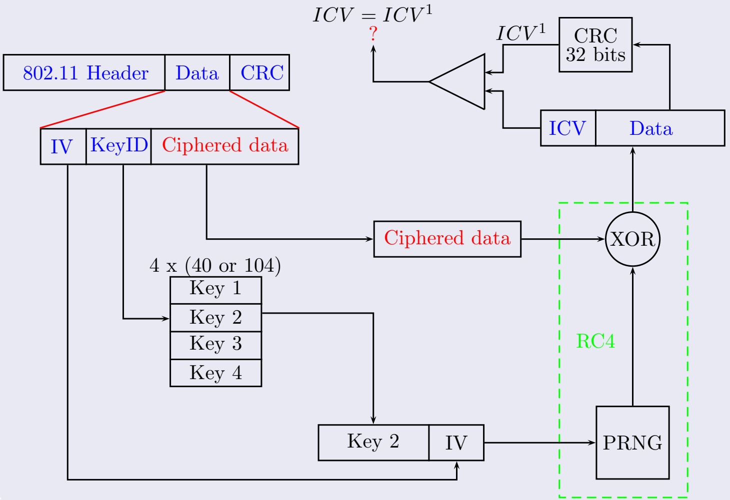
WEP Cipher method

Based on RC4



WEP, Wireless Enhanced Privacy

WEP Decipher method



802.11i

802.11i facts

- Standard for wireless network security. Approved in July, 2004
- Improves security pitfalls on previous mechanisms
- WPA *(WiFi Protected Access)* is a subset of 802.11i
- Security methods
  - RSNA (Robust Security Network Association):
    - WPA: WEP + TKIP (Temporal Key Integrity Protocol)
    - WPA2: AES128 + CCMP (Counter Mode with CBC-MAC Protocol)
    - WPA3: AES128 + CCMP in personal mode. AES256-GCM-SHA384 (GCM: Galois Counter Mode) in enterprise mode. Replaces PSK by SAE (Simultaneous Authentication of Equals)
    - Key management
  - Pre-RSNA. (WEP)
- WPA2/3 modes may authenticate using PSK (Pre-Shared Keys) (WPA-Personal) or 802.1x (WPA-Enterprise)

802.11i

TKIP (Temporal Key Integrity Protocol)

- Creates a MIC (Message Integrity Code) based on frame data and header to enable authentication (Michael algorithm)
- Uses the temporal key obtained from key management (see later) to derive RC4 key and WEP seed
- MIC prevent attacks based on:
  - bit flipping
  - iterative guessing of the key
  - redirection and impersonation (changing MAC addresses)

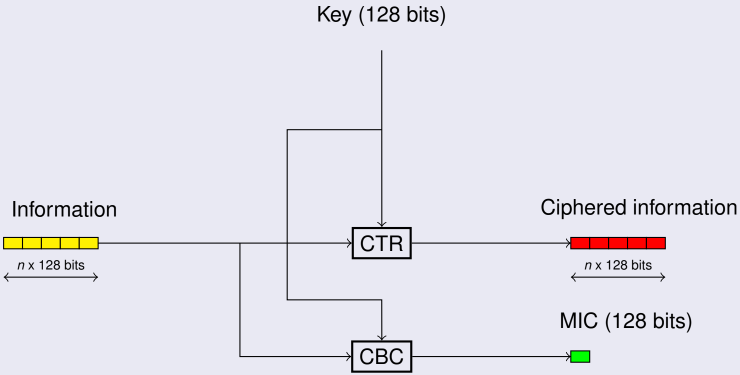
802.11i

Counter Mode with CBC-MAC Protocol (CCMP)

- AES (Advanced Encryption Standard) based cipher method. Cipher function with 128, 192 or 256 bits length security
- Algorithm CCM (Counter mode with CBC-MAC) employed, giving privacy, integrity and authentication
- CCMP is mandatory when 802.11i employed
- Two CCM **cipher modes**: CTR *(Counter)* and CBC *(Cipher Block Chaining)* using the **same key** with 2 different objectives:
  1. CTR. Ciphers information. Converts a block cipher as AES into a stream cipher mechanism
  2. CBC.Uses the last ciphered block as a Message Integrity Code (MIC)

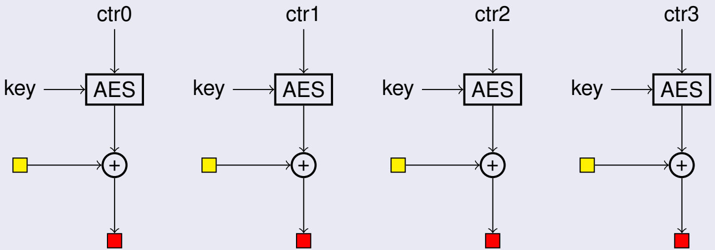
802.11i

CCM outline



802.11i

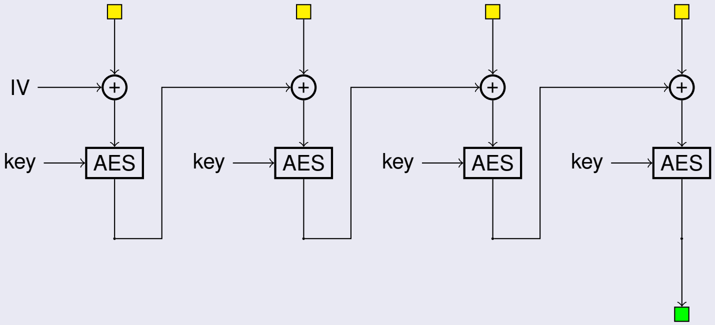
CCM: CTR mode



- ctr$i$: 128 bits length block, no secret, different, generated for each key

802.11i

CCM: CBC mode



- IV. Initialization vector.
  0x00000000000000000000000000000000

802.11i

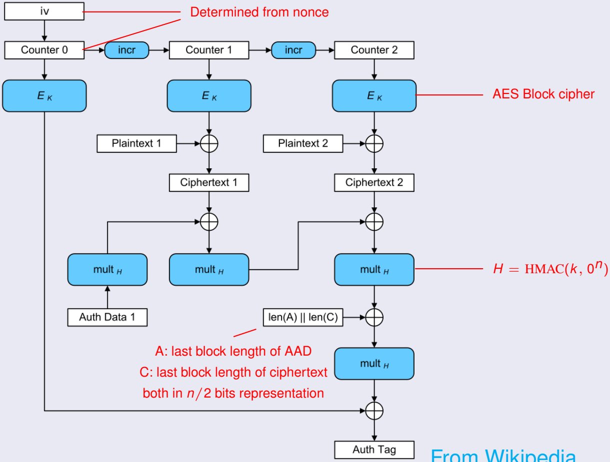
Galois Counter Mode (GCM)

- Included in TLS1.3 and WPA3
- Authenticated encryption. Uses AAD (Additional and Authenticated Data) to generate a MIC (tag) field for authentication
- As in Counter Mode Ciphers (as CCMP) it is a stream cipher
- Operates in $GF(2^n)$ where n is the block size (128,256, ...)
- `AESGCM` parameters for ciphering:
  - Key
  - Nonce (initializes IV)
  - AAD (A)
  - Plaintext

  outputs:
  - Ciphertext (C)
  - Authentication tag

802.11i

Galois Counter Mode (GCM)



From Wikipedia

802.11i

Key management

- RSNA defines two key hierarchies:
  - Pairwise key. Protects unicast traffic
  - GTK (Group Temporal Key). Protects multicast and broadcast traffic
- Key exchange at frames EAPOL-Key
- First, PMK (Pairwise Master Key) is set at both ends based on:
  - Pre-shared keys (PSK) (WPA2-Personal)
  - 802.1x negotiation (WPA2-Enterprise)
- Then, 4-way handshake is used to derive:
  - PTK (Pairwise Temporal Key): protects handshake traffic
  - GTK
  - TK (Temporal Key): protects unicast traffic
- Handshake may be periodically updated to renew keys in a session

802.11i

4-way handshake

supplicant

authenticator

a_nonce ←

Compute PTK=PMK+a_nonce +s_nonce+a_MAC+s_MAC

s_nonce + MIC →

PTK computation

GTK + MIC ←

ack →

Ciphered traffic

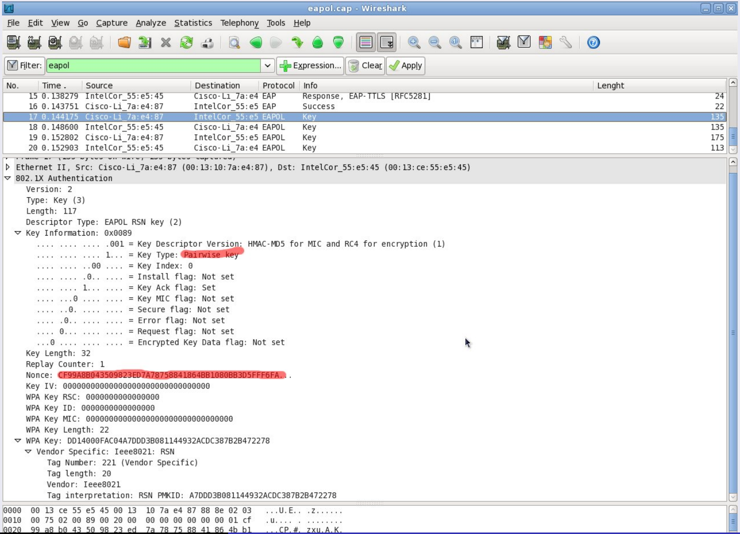
PTK: Pairwise Temporal Key

GTK: Group Temporal Key

MIC: Message Integrity Code

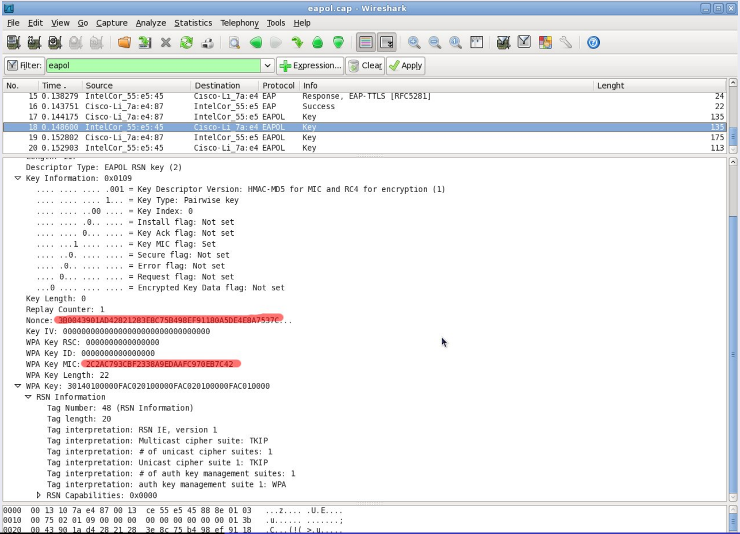
802.11i

4-way handshake example



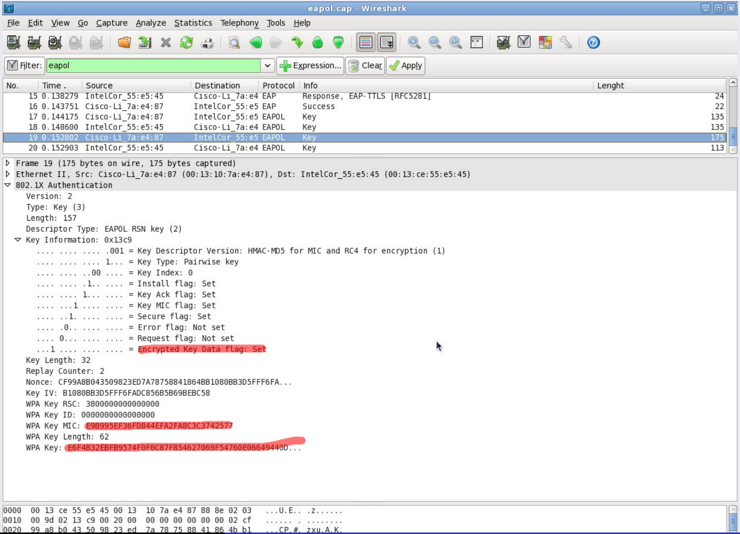
802.11i

4-way handshake example



802.11i

4-way handshake example



802.11i

802.1x authentication and master key establishment

- Different authentication mechanisms supported by EAP
- Some of them also allow to establish secure keys at both ends
- TLS *(Transport Layer Security)*. More reliable mechanism
- Find here more on TLS
- Problem: Certificates required in order to authenticate clients
- TTLS *(Tunneled TLS)* relax previous requirement (no client certificate required). An AAA server may be used for client authentication
- Both mechanisms end with the establishment of a 384 random bits block (**Master Block**), only known by both communicating parts

802.11i

WPA2-Personal in detail (AES128-CCMP)

- PSK=PBKDF2HMAC(key='passphrase', algo=SHA1, salt=SSID,length=32,iteration=4096)
- data='Pairwise key expansion' || `0x00` || `MAC_add1` || `MAC_add2` || `nonce_1` || `nonce_2`
- `MAC_add1`, `MAC_add2`, `nonce_1`, `nonce_2` correspond to MAC addresses 1 and 2 of MAC header and nonces of handshake 1 and 2. (Ordered: less first)
- PTK = SHA1_HMAC(key=PSK, in=data, length=48)

```
def  SHA1_HMAC(key, in, length):
  r=''
  for i in [0:⌈ length/20 ⌉]: #(20 is the size of SHA1)
    r+=HMAC(key, algo=SHA1, in=in || i (1 byte))
  return r[:length]
```

- KCK=PTK[0:16]. EAPOL-Key Confirmation Key. Used to compute MIC on WPA EAPOL Key message
- KEK=PTK[16:32]. EAPOL-Key Encryption Key (KEK). Used to encrypt GTK
- TK=PTK[32:48]. Temporal Key (TK). Used to encrypt/decrypt Unicast data packets
- MIC for handshake messages from 2 to 4 is computed as:
  - i $\in$ [2, 4]
  - `mess_i` is the 802.1x authentication part of handshake message i
  - data=`mess_i`[0:81] || (`0x00`)*16 || `mess_i`[81+16:] (MIC field masked with 0)
  - MIC=HMAC(key=KCK, algo=SHA1, in=data)
  - If MIC == `mess_i`[81:81+16] message is authentic

802.11i

WPA2-Personal in detail (AES128-CCMP)

- Unwrap GTK
  - data is WPA Key Data in handshake message 3 (GTK AES wrapped)
  - GTK=AES_UNWRAP(key=KEK, in=data)[30:46]
  - Used to encrypt/decrypt multicast/broadcast data packets
- Decrypt a data packet. AESCCMP requires:
  - A nonce (to initialize IV)
  - AAD (Additional Authenticated Data) to compute the MIC (also called tag)
- If frame has QoS field:
  - AAD = FrameControl (2 bytes) || Address_1 (6 bytes) || Address_2 || Address_3 || `0x0000` || QoSControl[0:2]
  - nonce=QoSControl[0:1] || Address_2 || CCMPpar[0:2] || CCMPpar[4:8]
- If QoS does'nt exist:
  - AAD = FrameControl || Address_1 || Address_2 || Address_3 || `0x0000`
  - nonce=`0x00` || Address_2 || CCMPpar[0:2] || CCMPpar[4:8]
- CCMPpar is a 8 bytes field in 802.11 data frame. Implements an incremental counter
- AESCCM_decrypt(key=TK, tag_length=8, in=encrypted_data, nonce=nonce, associated_data=AAD) Unicast packets
- AESCCM_decrypt(key=GTK, tag_length=8, in=encrypted_data, nonce=nonce, associated_data=AAD) Multicast/Broadcast packets

802.11i

WPA2-Enterprise in detail (TLS-AES256-GCM-SHA384)

Getting the Master Key

- Even ciphersuite is TLS-AES256-GCM-SHA384:
  - AES256-GCM-SHA384 for tunneling encryption
  - WPA2 will use AES128-CCMP in the 4-way-handshake
- pm: decrypted premaster from Client Key Exchange
- `def` PRF(key,label,seed,algo,n): # Pseudo Random Function

  seed=label || seed

  A_0=seed , B=""

  `for` i `in` [1:n+1]:

  A_i= HMAC(key=pm,in=A_{i-1},algo=algo)

  `for` i `in` [0:n]:

  $B = B$ || HMAC(key=pm,in=A_{i+1}|| seed,algo=algo)

  `return` B
- s = SHA384(`ClientHello` || `ServerHello` || `ServerCert` || `ServerHelloDone` || `ClientKeyExchange`)
- MasterKey = PRF(key=pm,label="extended master secret",seed=s, algo=SHA384, n=1)[0:48]

802.11i

WPA2-Enterprise in detail (TLS-AES256-GCM-SHA384)

Decrypting inner authentication (EAP-PAP/CHAP/...)

- AES256-GCM-SHA384 requires:
  - 64 bytes for client and server keys
  - 8 bytes for client and server IV
  - No MAC keys needed
- s = `ServerHello.random` || `ClientHello.random`
- KeyBlock = PRF(key=MasterKey, label="key expansion",seed=s, algo=SHA384, n=2)[0:72]
- `client_write_key` = KeyBlock[0:32]
- `server_write_key` = KeyBlock[32:64]
- `client_write_iv` = KeyBlock[64:68]
- `server_write_iv` = KeyBlock[68:72]
- Assume data being the encrypted EAP message
- tag = data[-16:] Authentication tag
- GCM Nonce has two parts:
  - Explicit: goes in the data. First 8 bytes
  - Implicit: derived from IV
- `client_nonce` = `client_write_iv` || data[0:8]

802.11i

WPA2-Enterprise in detail (TLS-AES256-GCM-SHA384)

Decrypting inner authentication (EAP-PAP/CHAP/. . .)

- `seq_num` = `0x0000000000000001`
- `content_type` = `0x17`
- `version` = `0x0303`
- `ciphertext_length` = len(data)-24 (2 bytes). 8 explicit nonce + 16 tag
- AAD = `seq_num` || `content_type` || `version` || `ciphertext_length`
- AESGCM_decrypt(in=data[8:],nonce= `client_nonce` , key=`client_write_key`, associated_data=AAD)

802.11i

WPA2-Enterprise in detail (TLS-AES256-GCM-SHA384)

4-way handshake

- s = `ClientHello.random` || `ServerHello.random`
- KeyBlock = PRF(key=MasterKey, label="ttls keying material",seed=s, algo=SHA384, n=2)
- MSK = KeyBlock[0:64]
- data='Pairwise key expansion' || `0x00` || `MAC_add1` || `MAC_add2` || `nonce_1` || `nonce_2`
- `MAC_add1`, `MAC_add2`, `nonce_1`, `nonce_2` correspond to MAC addresses 1 and 2 of MAC header and nonces of handshake 1 and 2. (Ordered: less first)
- PTK = SHA1_HMAC(key=MSK[0:32], in=data, length=48)
- KCK, KEK and TK as before
- Handshake messages authenticated as before
- GTK decrypted as before
- Data packet decrypted as before

Contents

Wifi deployments

The challenges

A medium/large size wifi deployment presents some challenges:

1. **Coverage**
   - Limited coverage range per AP (less than 100 mts). Infrastructure/building dependent
   - Trade-off between density deployment and cost
   - Radio Frequency plan required to avoid interferences
   - Network backbone determines AP situation. Mesh networks
2. **Capacity**
   - Some spot areas may require higher bandwidth. Dual 802.11 b/g and 802.11a deployments
   - Roaming may be required. IP mobility
   - Non stationary scenario. People moves, so bandwidth requirement changes
3. **Security**
   - Per user based security profiles (students, staff, visitors, . . .)
   - Don't rely on weak encryption methods
   - Integration to the corporate authenticators

Wifi deployments

Two approaches

- **Fat APs**
  - Suitable for small deployments
  - AP contains full configuration parameters
  - Cheap solution but hard to manage
  - Open source initiatives DD-WRT
- **Centralized control and Thin APs**
  - AP boots configuration from controller
  - APs merely radio repeaters
  - Controller have the full network configuration
  - Many integrated features: firewall, automatic radio management, radio frequency planner, . . .
  - Easy to manage
  - Proprietary solutions: Alcatel-Lucent, Aruba, Cisco, . . .

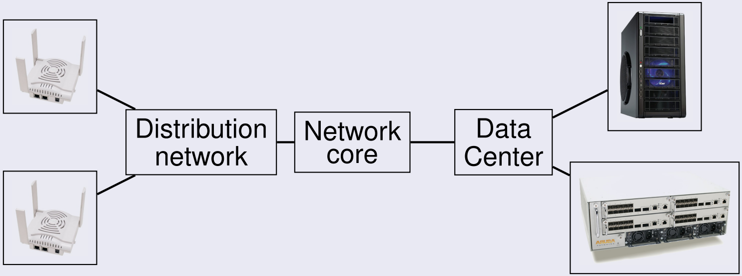
Centralized control architecture

The components

- **Controller**
  - Performs all the configuration and management tasks for WLAN
  - Provides APs their config parameters
  - Control over radio assignments (frequency and power), avoids interferences, central security checks
  - Ends communication AP tunnels
  - Must be sized according to the number of APs
- **Thin APs**
  - Mere radio repeaters
  - Boots from controller
  - Multiple SSID (virtual AP)
  - Consider 20/30 users per AP
- **Software modules**. Define WLAN features: firewall, mesh, mobility, intrusion detection and response, adaptive radio management, . . .
- **Licenses**. May be based on; number sessions, number APs, WLAN features, . . .

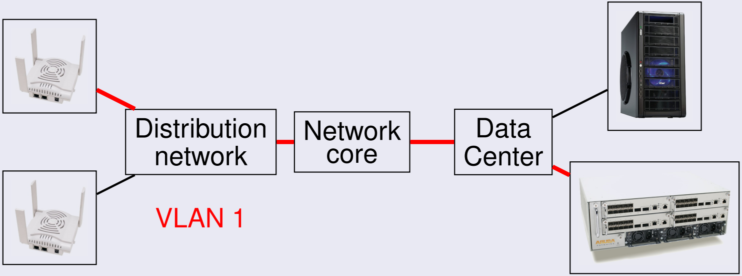
Centralized control architecture

Architecture outline



Centralized control architecture

Architecture outline



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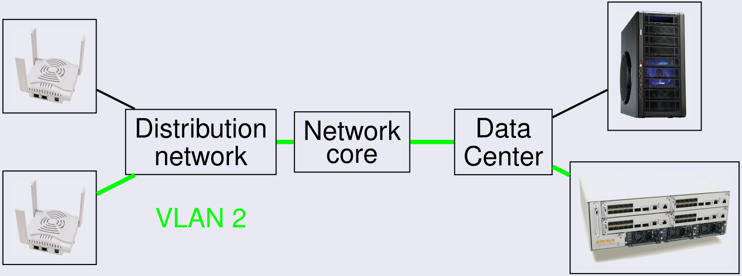

Centralized control architecture

AP booting process

1. AP must be able to obtain IP by DHCP
2. As well as the controller IP (statically or dynamically through DHCP option 41)
3. GRE tunnels are established between APs and controller
4. All AP traffic flows through controller (unless alternative AP operation modes specified; remote AP, . . .)

Alcatel-Lucent Instant AP

Description

- Small deployments with centralized control not much expensive
- No controller needed. Control tasks assumed by an AP
- Up to 16 APs and 256 users per deployment
- APs family supported (IAP-105, 92, 93, 134 and 135)

Alcatel-Lucent Instant AP

Main features

- Easy configuration. Automatic master controller AP establishment (virtual controller)
- Web control interface
- Mesh networks support
- Authentication methods:
  - 802.1x
  - Captive portal
  - Based on MAC
- Firewall capabilities. Rules can be created
- Adaptive Radio Management (ARM)
  - Voice and load aware
  - Band steering (2.4 - 5 GHz)
  - Load balancing and air-time fairness
- Intrusion and Detection System (IDS). Rogue detection and containment methods

Contents

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- RFC 5281. Extensible Authentication Protocol Tunneled Transport Layer Security Authenticated Protocol Version 0 (EAP-TTLSv0)