WLAN IEEE 802.11
aka Wi-Fi

Max Riegel

Lectures overview

June 27th

- Wi-Fi deployments
- Standardization environment
- Wi-Fi system architecture
- Wi-Fi security

July 4th

- Medium access functions
- MAC layer management frame formats
- Quality of Service
- Wi-Fi roaming and Hotspot 2.0
- WLAN management

July 11th

- Wireless channel characteristics
- Wi-Fi radio for 2.4 GHz and 5 GHz bands
- WiGig extension for 60 GHz bands
- HaLow extension for below 1GHz bands

Standards environments

STANDARD REFERENCE

IEEE Std 802.11™-2016

IEEE Standard for Information technology—
Telecommunications and information exchange between systems
Local and metropolitan area networks—
Specific requirements

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

IEEE Computer Society

- *Can be downloaded at no charge by IEEE Get Program*
  - *http://standards.ieee.org/getieee802/download/802.11-2016.pdf*
- *No all the features specified in the standard are available in real Wi-Fi products*
- *Where appropriate presentation adopts behavior of real Wi-Fi products as specified by Wi-Fi Alliance in its certification programs*
  - *https://www.wi-fi.org/discover-wi-fi/specifications*

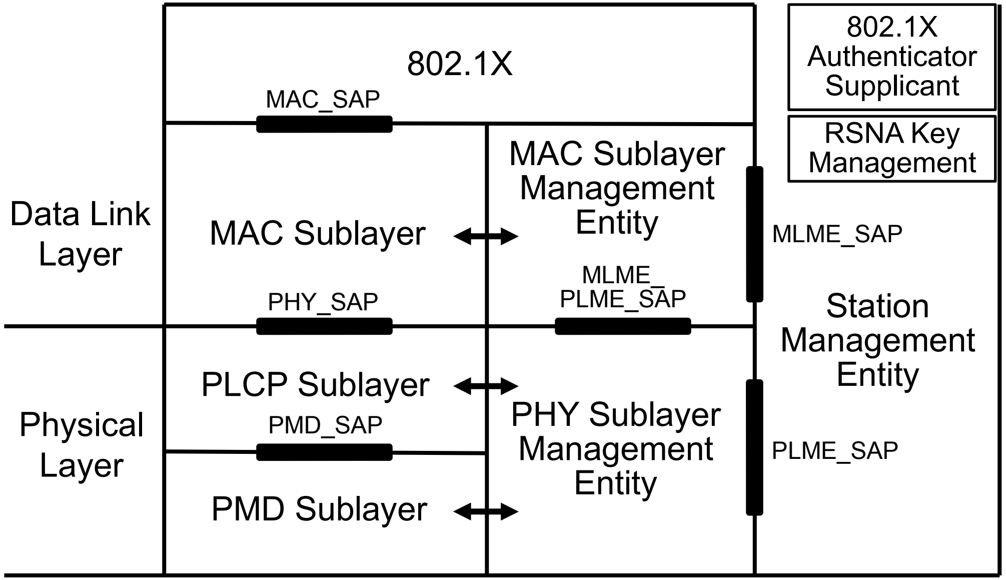
IEEE Standard for Information technology

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

- Revision of IEEE Std 802.11-2012
  - Revision of IEEE Std 802.11-2007
    - Revision of IEEE Std 802.11-1999
      - First IEEE 802.11 standard release in 1997
- Comprises initial IEEE Std 802.11-1999 together with all amendments IEEE 802.11a-1999 … IEEE 802.11af-2013
  - *i.e.:* a, b, d, e, g, h, I, j, k, n, p, r, s, u, v, w, y, z, aa, ac, ad, ae, af

IEEE802.11 Protocol architecture

- 802.1X
  - Port Access Entity
  - Authenticator/Supplicant
- RSNA Key Management
  - Generation of Pair-wise and Group Keys
- Station Management Entity (SME)
  - interacts with both MAC and PHY Management
- MAC Sublayer Management Entity (MLME)
  - synchronization
  - power management
  - scanning
  - authentication
  - association
  - MAC configuration and monitoring
- MAC Sublayer
  - basic access mechanism
  - fragmentation
  - encryption
- PHY Sublayer Management Entity (PLME)
  - channel tuning
  - PHY configuration and monitoring
- Physical Sublayer Convergence Protocol (PLCP)
  - PHY-specific, supports common PHY SAP
  - provides Clear Channel Assessment signal (carrier sense)
- Physical Medium Dependent Sublayer (PMD)
  - modulation and encoding



WLAN IEEE 802.11

MEDIUM ACCESS FUNCTIONS

Medium Access Functions in IEEE802.11 architecture

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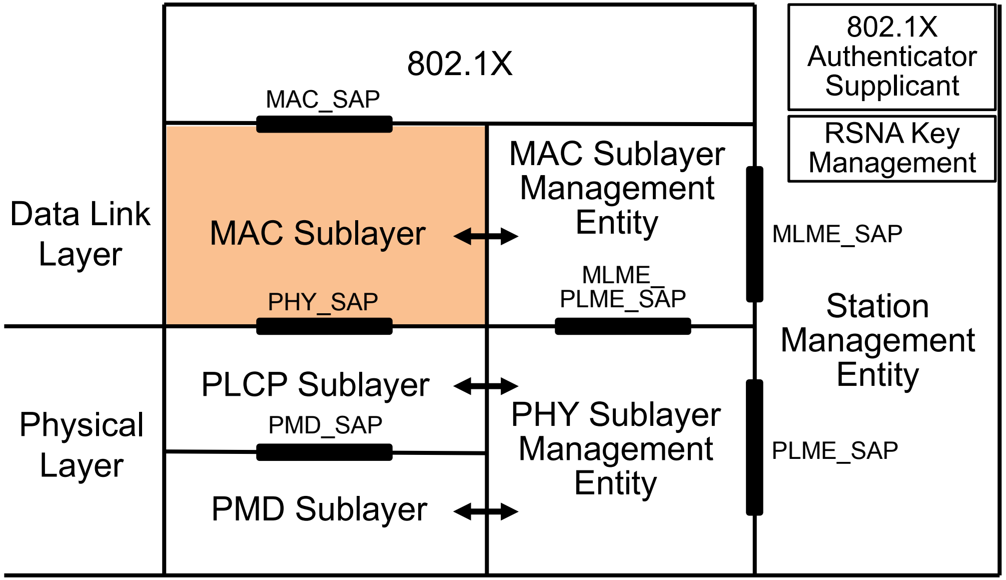
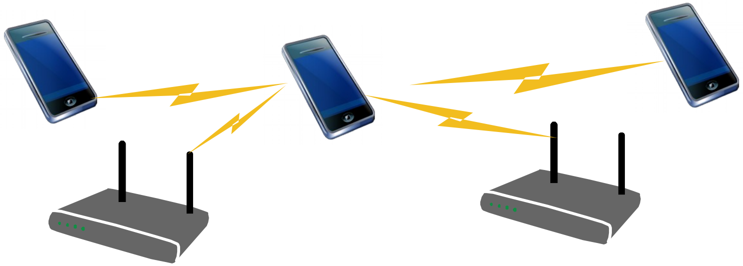


Topics covered in this section

- Medium access functions
  - Challenges
  - CSMA/CA
  - Distributed Coordination Function
  - RTS/CTS
  - Hidden node treatment
  - Fragmentation

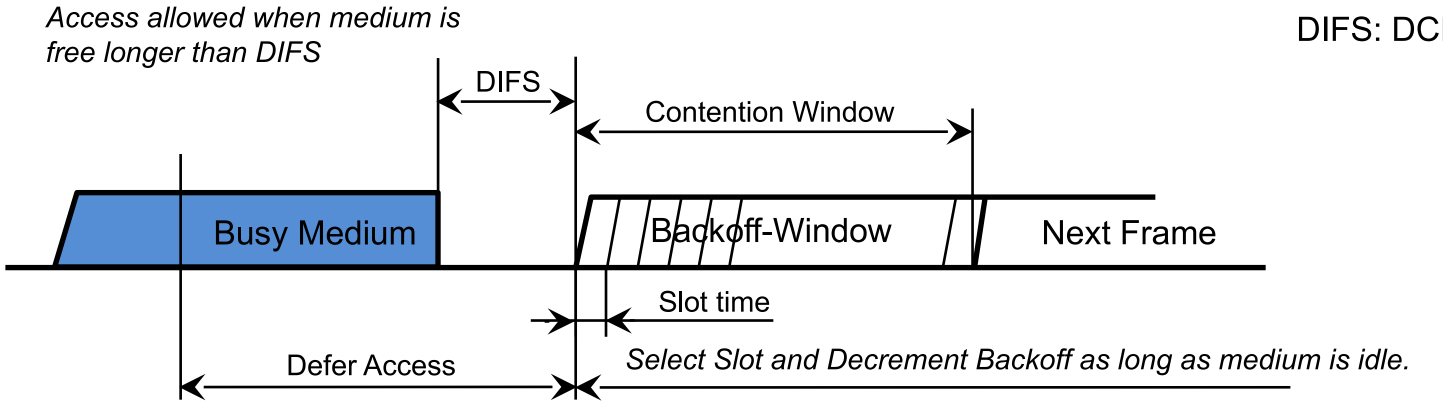
Medium Access Challenges

- Multiple concurrent transmissions on the same channel create collisions
  - Receiver can't decode the transmitted frames



- Same issue exists in shared wired medium
  - Ethernet introduced CSMA/CD (Carrier Sense Multiple Access/Collision Detection) to minimize impairments through collisions
- Wireless medium is more difficult
  - When transmitter is on, a station is not able to detect collisions
    - Access to medium is blocked by transmitter
  - Collisions only detectable through missing acknowledgements of receiver
    - More care necessary to avoid collisions

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

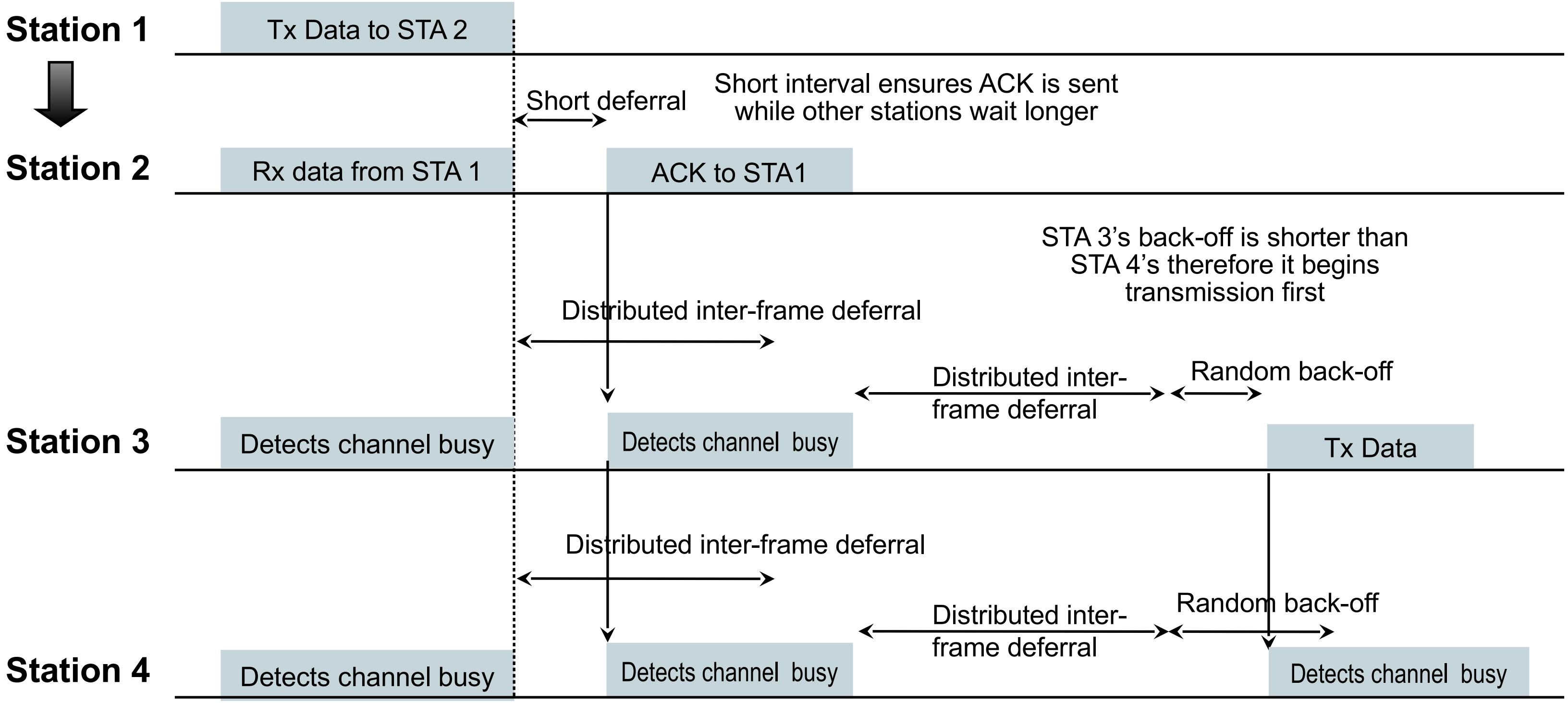


Access allowed when medium is free longer than DIFS
DIFS
Contention Window
Busy Medium
Backoff-Window
Next Frame
Slot time
Defer Access
Select Slot and Decrement Backoff as long as medium is idle.

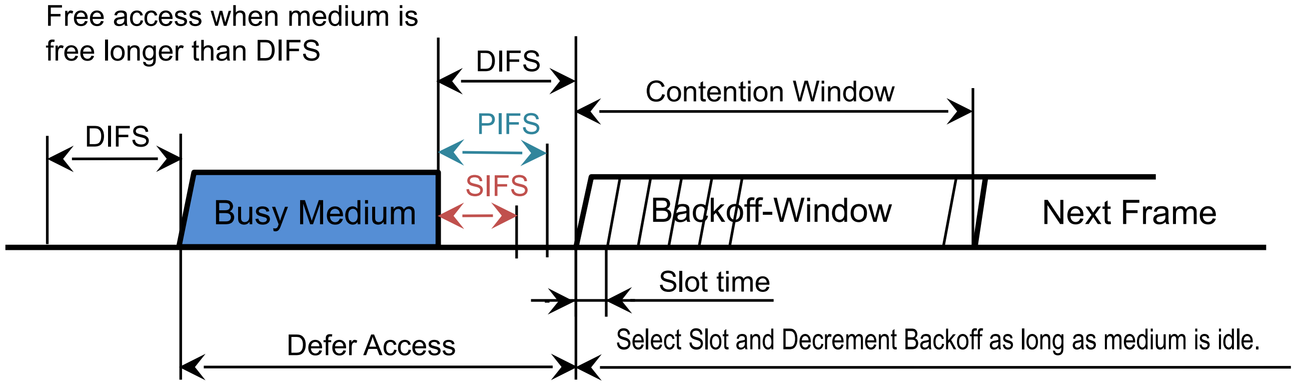
DIFS: DCF Inter Frame Space

- Reduce collision probability where mostly needed.
  - Stations are waiting for medium to become free.
  - Random backoff is used after a defer, resolving contention to avoid collisions.
    - Random backoff is an equally distributed value in the range 0..CWmin; CWmin = 15
  - Exponential backoff is used in the case of retransmissions
    - CW = $(2^k - 1)$ with k = n+4 with n= number of retransmission; CWmax = 1023
    - Efficient Backoff algorithm stable at high loads.
  - Backoff timer elapses only when medium is idle.

Distributed Coordination Function (DCF)


Station 1
Tx Data to STA 2
Short deferral
Short interval ensures ACK is sent while other stations wait longer
Station 2
Rx data from STA 1
ACK to STA1
STA 3's back-off is shorter than STA 4's therefore it begins transmission first
Distributed inter-frame deferral
Distributed inter-frame deferral
Random back-off
Station 3
Detects channel busy
Detects channel busy
Tx Data
Distributed inter-frame deferral
Distributed inter-frame deferral
Random back-off
Station 4
Detects channel busy
Detects channel busy
Detects channel busy

CSMA/CA Timing

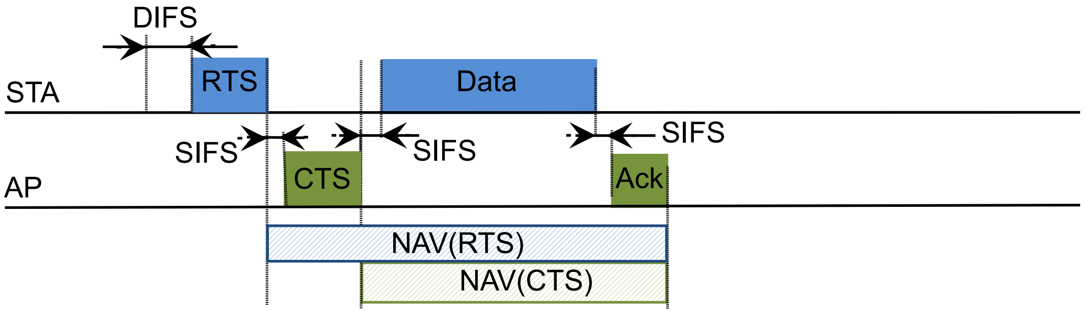

Free access when medium is free longer than DIFS
DIFS
DIFS
Contention Window
PIFS
SIFS
Busy Medium
Backoff-Window
Next Frame
Slot time
Select Slot and Decrement Backoff as long as medium is idle.
Defer Access

SIFS: Short Inter Frame Space
PIFS: PCF Inter Frame Space
DIFS: DCF Inter Frame Space
DIFS = SIFS + 2x Slot time

Standard	Slot time (µs)	DIFS (µs)
IEEE 802.11b	20	50
IEEE 802.11a/n/ac	9	34
IEEE 802.11g/n	9	28

Request-To-Send/Clear-To-Send (RTS/CTS)

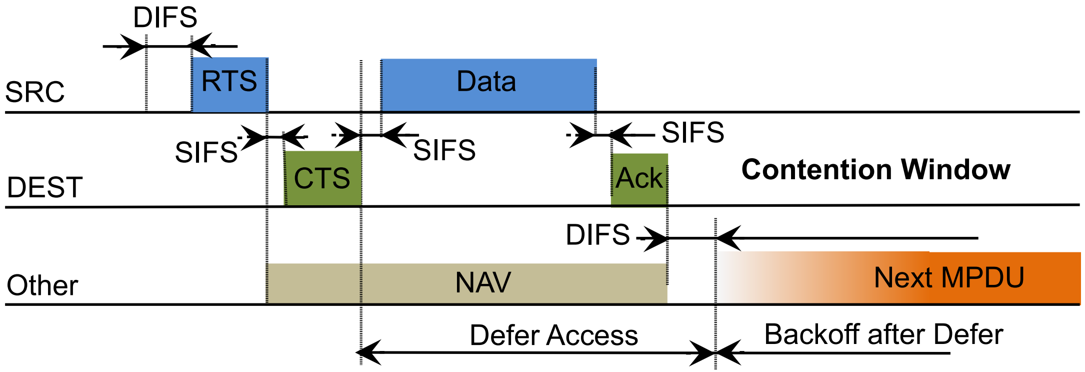
- Used to handle congested/heavily loaded radio environment through control of AP



- STA sends a RTS frame to the AP with the amount of time stated in the NAV (Network Allocation Vector) to transmit its data frame including the ACK
  - NAV represents the overall transmission duration, i.e. the time needed for transmitting the data frame including the following ACK
- The AP acknowledges the medium reservation with a CTS frame, which contains the updated reservation time in the NAV
- STA might start transmitting its data when the CTS message arrives
- All stations monitor RTS/CTS frames and use the gathered information from the NAV to adjust their channel access procedure

CSMA/CA protocol

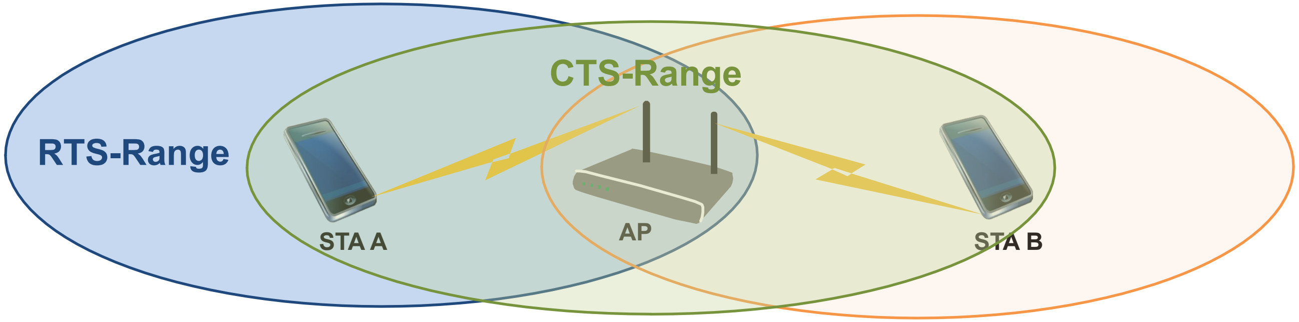
- Defer access based on Carrier Sense.
  - Either physical through CCA (Clear Channel Assessment) from PHY
  - Or virtual carrier sense state through NAV (Network Allocation Vector)



- Direct access when medium is sensed free longer then DIFS, otherwise defer and backoff.
- Receiver of directed frames return ACK immediately when CRC is correct.
  - When transmitter does not receive ACK then retransmission of frame is initiated after a random backoff

Hidden Node Problem

- Problem occurs when contending stations for the medium do not hear each other

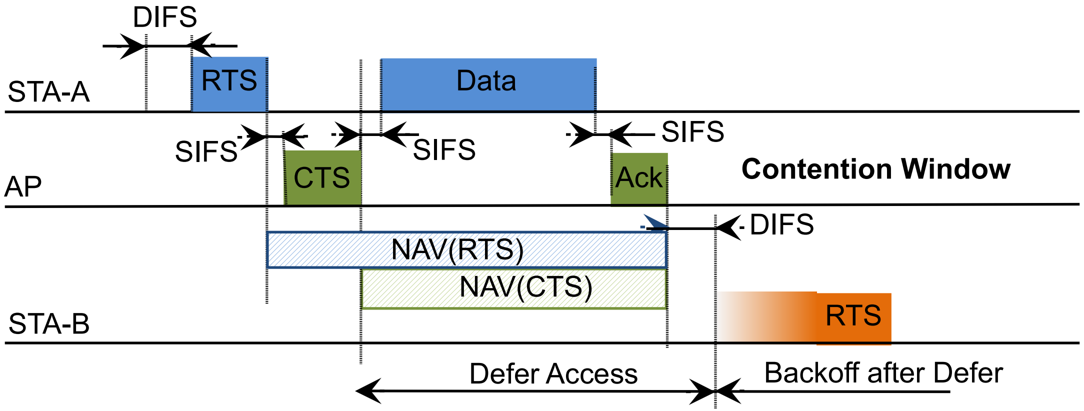


  - STA-B cannot detect when STA-A occupies the medium.
  - STA-B may interfere with transmissions of STA-A to the AP
- Without further measures the performance may be seriously impacted

- WLAN provides an mechanism to solve the hidden station problem:
  - Medium access control with RTS (Request To Send) and CTS (Clear To Send)

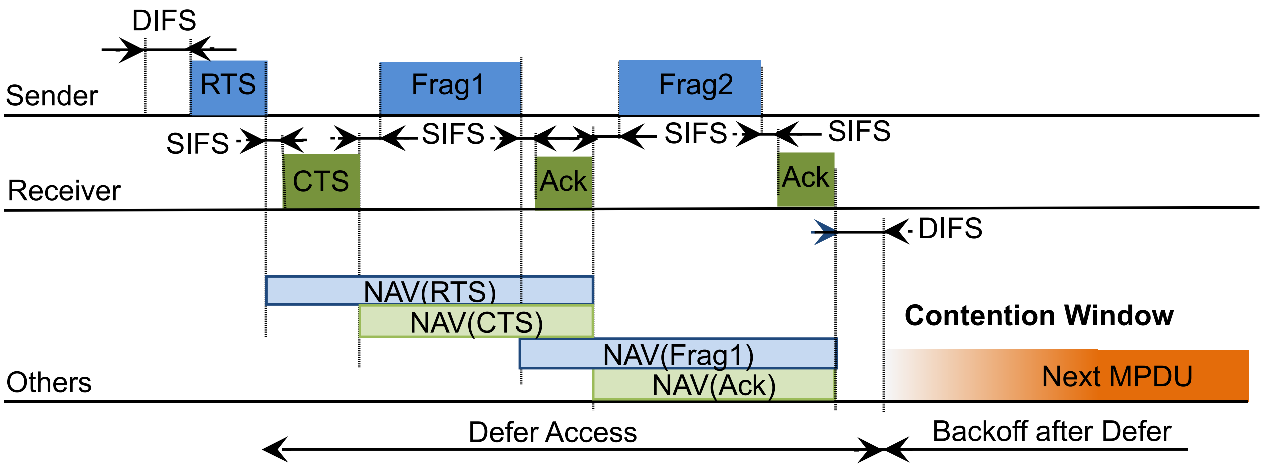
Hidden Station Solution

- STA-A sends a RTS frame to the AP with the amount of time stated in the NAV (Network Allocation Vector) to transmit its data frame including the ACK
  - The AP acknowledges the medium reservation with a CTS frame, which contains the updated reservation time in the NAV
  - STA-A might start transmitting its data when the CTS message arrives
- All stations monitor RTS/CTS frames and use the gathered information from the NAV to adjust their channel access procedure
  - STA-B only starts its transmission after expiration of the NAV preferably with RTS to let AP inform hidden neighbors about ongoing transmission.



Fragmentation

- Packet loss probability increases when data packets are becoming big in a noisy environment
- Limiting the maximum packet size reduces the probability that a packet is hit by a bit failure.
- The MAC Layer provides the function to split packets into multiple smaller frames for transmission



Summary: Basic Access Protocol Features

- Distributed Coordination Function (DCF) for efficient medium sharing.
  - Use CSMA with Collision Avoidance derivative.
  - Based on Carrier Sense function in PHY called Clear Channel Assessment.
- Robust for interference.
  - CSMA/CA + ACK for unicast frames, with MAC level recovery.
  - CSMA/CA for Broadcast frames.
- Parameterized use of RTS / CTS to provide a Virtual Carrier Sense function to protect against Hidden Nodes.
  - Duration information is distributed by both transmitter and receiver through separate RTS and CTS Control Frames.
- Includes fragmentation to cope with various PHY conditions and longer frame sizes.

WLAN IEEE 802.11

MAC LAYER MANAGEMENT

MAC layer management in IEEE802.1 architecture

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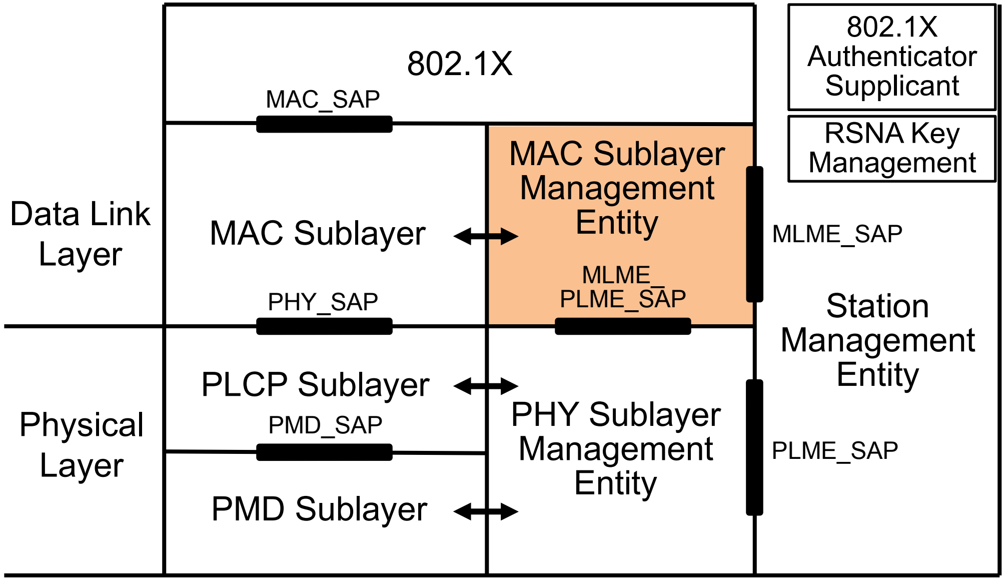


Topics covered in this section

- MAC layer management
  - Overview
  - System management
    - Timer synchronization function
    - Power management
  - Session management
    - Session establishment
    - Scanning
    - Network selection
    - Authentication
    - Association
    - Mobility support
    - Message attributes

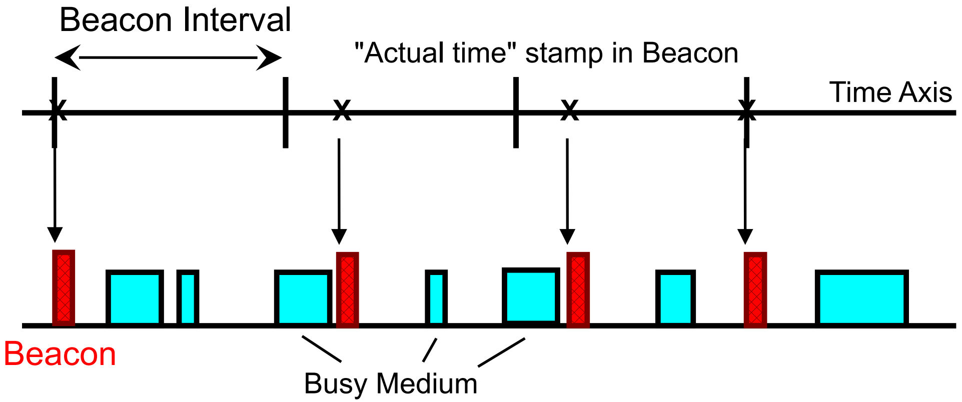
MAC Layer Management - Overview

- System Management
  - Synchronization (Timer Synchronization Function)
    - Synchronization of timers of STAs and APs
  - Power Management
    - Support of periodic sleep of STAs with power save mode
      - Buffering of downstream MAC frames in the AP
      - Indication of pending traffic by Traffic Indication Map in Beacon
- Session Management
  - Scanning for available networks and node of attachments
    - Beaconing
    - Active/passive scanning
  - Generic Advertisement Service
    - Pre-association information query
  - Authentication
  - Association/Disassociation/Re-association
    - Joining a WLAN network
    - Detaching from an AP
    - Transfer of connectivity from one AP to another AP

WLAN IEEE 802.11 MAC Layer Management

SYSTEM MANAGEMENT

Infrastructure Beacon generation



- APs send Beacons in infrastructure networks
  - Beacon is a broadcast frame recurrently send out at Beacon intervals
    - Beacon interval usually about every 100ms
  - Beacon contains SSID and further information about the functions offered by the AP
- Transmission may be delayed by CSMA deferral.
  - Subsequent transmissions at expected Beacon Interval
    - not relative to last Beacon transmission
    - next Beacon sent at Target Beacon Transmission Time
- Timestamp contains timer value at transmit time.

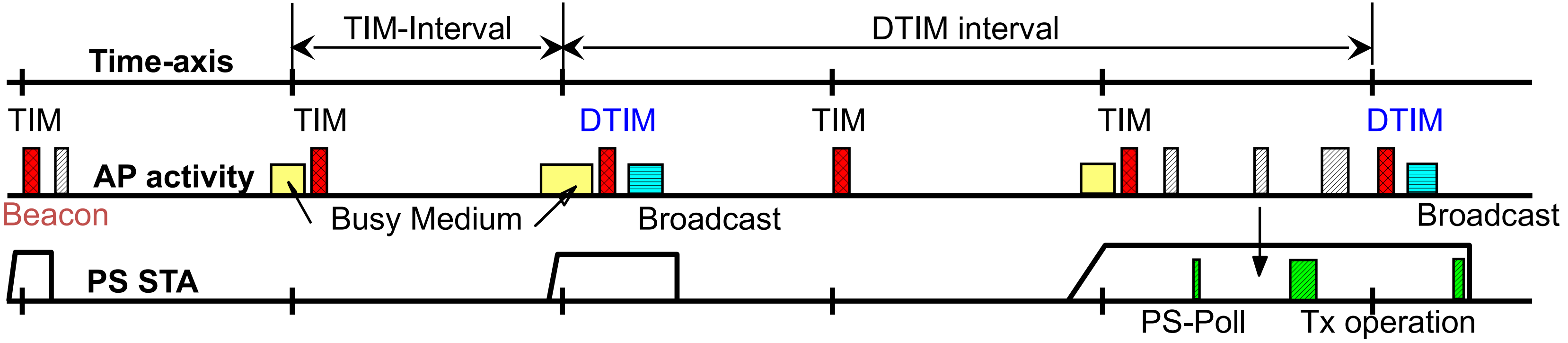
Timing Synchronization Function (TSF)

- All STAs maintain a local timer.
  - Used e.g. for NAV, Power Management and other purposes
    - All station timers in BSS are synchronized

- Timing Synchronization Function (TSF)
  - Keeps timers from all STAs in synch
  - AP controls timing in infrastructure networks
  - For IBSS realized by distributed procedure

- Timing conveyed by periodic Beacon transmissions
  - Beacons contain Timestamp for the entire BSS
  - Timestamp from Beacons used to calibrate local clocks
    - Not required to hear every Beacon to stay in synch

Power Management Procedure



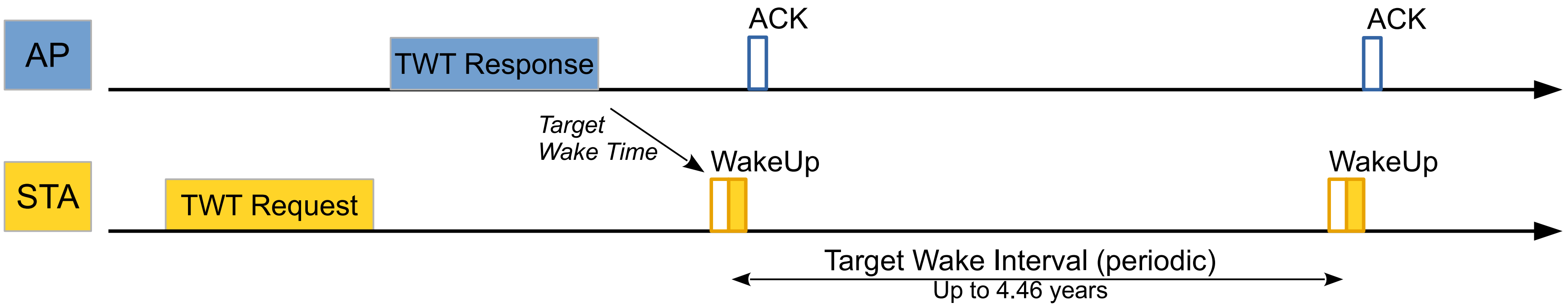
- STAs wake up shortly prior to an expected DTIM
  - DTIM = Delivery Traffic Indication Map
  - DTIM interval: interval at which buffered broadcast/multicast frames are transmitted
    - In the figure above: 3 beacon intervals
- If TIM indicates frame buffered for particular STA,
  - STA sends PS-Poll and stays awake to receive data
  - Else STA goes back to Power Save state
- Broadcast frames are also buffered in AP.
  - All broadcasts/multicasts are buffered
  - Broadcasts/multicasts are only sent after DTIM.
  - DTIM interval is a multiple of TIM interval

Enhanced Power Management Procedures

Power Save Feature	How does it work?
Unscheduled Asynchronous Power Save Delivery (U-APSD)	Allows a STA to retrieve unicast QoS traffic buffered in the AP within one TXOP by sending trigger frames.
Target Wake Time (TWT)	Allows a STA to stay asleep for (long) periods of time and wake up at timeslots that are pre-scheduled (targeted) with the AP.
Restricted Access Window (RAW)	During a 'RAW' only a pre-defined subset of STAs are allowed to conduct uplink transmissions. This can reduce power consumption due to reduced contention for the medium.
Extended Max Idle Period	Extends the period during which a STA is allowed to be asleep before the AP disregards the STA. Theoretical maximum period is over 5 years, in practice this will be implementation dependent.
Hierarchical TIM	Method to more efficiently encode the Traffic Indication Map to reduce the 'on air time' for the TIM and to accommodate large number of STAs per AP.
Non-TIM Operation	Removes the need for a STA to periodically wake up to check beacon messages. In addition, the TIM part of the beacon can be ignored, when receiving a beacon.

Target Wake Time (TWT) power save procedure

- STAs that expect to sleep for long periods of time can negotiate a TWT contract with the AP.
- The AP stores any traffic destined for the STA until the TWT is reached.
- When the STA wakes at the prescribed time, it listens for its beacon and engages the AP to receive and transmit any data required before returning to its sleep state.
- The interval between TWT wake times can be very short (microseconds) or very long (years).

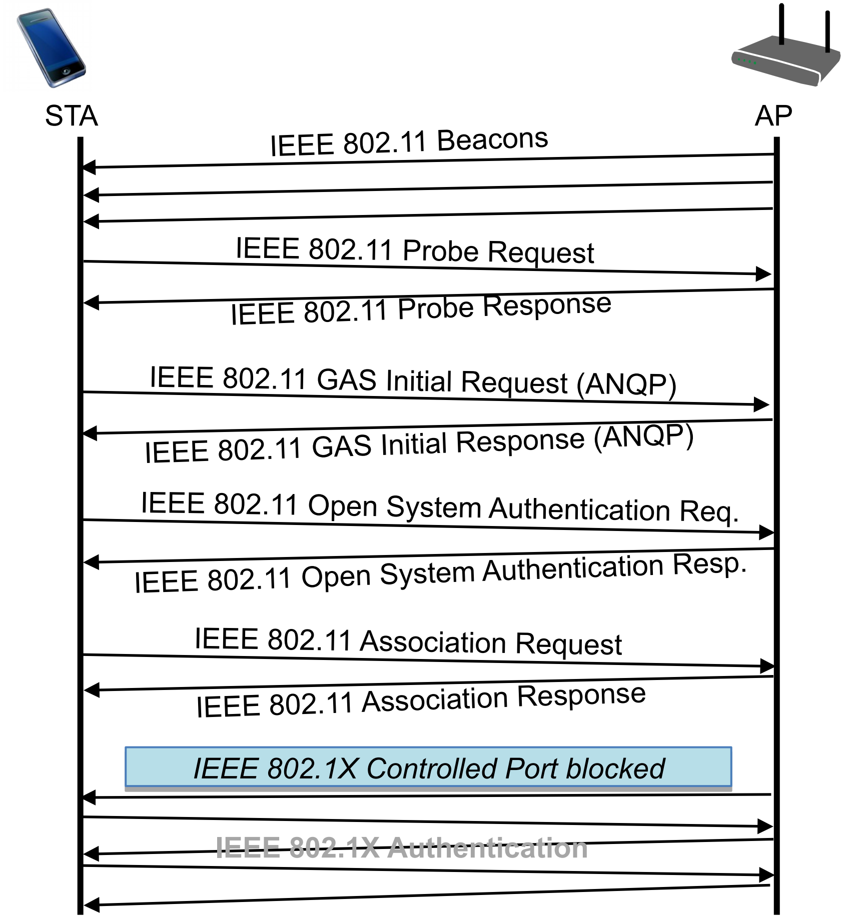


- Benefits of predefined TRX time
  - Wake-up time and channel access spread out
  - Allows AP to minimize contention
  - Reduces awake time for STAs, especially non-TIM STAs

WLAN IEEE 802.11 MAC Layer Management

SESSION MANAGEMENT

IEEE 802.11session establishment


STA
AP
IEEE 802.11 Beacons
IEEE 802.11 Probe Request
IEEE 802.11 Probe Response
IEEE 802.11 GAS Initial Request (ANQP)
IEEE 802.11 GAS Initial Response (ANQP)
IEEE 802.11 Open System Authentication Req.
IEEE 802.11 Open System Authentication Resp.
IEEE 802.11 Association Request
IEEE 802.11 Association Response
IEEE 802.1X Controlled Port blocked
IEEE 802.1X Authentication

- Scanning
  - Beacon
  - Probe Request/Response
- Network Selection
  - GAS (ANQP Request/Response)
- Authentication
  - For legacy reasons OpenSystem Authentication Request/Response retained
    - Initially no use of IEEE 802.1X
- Association
  - Association Request/Response
- 802.1X Authentication/Authorization
  - IEEE 802.1X EAPoL follows association message exchange
    - Controlled port blocked
    - Uncontrolled port used for exchange of authentication messages
  - Authorization provided by AAA server to AP for configuration of data path

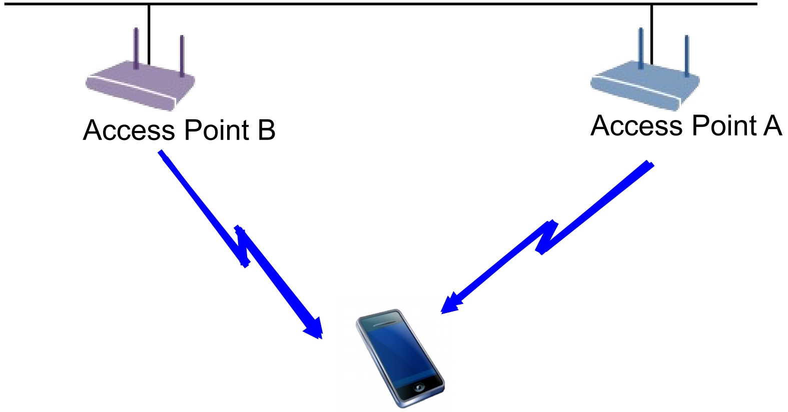
Session Management

SCANNING

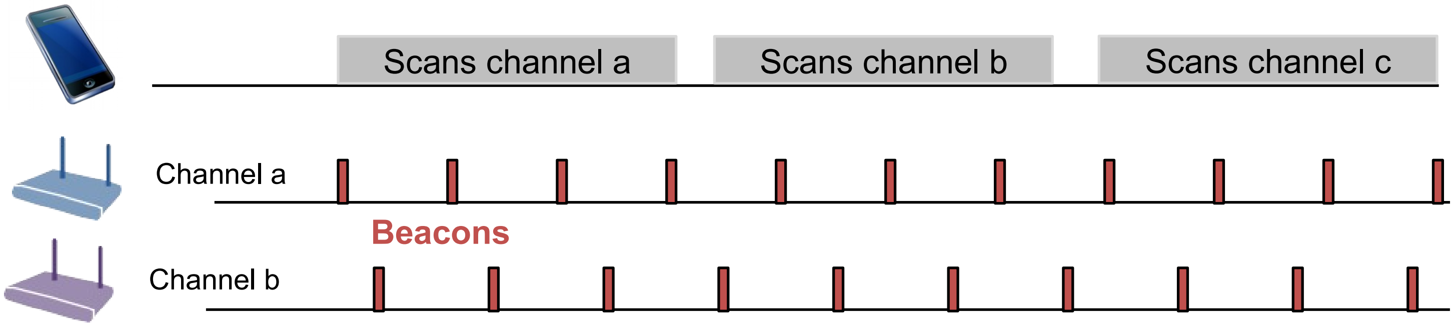
Scanning

- Scanning is process of finding available APs and WLANs
  - WLANs identified by Service Set Identifier (SSID)
    - SSID is an arbitrary human readable network name with up to 32 ASCII characters
    - All APs of a WLAN (= Extended Service Set) have the same SSID
      - SSIDs are not necessarily unique
    - To enable unique WLAN names, SSID can be amended by Homogeneous Extended Service Set Identifier (HESSID)
      - HESSID is a MAC address (BSSID) of one of the APs of the ESS
  - APs identified by Basic Service Set Identifier (BSSID)
    - BSSID is the MAC address used in the radio transmission frames as AP address
- WLAN identification information can be detected
  - Either by decoding information carried in the Beacons
    - Passive Scanning
  - Or by sending out broadcast frames querying responses with WLAN identification information from adjacent Aps
    - Active Scanning

Passive scanning



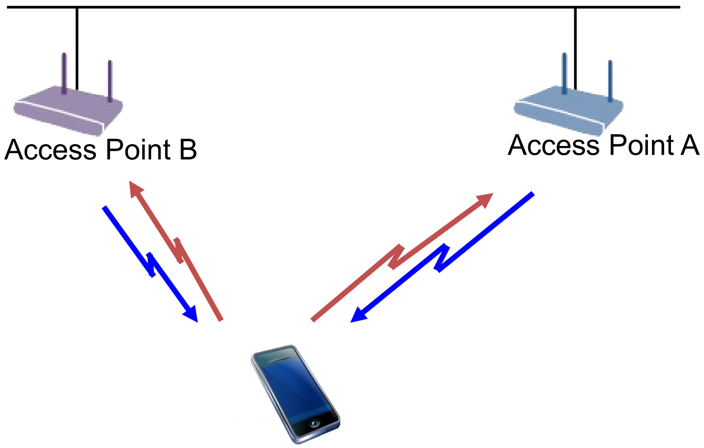
- STA subsequently tunes to all channels and listens for Beacons
- To successfully detect all Beacons, STA stays on a channel for about 200-300ms
- Scan of 2.4 GHz band takes about 2.5-4 s



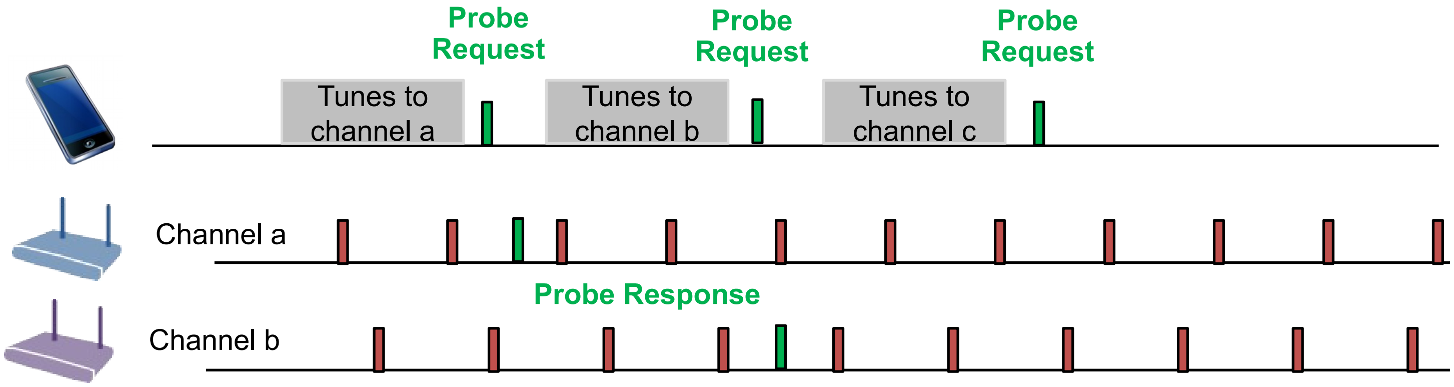
Active scanning

← Station sends Probe.

→ APs send Probe Response.



- STA tunes to all channels an sends Probe Requests.
- APs respond within a few ms.
- Query can either be directed to a particular WLAN or can send to all WLAN to respond.
- Even when transmitter is engaged in STA, active scanning is often more power effective.



Session Management

NETWORK SELECTION

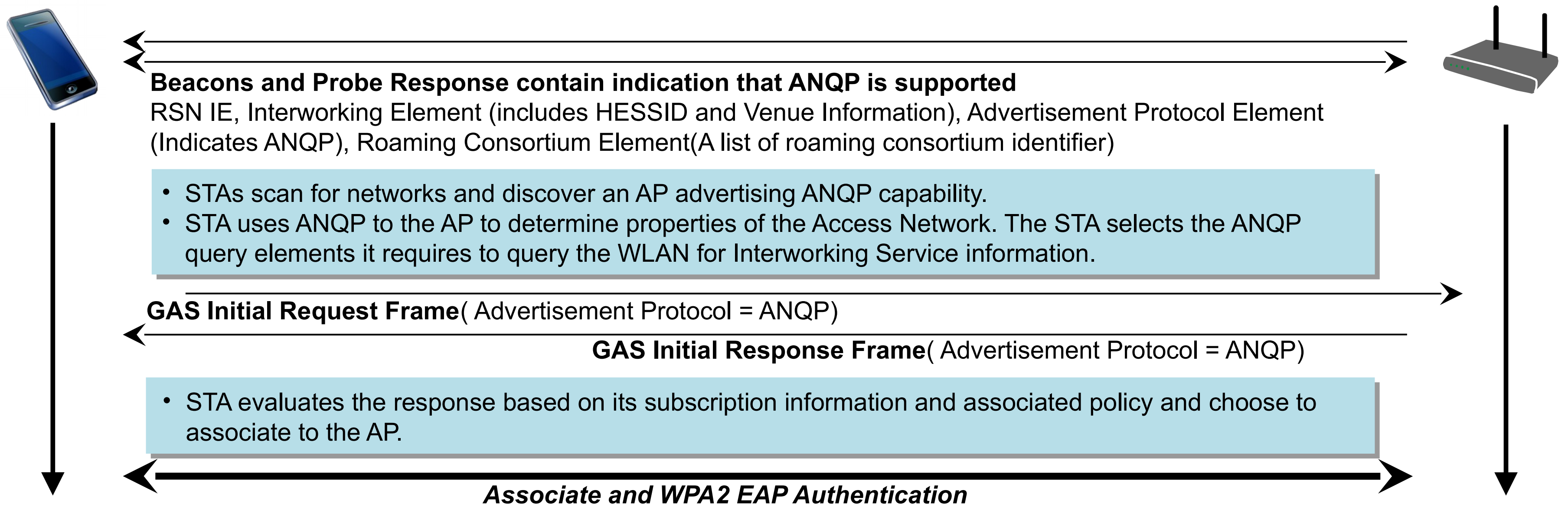
Generic Advertisement Service

- A Wi-Fi terminal scans the air for finding the near-by access points
  - Either by passive scanning (Beacon)
  - or by active scanning (Probe Request & Probe Response)
- Questions arising when discovering an access point:

- ***Is this my Home Service Provider?***
- ***Is this a Visited Service Provider?***
- ***Will this Service Provider offer the services I need?***
- ***Do I need any provisioning for this Service Provider?***

- The information in the beacon or probe response is often not sufficient to make the appropriate decision
- Introduced by 802.11u, IEEE 802.11 defines a protocol allowing to query additional information about the Wi-Fi access before initiating the association and authentication
- GAS (Generic Advertisement Service) provides a container for the ANQP (Access Network Query Protocol), which provides more information about the Wi-Fi access

Network discovery by ANQP



Beacons and Probe Response contain indication that ANQP is supported
RSN IE, Interworking Element (includes HESSID and Venue Information), Advertisement Protocol Element (Indicates ANQP), Roaming Consortium Element(A list of roaming consortium identifier)

- STAs scan for networks and discover an AP advertising ANQP capability.
- STA uses ANQP to the AP to determine properties of the Access Network. The STA selects the ANQP query elements it requires to query the WLAN for Interworking Service information.

GAS Initial Request Frame(Advertisement Protocol = ANQP)

GAS Initial Response Frame(Advertisement Protocol = ANQP)

- STA evaluates the response based on its subscription information and associated policy and choose to associate to the AP.

Associate and WPA2 EAP Authentication

ANQP Attributes

- Venue Name
- Network Authentication Type
- Roaming Consortium
- IP Address Type Availability
- NAI Realm
- 3GPP Cellular Network
- Domain Name

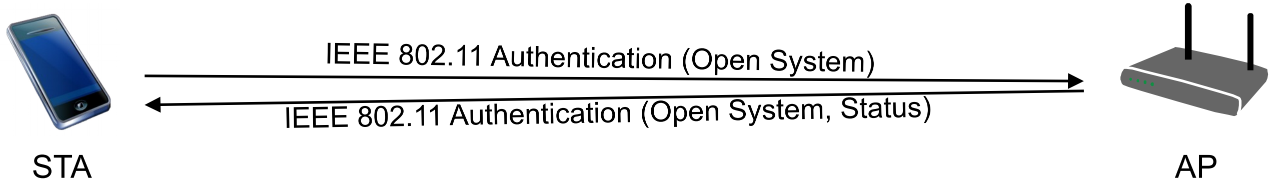
ANQP Attributes

- Venue Name
  - Provides zero or more venue names associated with the BSS to support the user’s selection.
- Network Authentication Type
  - Provides a list of authentication types carrying additional information like support for online enrollment or redirection URL.
- Roaming Consortium
  - Provides a list of information about the Roaming Consortium or Subscription Service Providers (SSPs) whose networks are accessible via this AP.
- IP Address Type Availability
  - Provides STA with the information about the availability of IP address version and type that could be allocated to the STA after successful association.
- NAI Realm
  - Provides a list of Network Access Identifier (NAI) realms corresponding to SSPs or other entities whose networks or services are accessible via this AP; optionally amended by the list of EAP Method, which are supported by the SSPs.
- 3GPP Cellular Network
  - Contains cellular information such as network advertisement information e.g., network codes and country codes to assist a 3GPP non-AP STA in selecting an AP to access 3GPP networks.
- Domain Name
  - Provides a list of one or more domain names of the entity operating the IEEE 802.11 access network.

Session Management

AUTHENTICATION

Authentication

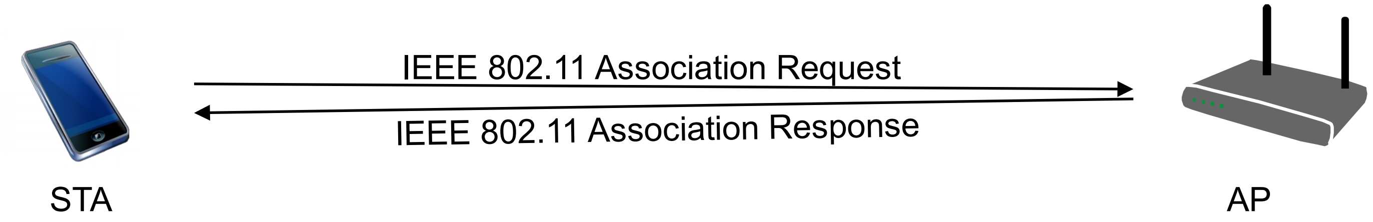

IEEE 802.11 Authentication (Open System)
IEEE 802.11 Authentication (Open System, Status)
STA
AP

- Authentication before association is ‘leftover’ of legacy IEEE Stds 802.11 without WPA2 support (prior to IEEE 802.11i aka WPA2).
- For conformance and compatibility reasons Open System Authentication is performed, which only checks for the MAC addresses of the STA.
  - In legacy IEEE 802.11, AP could authenticate STA by its WEP (Wire Equivalent Privacy).
    - WEP is depreciated now.
- Open System Authentication is the only check performed in unencrypted WLAN
  - MAC address authentication is often used to bypass captive portal in public access for ‘known’ users.
- Other methods for pre-association authentication can be used for Fast Transition (FT Authentication) and Mesh Networking (simultaneous authentication under equals (SAE)).

Session Management

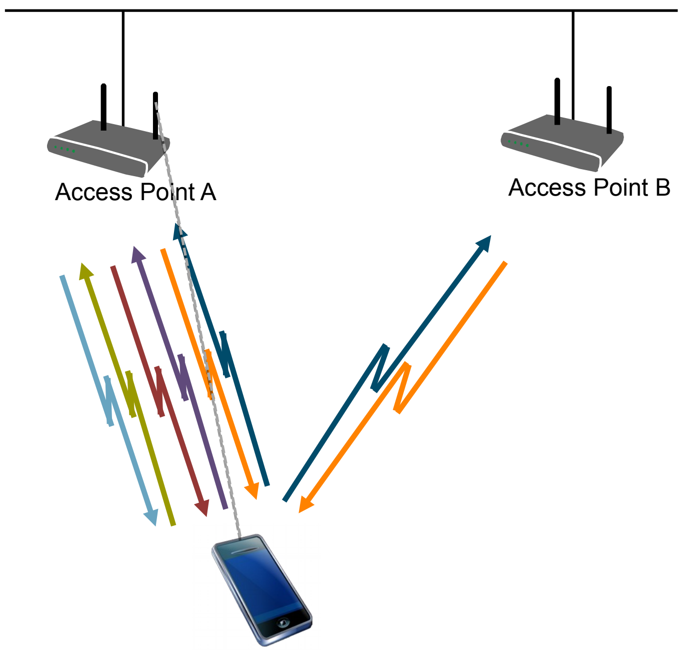
ASSOCIATION

Association


IEEE 802.11 Association Request
IEEE 802.11 Association Response
STA
AP

- Association establishes the data connection at the AP by assigning a virtual port for the STA
  - The STA sends an Association Request message containing its Listen Interval, various capabilities, the SSID to join and the supported transmission rates.
  - The AP checks for the acceptance of the parameters send in the Association Request frame and sends back an Association Response message, which contains an Association ID (AID), which allows unique identification of a station at the AP
    - AIDs are also needed for power management
- Once virtual port is available, Ethernet frames can be exchanged between STA and AP

Message sequence for successful association



Association with active scanning but without network selection by ANQP

Details:

← Station sends Probe Request

→ APs send Probe Response

=> Station chooses best AP

← Station sends Authentication Request to the chosen AP

→ AP sends Authentication Response (success)

← STA sends Association Request to the chosen AP

→ AP sends Association Response (success)

Disassociation, Re-association

- Disassociation
  - Frame containing a reason code for termination of an association
- Re-association
  - Special form of Association procedure to support reconnection to another AP of the same ESS
  - Request frame additionally contains BSSID of previous AP
    - Allows new AP to contact previous AP for transfer of previous session info and pending data frames
  - Re-association is used for realizing ‘mobility’ in IEEE 802.11 within the same ESS (SSID).

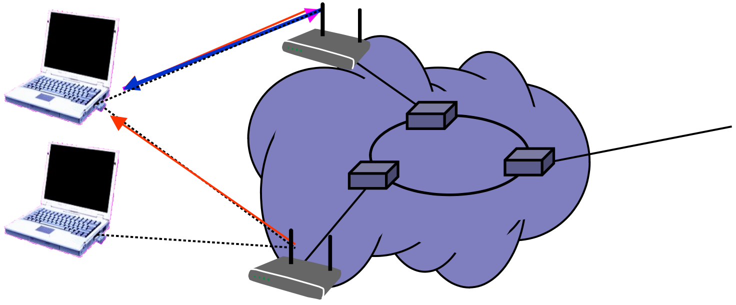
Session Management

MOBILITY SUPPORT

Mobility inside an ESS by link layer functions

Station decides that link to its current AP is poor…

- **Station uses scanning function to find another AP**
  - or uses information from previous scans
- **Station sends Re-association Request to new AP**
- **If Re-association Response is successful**
  - then station has roamed to the new AP
  - else station scans for another AP
- **If AP accepts Re-association Request**
  - Normally old AP is notified through Distribution System
  - AP indicates Re-association to the Distribution System



Process shown without reestablishing the security context!

Handoff Time

- Total handoff time not deterministic but influenced by statistical variations of multiple protocol steps
  - Main variation by scanning procedure and period (~ 90%)
  - Most of the messaging may occur for scanning
  - Actual handoff extremely fast (Reassociation Request & Response)
  - WPA2 security adds another challenge
    - Keying material to be established at the new AP
- Possibilities to reduce the handoff time:
  - Reduce time needed to detect new AP with better radio link
    - periodic scanning, despite being connected to the old AP
    - selective scanning (using only a subset of all possible channels)
    - exploiting other information about neighbor Aps
  - Reduce time to establish security context at new AP
    - Fast roaming support, introduced by 802.11r, allows for pre-establishment of keys

Layer 2 Mobility Considerations

- Link loss detection
  - The STA detects a low signal quality or no signal from the access point
    - Threshold decision (with hysteresis) (fast detection, commonly used)
  - The STA detects an increasing error rate of transmitted MAC frames
    - Slower than previous approach, but may be more predictive
- Requirement for the support of Layer 2 Mobility in WLAN:
  - All access points are connected directly over a single Ethernet
  - Inter access point communication happens by new AP informs infrastructure and previous AP by Layer-2 update frame on the wire
- For larger coverage areas this is not reasonable anymore
  - Layer 2 broadcast domains are of limited size
  - Multiple Distribution Systems are interconnected (usually with routers); Thus, layer 2 handoffs are not possible between the Distribution Systems
  - Solution by handoffs between the Distribution Systems are performed with higher layer mechanisms e.g. Mobile IP

Session Management

MAC MANAGEMENT MESSAGES

MAC Management messages attributes

- Beacon (9.3.3.3)
  - Timestamp, Beacon Interval, Capabilities, ESSID, Supported Rates, Parameters, …
  - Traffic Indication Map
- Probe Request (9.3.3.10)
  - SSID, Supported Rates, Parameters, …
- Probe Response (9.3.3.11)
  - Timestamp, Beacon Interval, Capabilities, SSID, Supported Rates, Parameters, ….
    - Same as for Beacon except for TIM
- Authentication (9.3.3.12)
  - Authentication algorithm, Transaction number, Status code, Parameters, …
    - Same format used for various actions
- Deauthentication (9.3.3.13)
  - Reason code
- Association Request (9.3.3.6)
  - Capability, Listen Interval, SSID, Supported Rates, …
- Association Response (9.3.3.7)
  - Capability, Status Code, AID, Supported Rates, …
- Reassociation Request (9.3.3.8)
  - Capability, Listen Interval, SSID, Current AP Address, Supported Rates, …
- Reassociation Response (9.3.3.9)
  - Capability, Status Code, AID, Supported Rates, …
- Disassociation (9.3.3.5)
  - Reason code

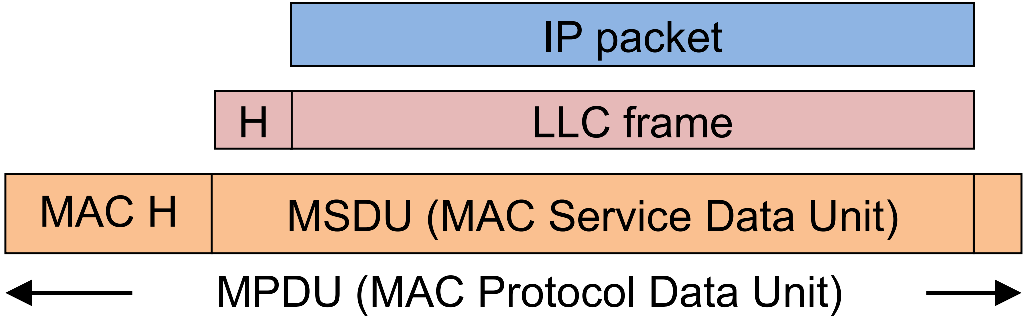
WLAN IEEE 802.11

MAC FRAME FORMATS

Topics covered in this section

- MAC frame formats
  - Overview and comparison
  - Frame structure
  - Addressing
  - Header information

Overview



- Differences to widely known MAC data units, e.g. Ethernet:
  - Up to 4 address values
    - Necessary to handle the message transfer over the air
  - Different types of MAC data units
    - Data frames for transporting the MAC Service Data Unit
    - Control data units for medium access control, e.g. RTS, CTS, ACK
    - Management data units for the MAC Layer management messages
  - Duration ID field
    - Duration value for the transmission of the frame to allow NAV/virtual sensing
  - Sequence Control fields
    - Fragment Number for marking fragments
    - Sequence Number for marking MAC service data units

IEEE 802.11 MAC Layer Frame Formats

802.11 MAC Header

Bytes:	2	2	6	6	6	2	6	0 - 2312	6
	Frame Control	Duration ID	Address1	Address2	Address3	Sequence Control	Address4	MSDU	CRC

Bits:	2	2	6	1	1	1	1	1	1	1	1
	Protocol Version	Type	SubType	To DS	From DS	More Frag	Retry	Pwr Mgmt	More Data	WEP	Rsvd

- MAC Header format differs per Type:
  - Control Frames (several fields are omitted)
  - Management Frames
  - MSDU Data Frames
- Includes Sequence Control Field for filtering of duplicate caused by ACK mechanism.

Addressing

2	2	4	1	1	1	1	1	1	1	1
Protocol Version	Type	SubType	To DS	From DS	More Frag	Retry	Pwr Mgmt	More Data	WEP	Rsvd

To DS	From DS	Addr 1	Addr 2	Addr 3	Addr 4
0	0	DA	SA	BSSID	-
0	1	DA	BSSID	SA	-
1	0	BSSID	SA	DA	-
1	1	RA	TA	DA	SA

- Addr 1 = Destination of the radio frame
- Addr 2 = Transmitter Address (TA) identifies entity to receive the ACK frame
- Addr 3 = Entity on DS sending/receiving frame
- Addr 4 = Needed to identify the original source in case of WDS (bridging over the air).

Header field descriptions

2	2	4	1	1	1	1	1	1	1	1
Protocol Version	Type	SubType	To DS	From DS	More Frag	Retry	Pwr Mgmt	More Data	WEP	Rsvd

- Type / Subtype:
  - MAC frames function (management frame, control frame, data frame)
- More Frag:
  - Indicates whether the frame has been split
    and more fragments are about to follow
- Retry
  - Indicates that this frame has been retransmitted
- Pwr Mgmt (Power Management)
  - Indicates that the station is in power save mode
- More Data
  - Indicates that more frames follow
- WEP
  - Indicates that the payload is encrypted

WLAN IEEE 802.11

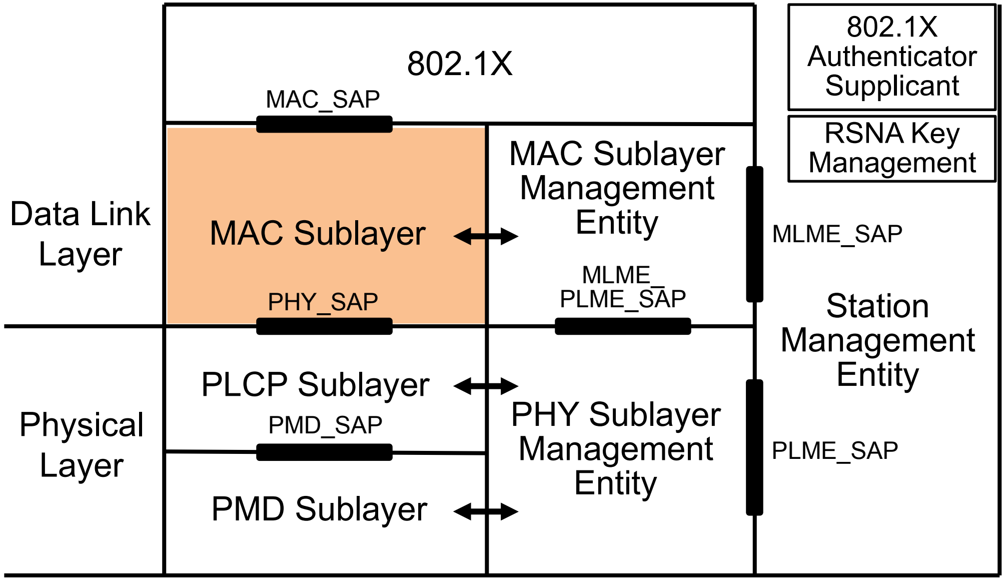
QUALITY OF SERVICE

Topics covered in this section

- Quality of Service
  - DCF and legacy PCF
  - IEEE 802.11e - 2005
  - Wi-Fi Multimedia (WMM)
  - Wi-Fi QoS in action

QoS in IEEE 802.11 is mainly part of MAC Sublayer

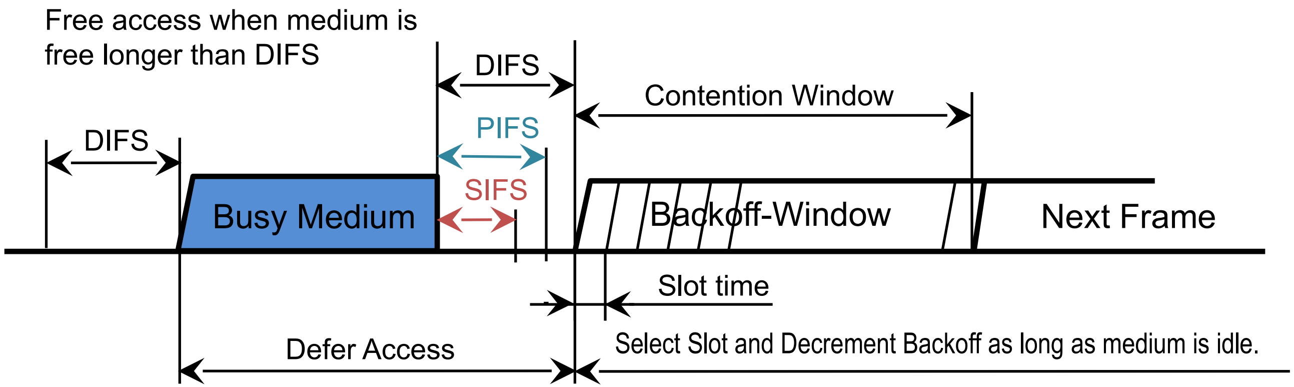
- 802.1X
  - Port Access Entity
  - Authenticator/Supplicant
- RSNA Key Management
  - Generation of Pair-wise and Group Keys
- Station Management Entity (SME)
  - interacts with both MAC and PHY Management
- MAC Sublayer Management Entity (MLME)
  - synchronization
  - power management
  - scanning
  - authentication
  - association
  - MAC configuration and monitoring
- MAC Sublayer
  - basic access mechanism
  - fragmentation
  - encryption
- PHY Sublayer Management Entity (PLME)
  - channel tuning
  - PHY configuration and monitoring
- Physical Sublayer Convergence Protocol (PLCP)
  - PHY-specific, supports common PHY SAP
  - provides Clear Channel Assessment signal (carrier sense)
- Physical Medium Dependent Sublayer (PMD)
  - modulation and encoding



WLAN IEEE 802.11

DCF AND LEGACY PCF

DCF is based on Clear Channel Access (CCA)


Free access when medium is free longer than DIFS
DIFS
DIFS
PIFS
SIFS
Contention Window
Busy Medium
Backoff-Window
Next Frame
Slot time
Defer Access
Select Slot and Decrement Backoff as long as medium is idle.

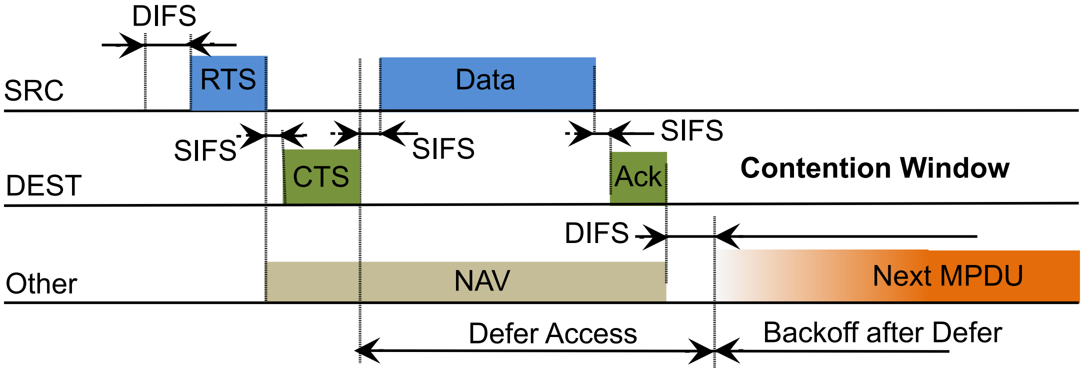
Standard	Slot time (µs)	DIFS (µs)
IEEE 802.11b	20	50
IEEE 802.11a/n/ac	9	34
IEEE 802.11g/n	9	28

SIFS: Short Inter Frame Space
PIFS: PCF Inter Frame Space
DIFS: DCF Inter Frame Space
DIFS = SIFS + 2x Slot time

- Stations are waiting for medium access by CCA
  - Medium has to be(come) idle.
  - Random backoff is used after a defer, resolving contention to avoid collisions.
    - Random backoff is an equally distributed value in the range 0..CWmin; CWmin = 15
  - Exponential backoff is used in the case of retransmissions
    - CW = $(2^k - 1)$ with k = n+4 with n= number of retransmission; CWmax = 1023
    - Efficient Backoff algorithm stable at high loads.
  - Backoff timer elapses only when medium is idle.

CSMA/CA protocol

- Defer access based on Carrier Sense.
  - Either physical through CCA (Clear Channel Assessment) from PHY
  - Or virtual carrier sense state through NAV (Network Allocation Vector)



- Direct access when medium is sensed free longer then DIFS, otherwise defer and backoff.
- Receiver of directed frames return ACK immediately when CRC is correct.
  - When transmitter does not receive ACK then retransmission of frame is initiated after a random backoff

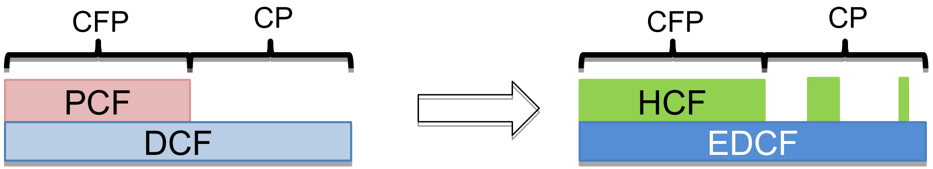
QoS Limitations of legacy IEEE 802.11 MAC

- DCF (Distributed Coordination Function)
  - Relies on CSMA/CA and optional 802.11 RTS/CTS for sharing the radio resource between STAs
    - Only support best-effort services
    - No guarantee in bandwidth, packet delay and jitter
    - No Quality of Service (QoS) guarantees.
      - In particular, there is no notion of high or low priority traffic.
    - Throughput degradation in heavy loaded environments due to collisions
- PCF (Point Coordination Function)
  - Defined in legacy IEEE 802.11, now obsolete
  - AP assuming the full control over the medium during CFP
    - Not taking into account real scenarios with overlapping WLANs
  - Transmission duration of the polled stations is not known to the AP
  - Inefficient and complex central polling scheme

WLAN IEEE 802.11 Quality of Service

IEEE 802.11E-2005

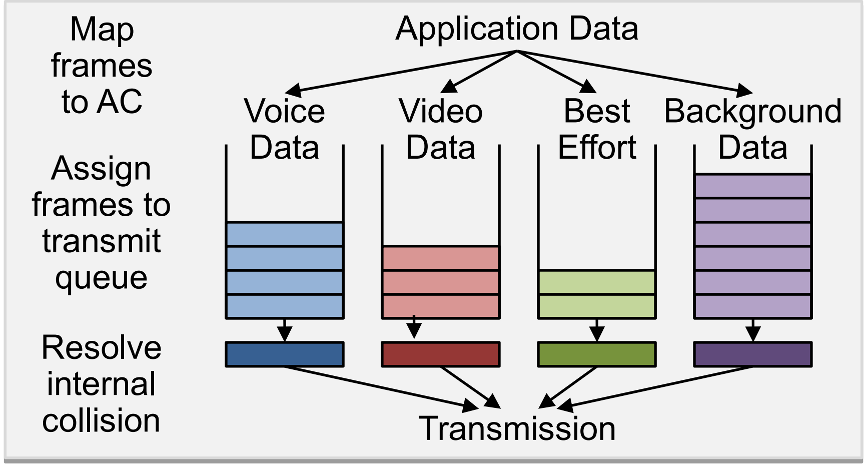
WLAN QoS in IEEE 802.11e – the theory



- IEEE 802.11e introduced MAC enhancements to IEEE 802.11 to facilitate QoS
  - Supports both IntServ and DiffServ models
  - Backward compatible with the DCF and PCF
- HCF (Hybrid Coordination Function)
  - Replaces both DCF and PCF
  - Consists of HCF Controlled Channel Access (HCCA) for contention free period and Enhanced Distributed Channel Access (EDCA) for contention period
  - Based on Traffic Categories (TC) for different services
  - Can meet predefined service rate, delay and/or jitter requirements of particular traffic flows.
  - Enhanced DCF (EDCF)
    - differentiated DCF access to the wireless medium for prioritized traffic categories (8 different traffic categories)
- Transmission Opportunities (TXOP)
  - An interval of time when a STA has the right to initiate transmissions
    - Multiple frames (i.e., MSDUs) can be transmitted during a TXOP with certain rules
- Block ACK
  - Group of frames received consecutively acknowledged by a BlockAck
- Direct Link Protocol (DLP)
  - STA-to-STA transmission in the infrastructure mode
- Unscheduled Asynchronous Power Save Delivery (U-APSD)
  - Allows a STA to retrieve unicast QoS traffic buffered in the AP within one TXOP by sending trigger frames.

Quality of Service by Traffic Priorization

- Traffic is classified according to its importance and forwarding requirements
- Traffic Categories (TC) for prioritization
  - Differentiated channel access for frames with different user priorities
  - 8 different priorities, similar to IEEE 802.1Q specification


Map frames to AC

Assign frames to transmit queue

Resolve internal collision

Application Data

Voice Data

Video Data

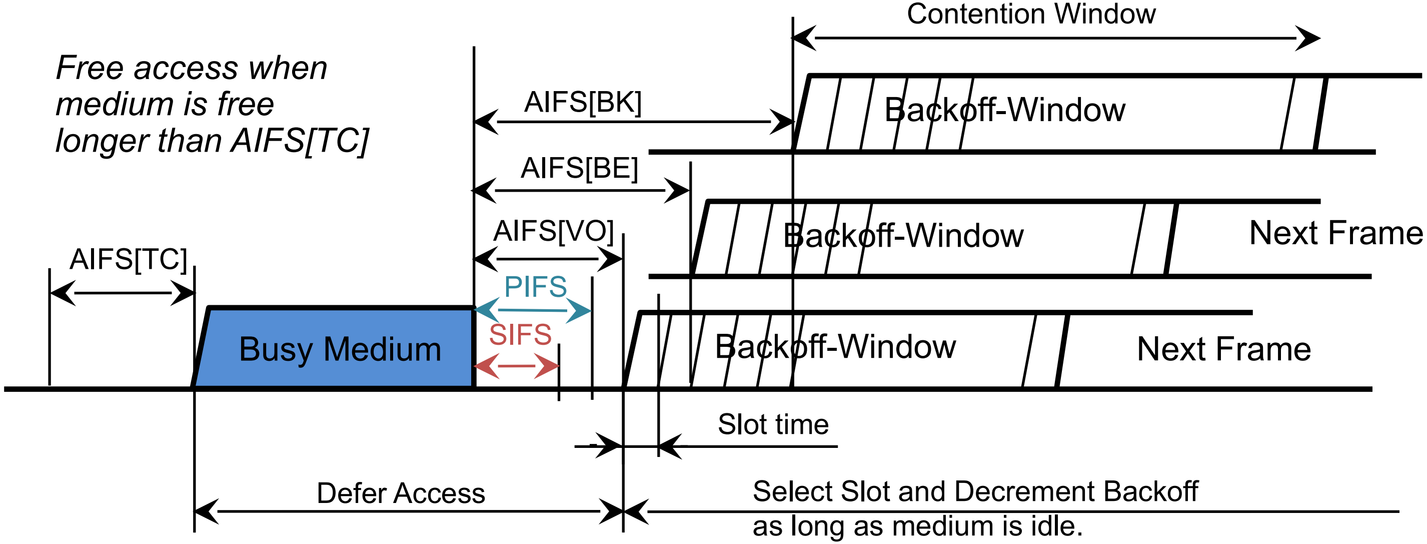
Best Effort

Background Data

Transmission

-	802.1p contained in IEEE 802.1Q			802.11e	
Priority	PCP	Acronym	Traffic Type	Access Category	Designation
Lowest	1	BK	Background	AC_BK	Background
	0	BE	Best Effort	AC_BE	Best Effort
	2	EE	Excellent Effort	AC_BE	Best Effort
	3	CA	Critical Applications	AC_VI	Video
	4	VI	Video	AC_VI	Video
	5	VO	Voice	AC_VO	Voice
	6	IC	Internetwork Control	AC_VO	Voice
Highest	7	NC	Network Control	AC_VO	Voice

EDCF



Standard	Slot time (µs)	DIFS (µs)
IEEE 802.11b	20	50
IEEE 802.11a/n/ac	9	34
IEEE 802.11g/n	9	28

SIFS: Short Inter Frame Space
PIFS: PCF Inter Frame Space
DIFS: DCF Inter Frame Space
DIFS = SIFS + 2x Slot time

- Based on modification of CSMA/CA access function with shorter arbitration inter-frame space (AIFS) for higher priority packets.
- High priority traffic waits a little less before packets are sent
  - High-priority traffic has a higher chance of being sent than low-priority traffic

WLAN IEEE 802.11 Quality of Service

WI-FI MULTIMEDIA (WMM) QOS IN REAL EQUIPMENT

QoS support by Wi-Fi Multimedia

- Wi-Fi Multimedia (WMM) defines the features of IEEE 802.11e that are implemented in real products.
  - WMM supports only EDCA but not HCCA.
  - Prioritized QoS identifies 4 traffic classes (Access Categories)
    - Aligned to the 8 priorities defined within IEEE 802.1Q.

Access Category	Description	802.1p
WMM Voice Priority	Highest priority. Allows multiple concurrent VoIP sessions with low latency and jitter	7, 6
WMM Video Priority	Prioritize video traffic above other data traffic	5, 4
WMM Best Effort Priority	Traffic from legacy devices, or traffic from applications that do not require prioritization	3, 0
WMM Background Priority	Low priority traffic that does not require low latency or guaranteed throughput	1, 2

  - Parameterized QoS is only partially supported by an admission control scheme (due to missing HCCA)

EDCF Parameters

- Levels of priority in EDCF are called Access Categories (ACs).
- Contention window (CW) set according to the traffic in AC
  - Wider window needed for categories with heavier traffic.
- CWmin and CWmax derived from aCWmin and aCWmax values
  - Separately for each physical layer.

AC	CWmin	CWmax
Background (AC_BK)	aCWmin	aCWmax
Best Effort (AC_BE)	aCWmin	aCWmax
Video (AC_VI)	(aCWmin+1)/2-1	aCWmin
Voice (AC_VO)	(aCWmin+1)/4-1	(aCWmin+1)/2-1

- Default EDCA Parameters for each AC (e.g. 802.11a/n)

Access Category	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	15	1023	7	0
Best Effort (AC_BE)	15	1023	3	0
Video (AC_VI)	7	15	2	3.008ms
Voice (AC_VO)	3	7	2	1.504ms
Legacy DCF	15	1023	2	0

Parameterized QoS for Traffic Stream

- QoS is characterized by a set of parameters, called Traffic Specification (TSPEC)
- A Traffic Stream (TS) is set up between transmitter and receiver
  - TSPEC specifies service rate, delay and jitter requirements of particular traffic flows.

Octets: 3	2	2	4	4	4	4	4	4
TS Info	Nominal MSDU Size	Maximum MSDU Size	Minimum Service Interval	Maximum Service Interval	Inactivity Interval	Suspension Interval	Service Start Time	Minimum Data Rate

4	4	4	4	4	2	2
Mean Data Rate	Peak Data Rate	Maximum Burst Size	Delay Bound	Minimum PHY Rate	Surplus Bandwidth Allowance	Medium Time

- Management commands for negotiation of TSPECs between STA and AP:
  - ADDTS Request
  - ADDTS Response
  - DELTS
- After successful negotiation of a TSPEC a STA can contend for a TXOP and then leverage the medium up to the TXOP time limit.
  - TXOP time limits of an AP are conveyed in the beacon.

Improving channel utilization and efficiency

- Transmission Opportunities
  - TXOP is a time interval during in which a station can send as many frames as possible
    - But staying within the maximum duration of the TXOP
    - Frames too large for a single TXOP are fragmented into smaller frames.
    - TXOPs reduces the problem of low rate stations gaining too much channel time
- Block Acknowledgement
  - Group of frames received consecutively acknowledged by a BlockAck
- Direct Link Protocol (DLP)
  - STA-to-STA transmission in the infrastructure mode
    - DLP handles the problems related, e.g. power saving of the receiving STA
- Unscheduled Asynchronous Power Save Delivery (U-APSD)
  - Legacy power-save mode is based on DIFS without protection of medium access
  - Allows a STA to retrieve unicast QoS traffic within one TXOP buffered in the AP by sending trigger frames.
  - U-APSD exchange of frames occurs with SIFS separation
    - Medium remains locked during the exchange.

WLAN IEEE 802.11 Quality of Service

WI-FI QOS IN ACTION

WMM performance: Comparison DCF vs. EDCF

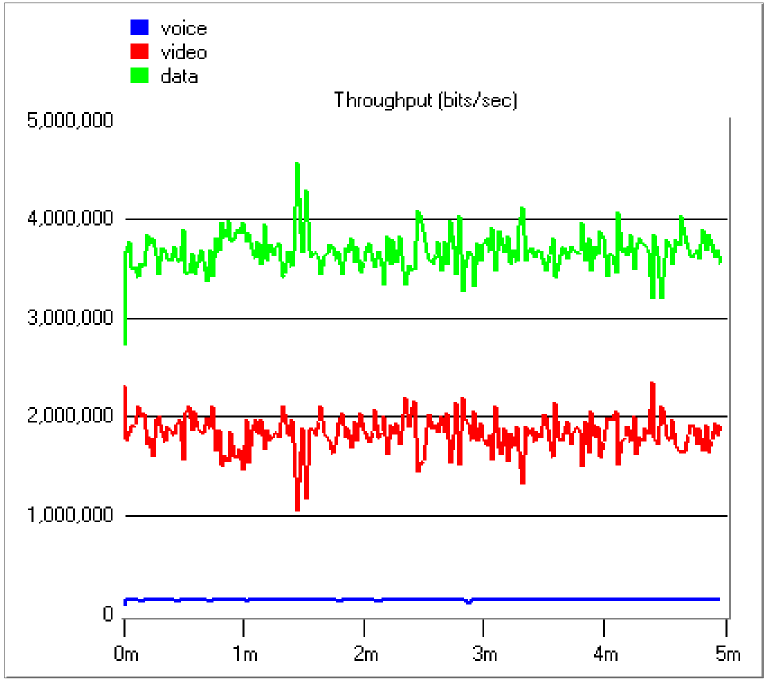
- E.g: Sunghyun Choi; J. del Prado; Sai Shankar N; S. Mangold,
  IEEE 802.11e contention-based channel access (EDCF) performance evaluation, IEEE International Conference on Communications, 2003.
  - http://www.cs.jhu.edu/~baruch/RESEARCH/Research_areas/Wireless/wireless-public_html/class-papers/802.11e-performance.pdf
  - Fixed data rate of 802.11b 11 Mbps; 2 video, 4 voice, and 4 data stations
  - Buffer size: 20 kbit for voice, 1Mbit for video, infinite for data
  - Traffic pattern and default EDCF parameters:

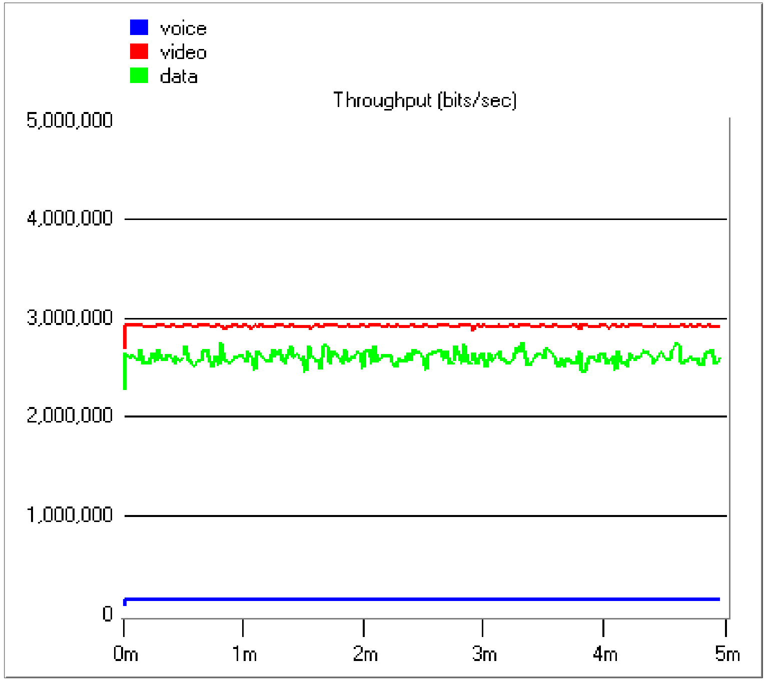
Type	Inter-arrival Time (Avg. in sec)	Frame Size (bytes)	Data Rate (Mbps)
Voice	Constant (0.02)	92	0.0368
Video	Constant (0.001)	1464	1.4
Data	Exponential (0.012)	1500	1.0

Type	Prior.	AC	AIFS	CWmin	CWmax	TXOP limit (msec)
Voice	7	3	PIFS	7	15	3
Video	5	2	PIFS	15	31	6
Data	0	0	DIFS	31	1023	0

DCF vs. EDCF

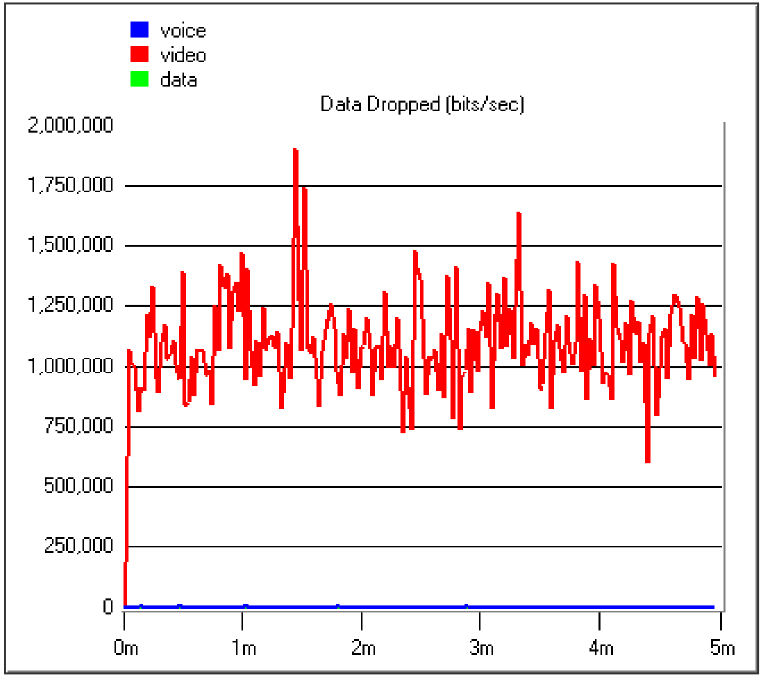
- Throughput comparison
  - Higher video throughput with EDCF

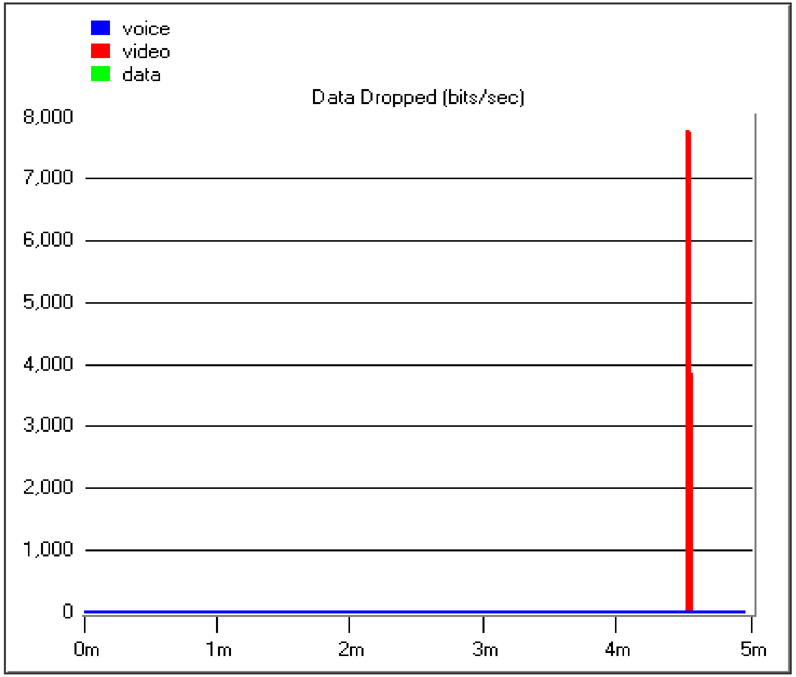




DCF vs. EDCF

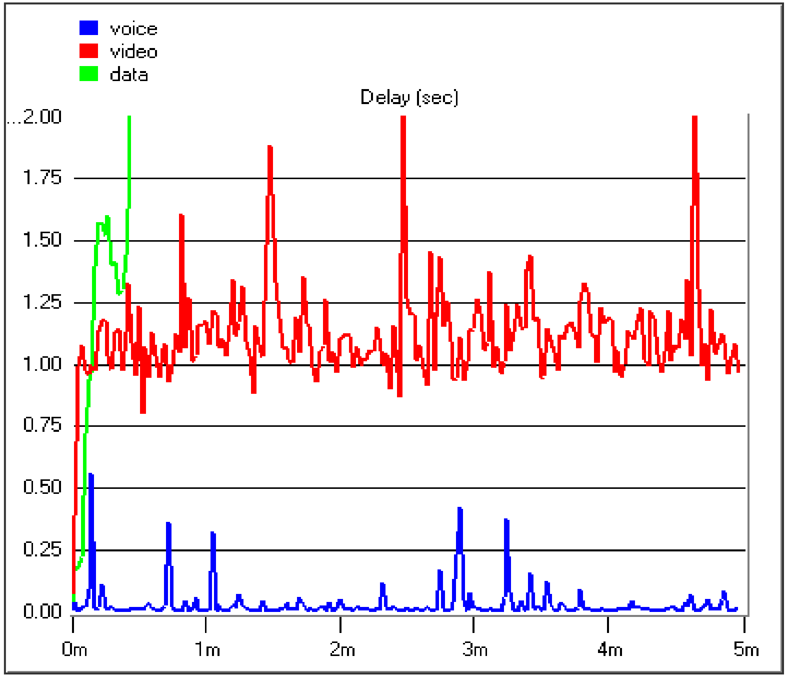
- Data dropping rate comparison
  - Video drop virtually gone with EDCF

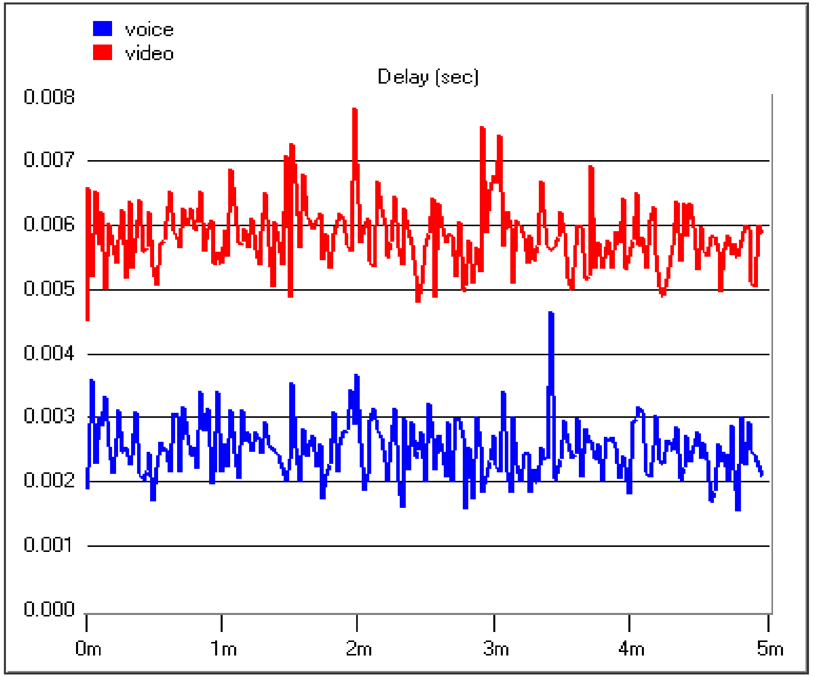




DCF vs. EDCF

- Delay comparison
  - Voice and video delays significantly reduced



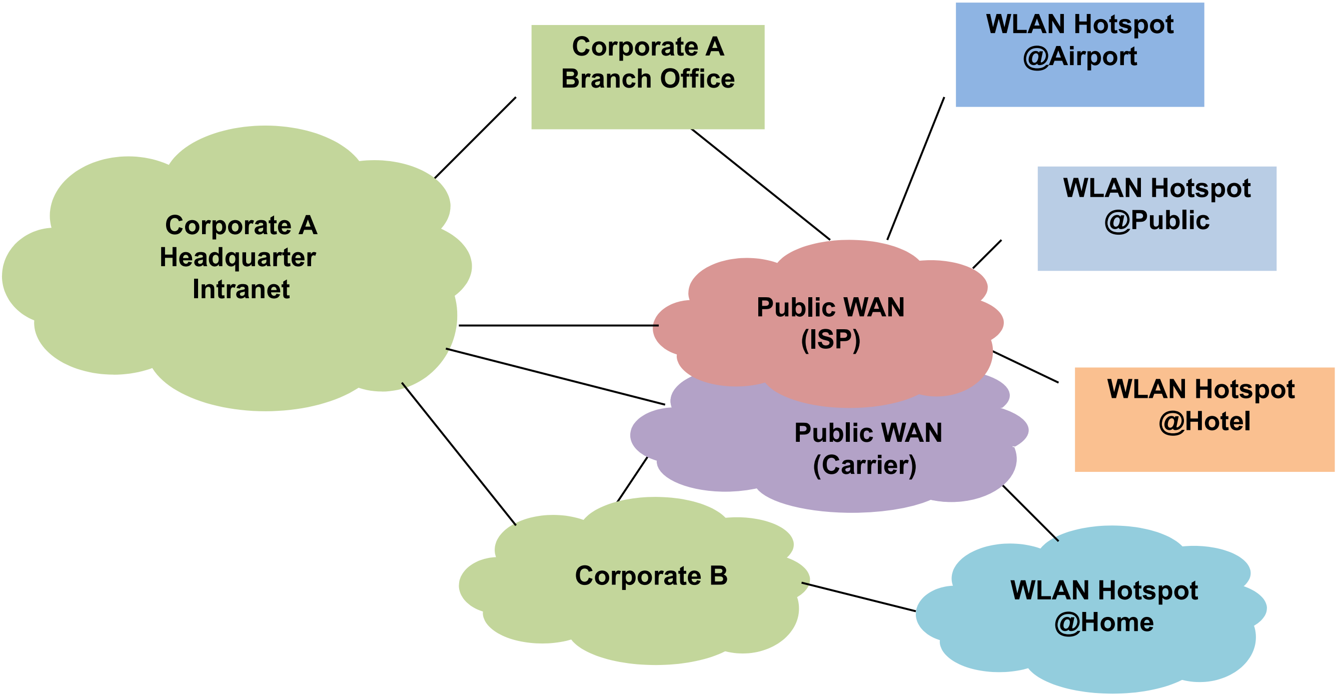


WLAN IEEE 802.11

WLAN ROAMING AND HOTSPOT 2.0

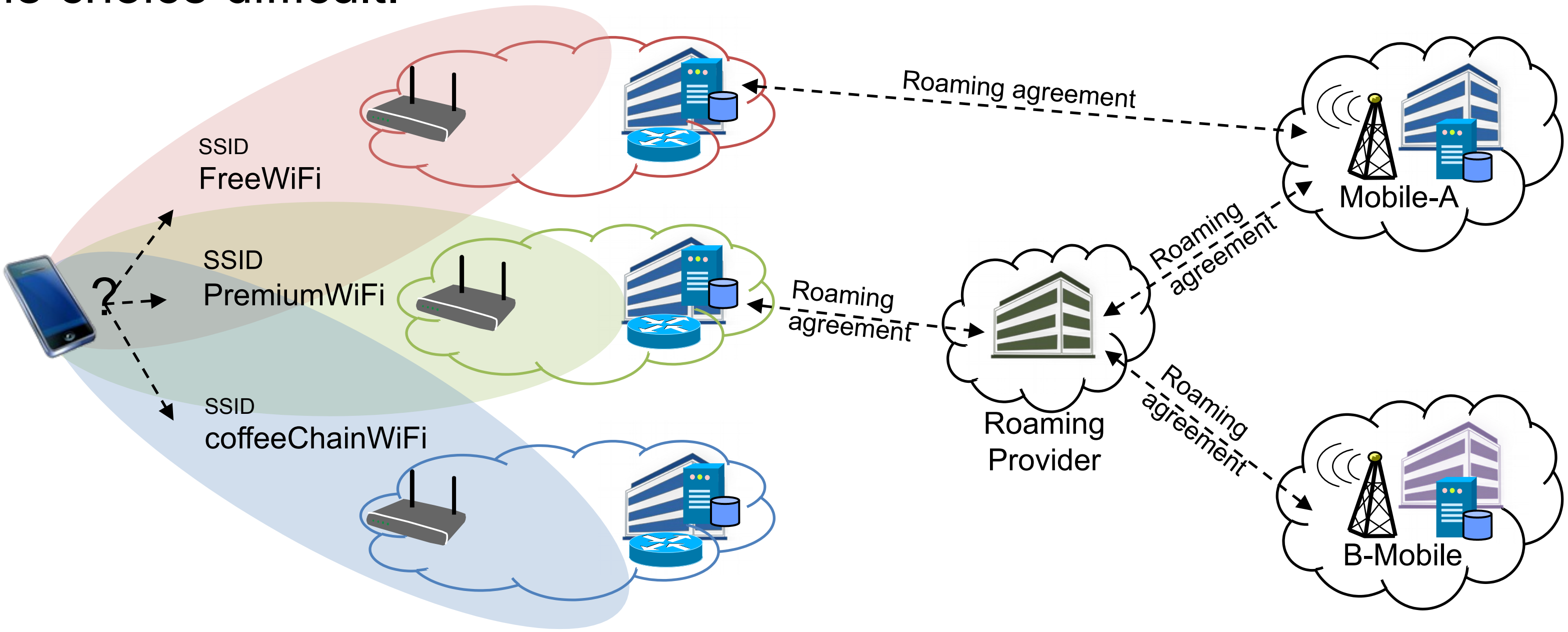
Wi-Fi hotspot deployments

- Public Wi-Fi access requires cooperation among hotspot operators.
- Roaming allows for users receiving services at ‘foreign’ hotspots.



Finding the ‘right’ Wi-Fi access

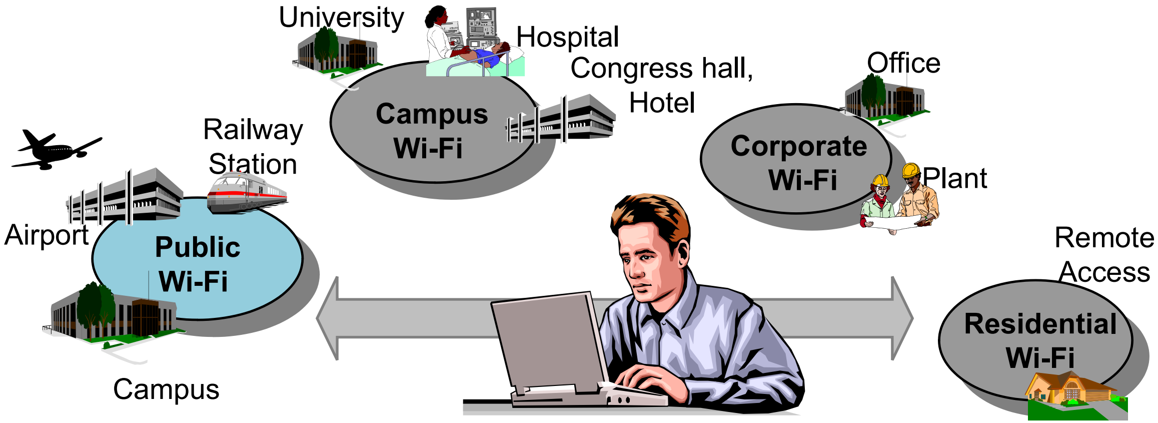
- Multiple subscriptions on the terminal and roaming arrangements behind the APs make the choice difficult.



- The terminal can’t rely only on the SSID for network selection but requires further information
  - Such information is required prior to association and authentication

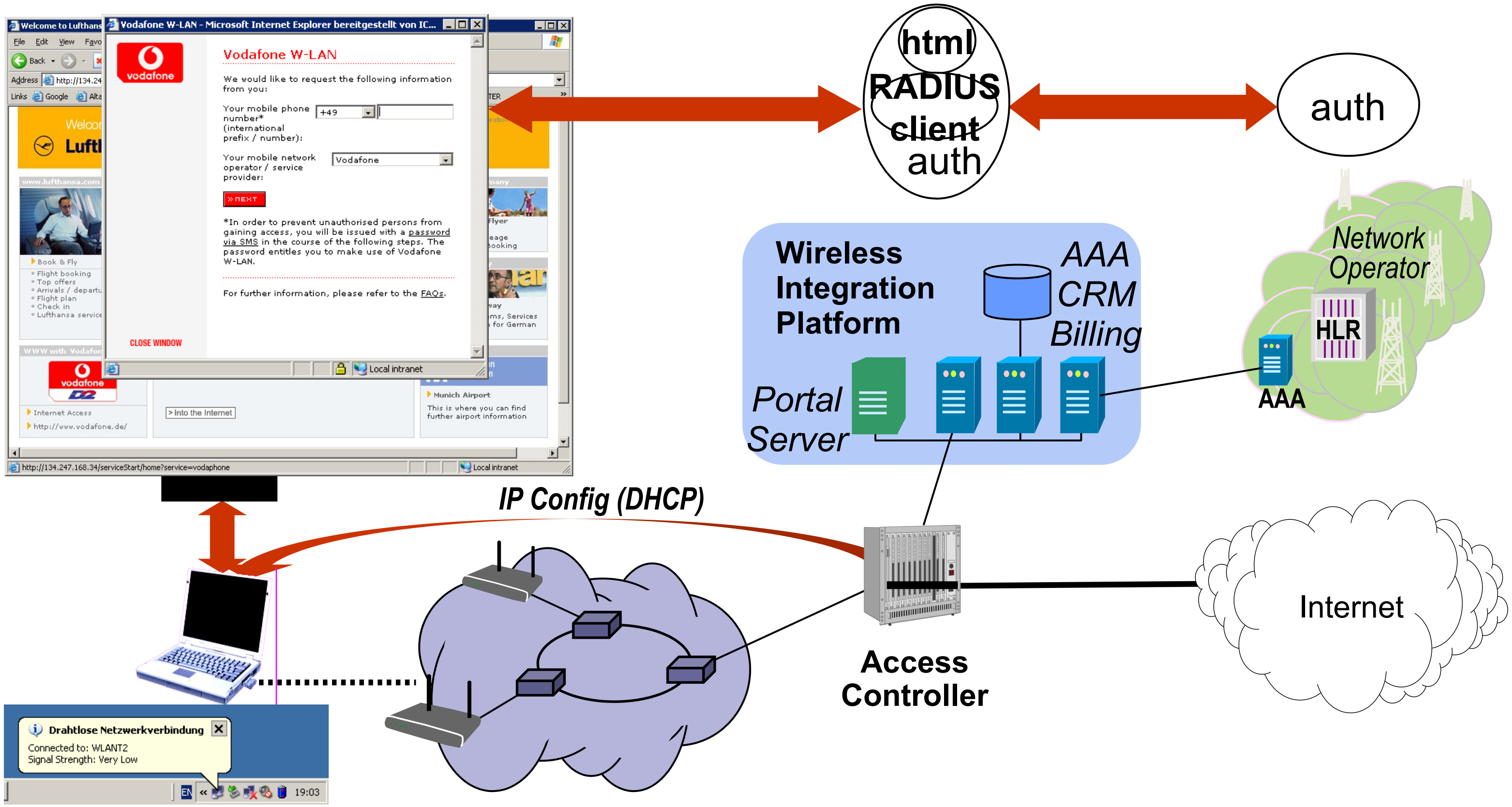
Public Wi-Fi access challenges

- Wi-Fi is used as a kind of nomadic Internet service.
- Secure automatic Wi-Fi connections exist for Residential Wi-Fi, Corporate Wi-Fi and Campus Wi-Fi.
  - Based on WPA2-PSK or WPA2-Enterprise



- Public Wi-Fi is still based on cumbersome captive portal pages for access network selection and authentication
  - Completely missing security requirements

Cumbersome captive portal based access control



Vodafone W-LAN - Microsoft Internet Explorer bereitgestellt von IC...

Vodafone W-LAN

We would like to request the following information from you:

Your mobile phone number* (international prefix / number): +49

Your mobile network operator / service provider: Vodafone

» NEXT

*In order to prevent unauthorised persons from gaining access, you will be issued with a password via SMS in the course of the following steps. The password entitles you to make use of Vodafone W-LAN.

For further information, please refer to the FAQs.

CLOSE WINDOW

http://134.247.168.34/serviceStart/home?service=vodaphone

Drahtlose Netzwerkverbindung

Connected to: WLANT2
Signal Strength: Very Low

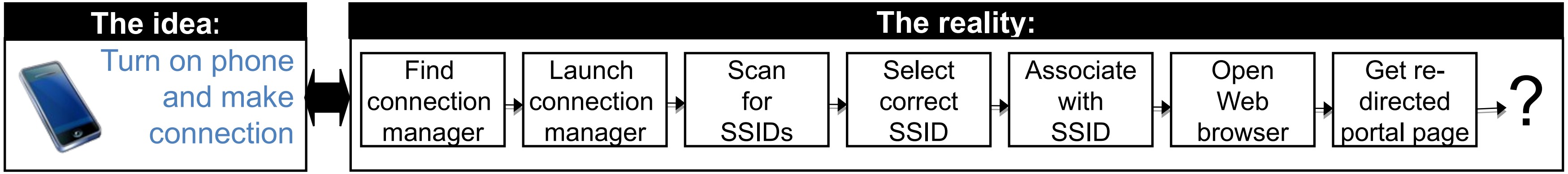
What’s wrong with (current) public Wi-Fi access?

- Usability Problems
  - Web-page redirection (browser hijacking)
    - Error prone for many reasons
  - Login process
    - Browser-based authentication required before any other application can be used.
  - Credentials with hidden time-limits
    - No reliable indication whether the service has been stopped due to problems or expiration
  - Hotspot selection.
    - Manual interaction and selection required when multiple hotspots appear
  - Hotspots operated by roaming partners
    - Roaming relationship can’t be detected before bringing up the portal pages

- Security Threats in portal-based hotspots
  - Evil twin attack
    - An attacker mimics a legitimate hotspot by a rogue access point using the same SSID
  - Session hi-jacking
    - An attacker takes over the Wi-Fi connectivity by causing the user’s mobile device to disassociate from the Wi-Fi network.
  - Eavesdropping
    - An attacker intercepts the Wi-Fi communications and derives personal information such as passwords, credit card numbers, photographs, and emails.
- Security threats are caused by missing link layer security!

Wi-Fi Alliance Hotspot 2.0

- Public Wi-Fi access as simple and easy as cellular communication



The idea:

Turn on phone and make connection

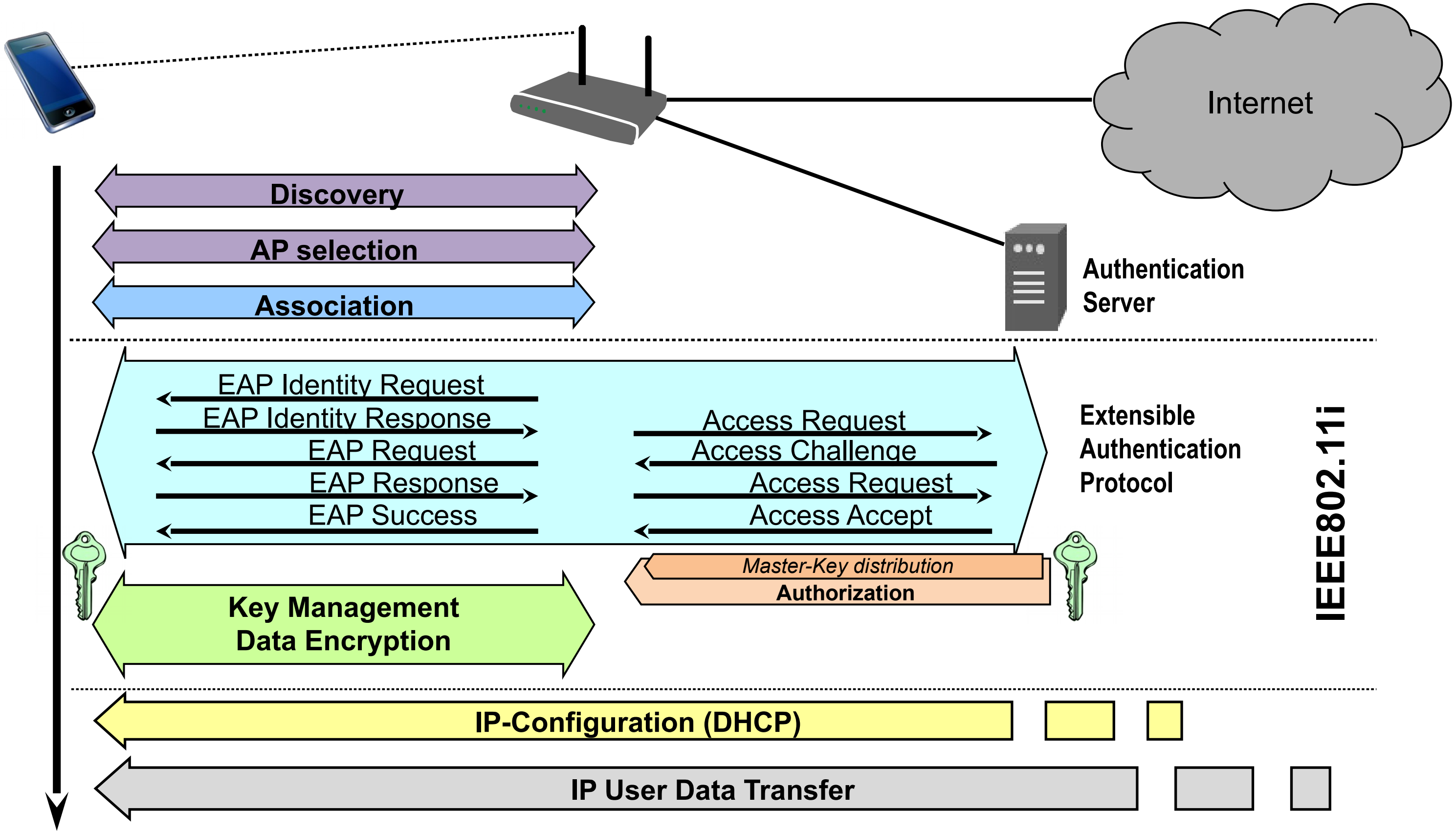
The reality:

Find connection manager → Launch connection manager → Scan for SSIDs → Select correct SSID → Associate with SSID → Open Web browser → Get re-directed portal page → ?

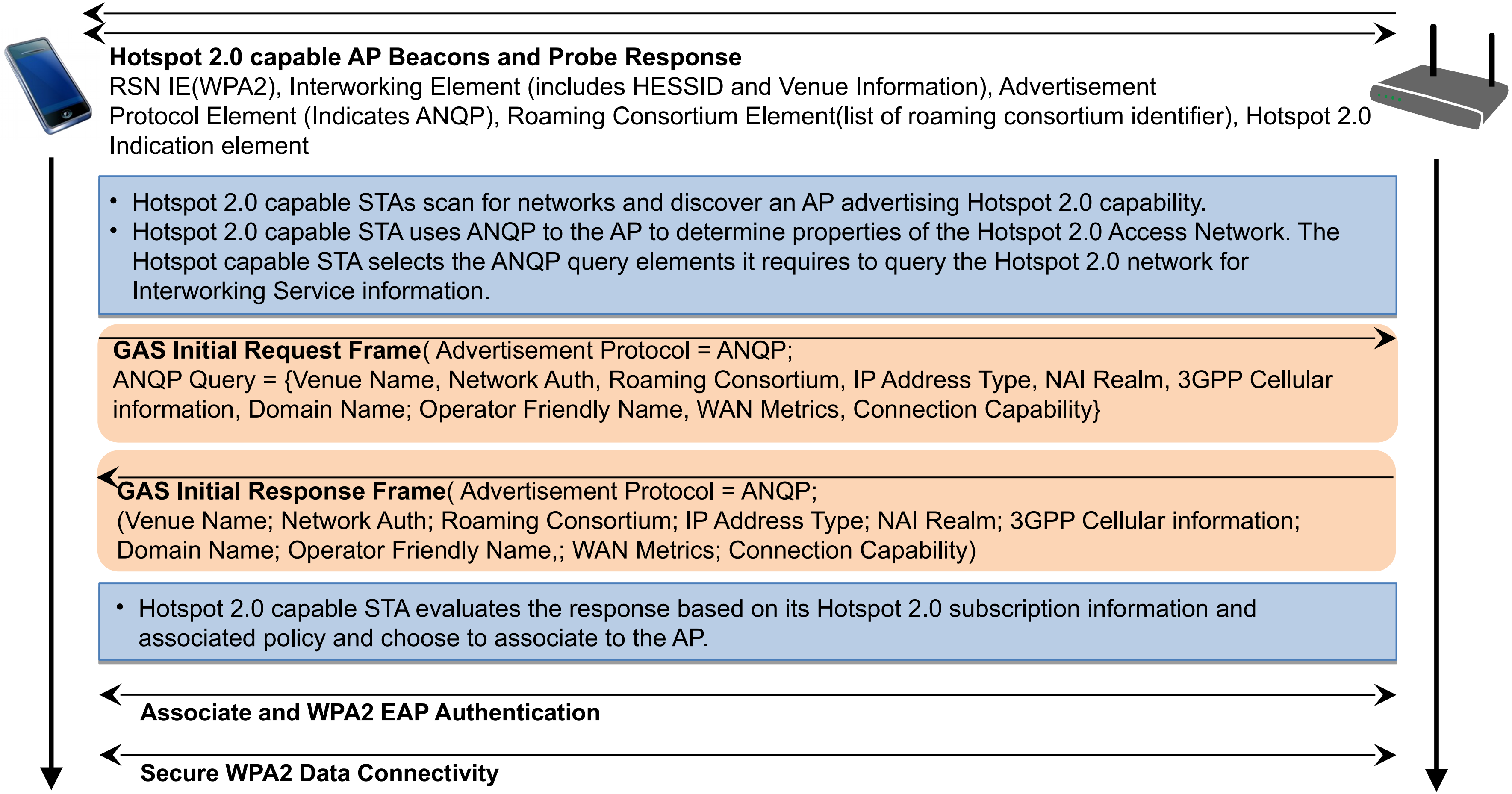
- Essential pieces already exist:
  - Appropriate Wi-Fi security framework already available (WPA2-Enterprise)
    - Widely deployed in Wi-Fi certified products for many years
  - Support of EAP-SIM/EAP-PEAP/EAP-TLS/EAP-TTLS in devices
  - Build-in Wi-Fi connection managers in mobile operating systems
    - Device configuration allowing prioritized selection of known Wi-Fi networks
  - Standard for Wi-Fi network discovery and selection support (IEEE 802.11u)
- Missing: network selection support for roaming, online registration, online provisioning
  - Wi-Fi Alliance Hotspot 2.0 program addressed the missing pieces => PASSPOINT™ Certified

Hotspot 2.0 security and automatic login

WPA2-Enterprise provides automatic login when there is a valid credential.



ANQP Usage by Hotspot 2.0



Hotspot 2.0 capable AP Beacons and Probe Response
RSN IE(WPA2), Interworking Element (includes HESSID and Venue Information), Advertisement Protocol Element (Indicates ANQP), Roaming Consortium Element(list of roaming consortium identifier), Hotspot 2.0 Indication element

- Hotspot 2.0 capable STAs scan for networks and discover an AP advertising Hotspot 2.0 capability.
- Hotspot 2.0 capable STA uses ANQP to the AP to determine properties of the Hotspot 2.0 Access Network. The Hotspot capable STA selects the ANQP query elements it requires to query the Hotspot 2.0 network for Interworking Service information.

GAS Initial Request Frame(Advertisement Protocol = ANQP;
ANQP Query = {Venue Name, Network Auth, Roaming Consortium, IP Address Type, NAI Realm, 3GPP Cellular information, Domain Name; Operator Friendly Name, WAN Metrics, Connection Capability}

GAS Initial Response Frame(Advertisement Protocol = ANQP;
(Venue Name; Network Auth; Roaming Consortium; IP Address Type; NAI Realm; 3GPP Cellular information; Domain Name; Operator Friendly Name,; WAN Metrics; Connection Capability)

- Hotspot 2.0 capable STA evaluates the response based on its Hotspot 2.0 subscription information and associated policy and choose to associate to the AP.

Associate and WPA2 EAP Authentication

Secure WPA2 Data Connectivity

E.g. ANQP Information Elements

IEEE 802.11 ANQP Information Elements

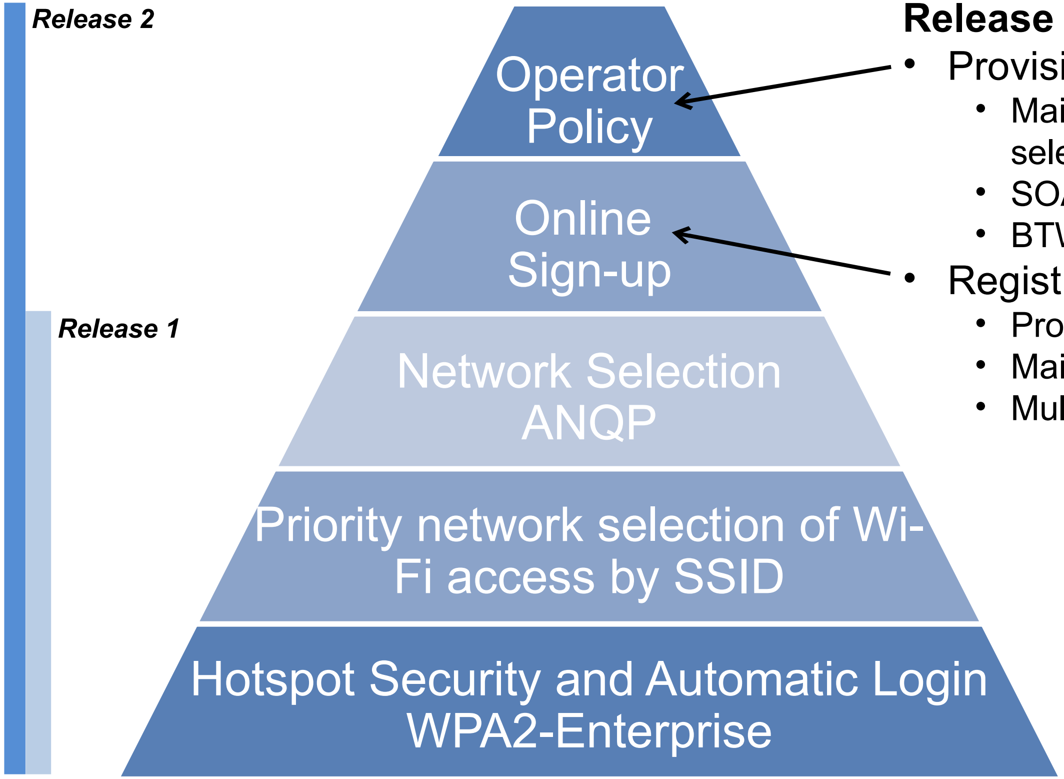
- Venue Name
  - Zero or more venue names associated with the BSS to support the user’s selection.
- Network Authentication Type
  - A list of authentication types carrying additional information like support for online enrollment or redirection URL.
- Roaming Consortium
  - A list of information about the Roaming Consortium and/or SSPs whose networks are accessible via this AP.
- IP Address Type Availability
  - Information about the availability of IP address version and type that could be allocated to the STA after successful association.
- NAI Realm
  - A list of network access identifier (NAI) realms corresponding to SSPs or other entities whose networks or services are accessible via this AP; optionally amended by the list of EAP Method, which are supported by the SSPs.
- 3GPP Cellular Network
  - Cellular information such as network advertisement information e.g., network codes and country codes to assist a 3GPP STA in selecting access 3GPP networks.
- Domain Name
  - A list of one or more domain names of the entity operating the IEEE 802.11 access network.

Hotspot 2.0 ANQP Information Elements

- HS Query list
  - A list of identifiers of HS 2.0 ANQP elements for which the requesting mobile device is querying in a HS ANQP Query.
- HS Capability list
  - A list of information/ capabilities that has been configured on an AP. The HS Capability list element is returned in response to a GAS Query Request.
- Operator Friendly Name
  - Zero or more operator names operating the IEEE 802.11 AN.
- WAN Metrics
  - Information about the WAN link connecting a IEEE 802.11 AN and the Internet.
- Connection Capability
  - Connection status of the most commonly used communications protocols and ports.
- NAI Home Realm Query
  - Used by the STA to determine if the NAI realms for which it has security credentials are realms corresponding to SPs or other entities whose networks or services are accessible via this BSS
- Operating Class Indication
  - Information on the groups of channels in the frequency band(s) the Wi-Fi access network is using

Hotspot 2.0 aka “Passpoint”

Also known as Next Generation Hotspot (NGH)


Release 2
Release 1
Operator Policy
Online Sign-up
Network Selection ANQP
Priority network selection of Wi-Fi access by SSID
Hotspot Security and Automatic Login WPA2-Enterprise

Release 2 adds to Release 1:

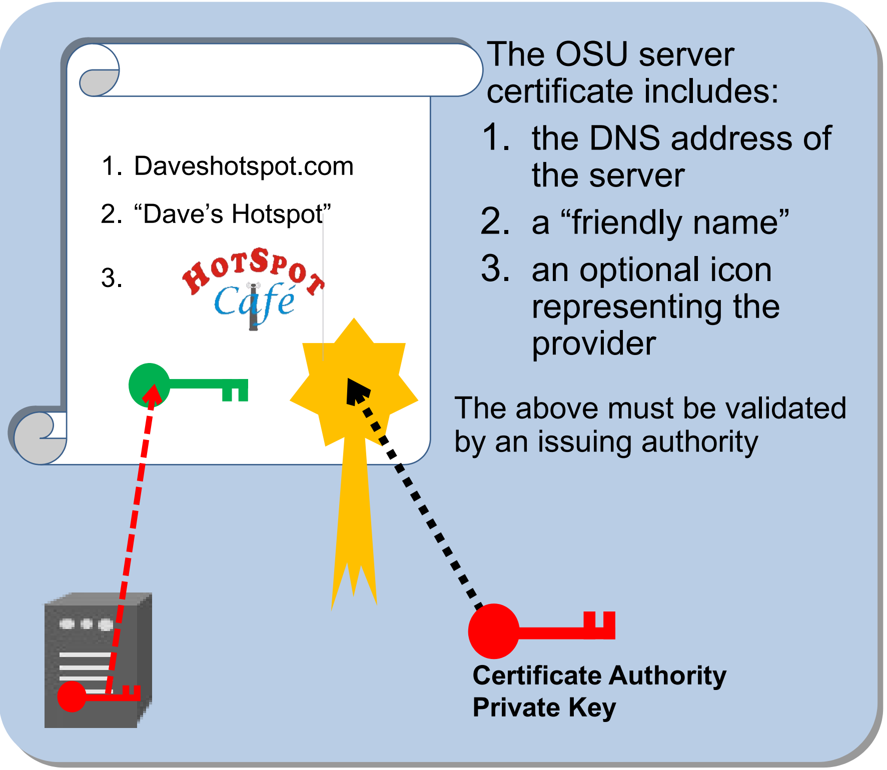
- Provisioning
  - Mainly provisioning of operator policies for automatic selection of preferred Wi-Fi access networks
  - SOAP XML provisioning protocol mandatory for UE
  - BTW: Management Object different to ANDSF
- Registration
  - Procedure to establish ‘online’ a new subscription
  - Mainly replacement of the legacy captive portal
  - Multi-phase approach with initial anonymous EAP-TLS

Online sign-up procedure

- Hotspots offering online sign have two ESSs:
  - An OSU ESS that supports online sign up
  - A production ESS that provides network access to the authenticated mobile device.
- In case of secure OSU ESS, same SSID as used for production ESS can be used, when un-authenticated STA is kept in ‘isolated’ mode with only access to OSU server.
- Registration procedures
  - The mobile device is setting up a new account with an SP or hotspot provider.
  - Begins with the mobile device authenticating the OSU server.
    - During the OSU procedure, the user will manually enter information, such as contact information and payment method, as required by the SP to obtain an account.
  - Credentials and related metadata provisioned are bound to this account.
- Provisioning procedures
  - Credentials and related metadata are downloaded to STA and installed for subsequent authenticated access to service

Client validation of authenticity of OSU information

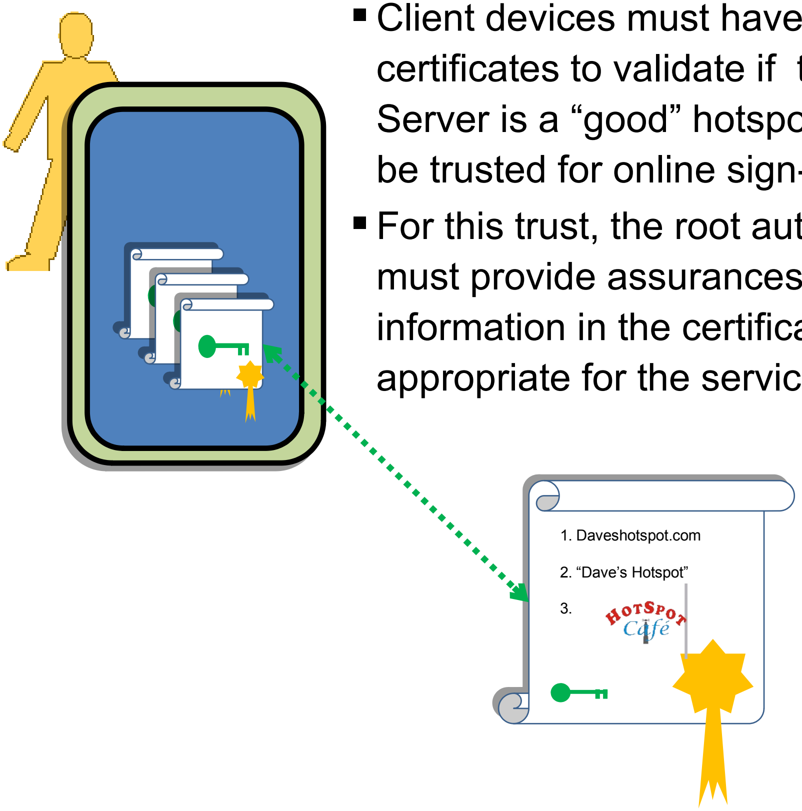
- Online Sign Up Server Certificates are used for validation



The OSU server certificate includes:

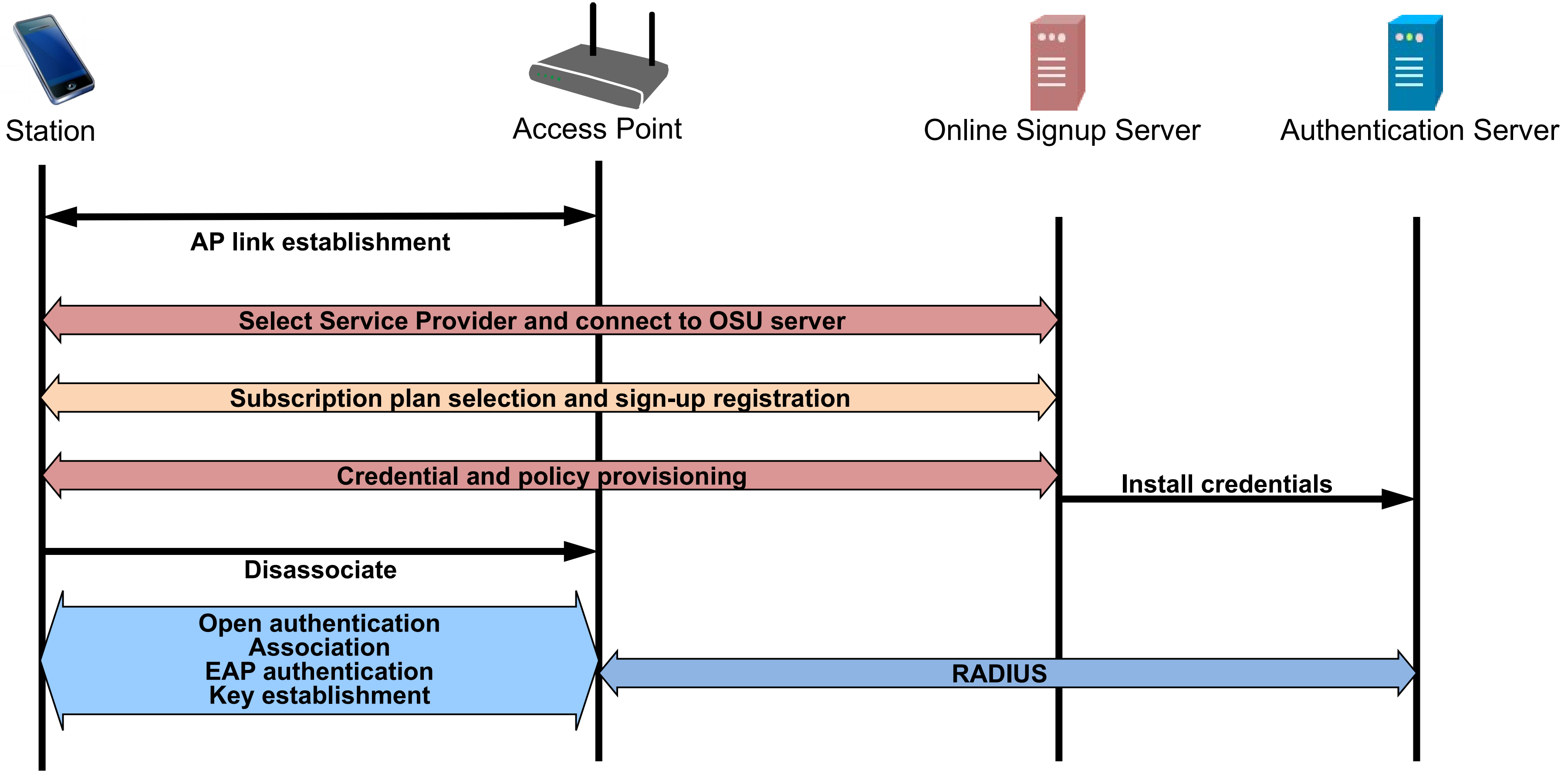
1. the DNS address of the server
2. a “friendly name”
3. an optional icon representing the provider

The above must be validated by an issuing authority



- Client devices must have “root” certificates to validate if the OSU Server is a “good” hotspot that can be trusted for online sign-up.
- For this trust, the root authorities must provide assurances that information in the certificate is appropriate for the service provider

Online-Signup Operational Phases

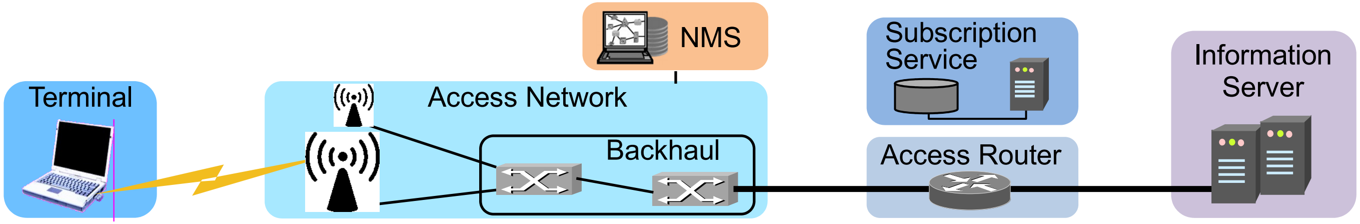


WLAN IEEE 802.11

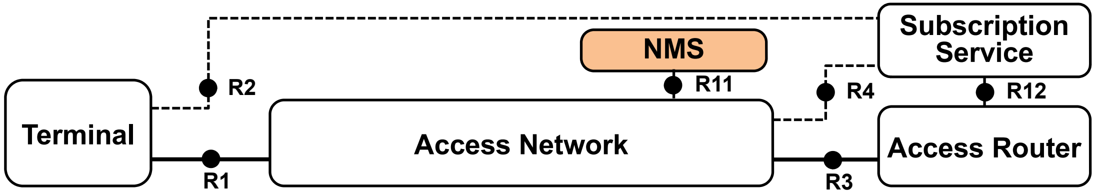
WLAN MANAGEMENT

Network Reference Model design

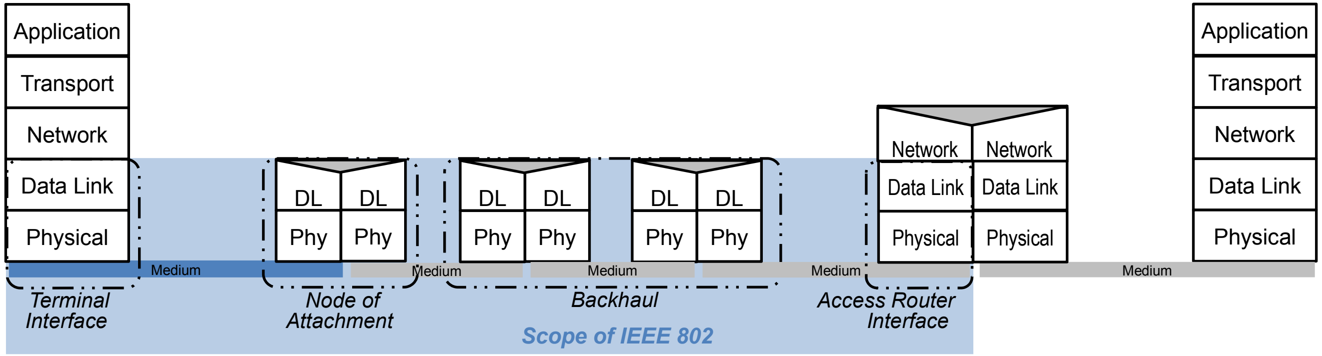
End-to-end communication network topology



Network Reference Model Schematic



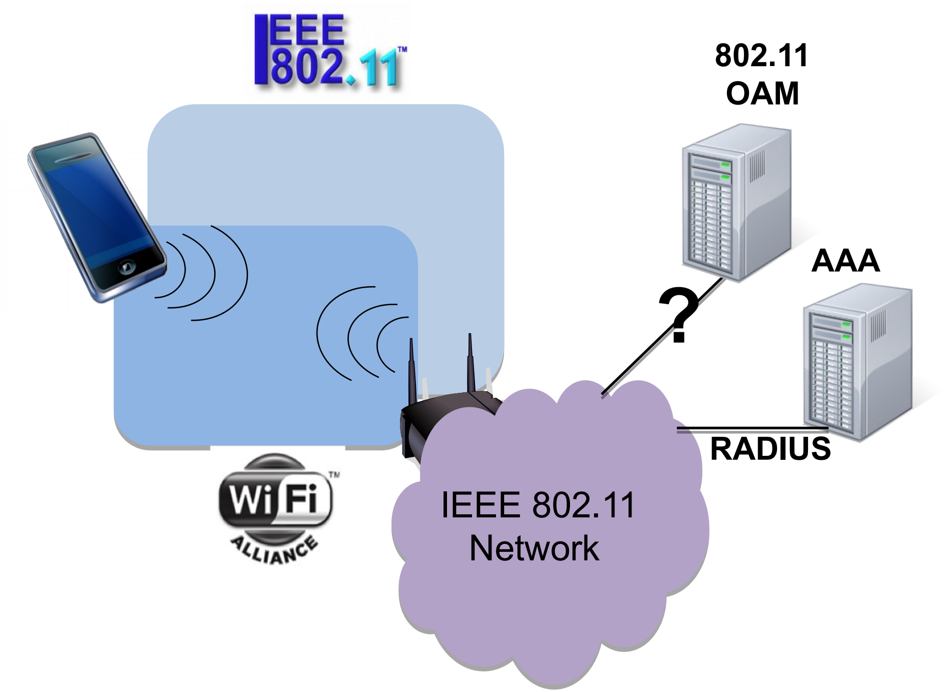
Data Path of Network Reference Model in the protocol layer architecture



WLAN IEEE 802.11

OAM FOR WI-FI

Standards for OAM of Wi-Fi



- IEEE 802.11 defines the radio interface of Wi-Fi
- Wi-Fi Alliance ensures compliance of the radio interface by certification
- OAM of the Wi-Fi radio interface is described by a comprehensive IEEE 802.11 MIB
- A couple of organizations developed special variants of OAM interfaces for Wi-Fi
- BTW: For AAA there is a single solution specified: RADIUS

RADIUS (Remote Authentication Dial-In User Service)

- RFC 2865 & RFC 2866 (RADIUS/RADIUS Accounting)
  - Common solution for the communication between Access Point and AAA server for user authentication, user authorization and user accounting.
- RFC3580 (IEEE 802.1X Remote Authentication Dial In User Service (RADIUS) Usage Guidelines).
  - Support of EAPoLAN (IEEE 802.1X), which was introduced to IEEE 802.11 through IEEE 802.11i-2004
- RFC7268 (RADIUS Attributes for IEEE 802 Networks)
  - Further IEEE802 specific attributes for support of interworking with external networks and enhanced security modes.
- RFC5580 (Carrying Location Objects in RADIUS and Diameter)
  - Transport of location information over the AAA infrastructure.

‘OAM’ Interface Specifications for 802.11

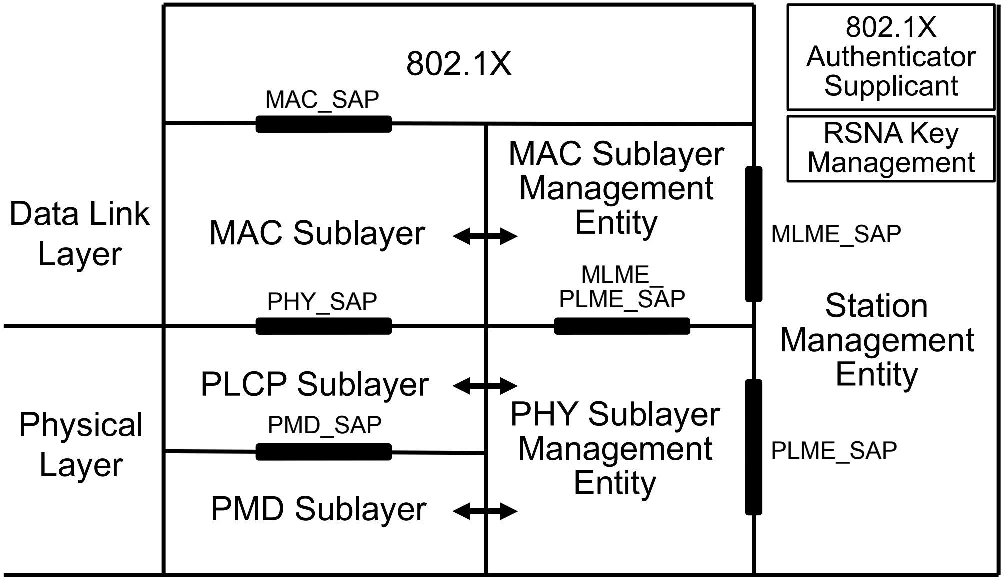
- IEEE 802.11 SNMP MIB
  - Comprehensive definition of all management information of IEEE 802.11
  - Aimed for SNMP management but rarely implemented
- BroadBandForum
  - Wi-Fi model and attributes of Device Data Model 2 (TR-181) for CPE WAN Management Protocol (TR-069)
  - CableLabs
    - Wi-Fi Provisioning Framework Specification (WR-SP-WiFi-MGMT)
- IETF CAPWAP
  - Control And Provisioning of Wireless Access Points (CAPWAP) Protocol Specification (RFC5415) and Binding for IEEE 802.11 (RFC5416)
- LINUX Wireless
  - mac80211 Wi-Fi driver architecture with cfg80211 kernel configuration module and nl80211 netlink user space interface

IEEE802.11 SNMP MIB

- IEEE 802.11 MIB follows the generic protocol architecture
  - Annex C of specification and available by http://www.ieee802.org/11/802.11mib.txt

Major sections

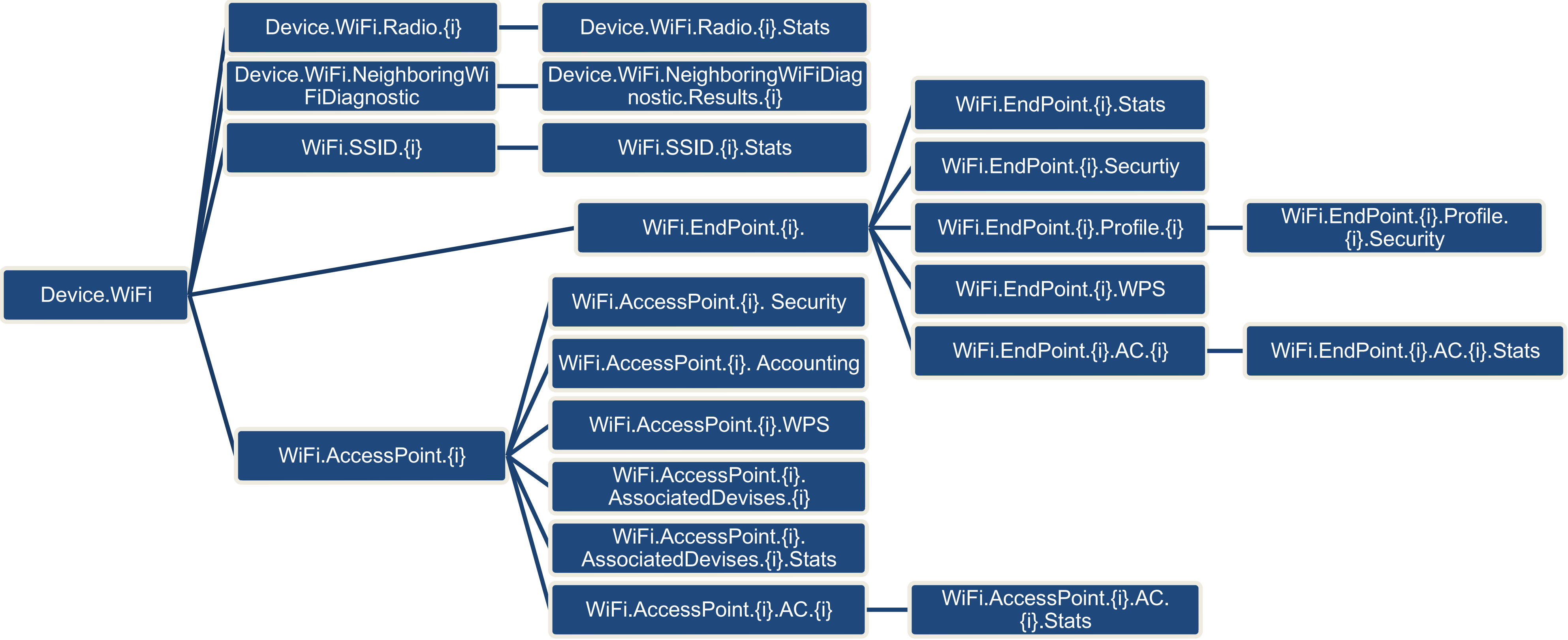
- Station Management (SMT) Attributes
  - dot11smt GROUPS
    - dot11StationConfigTable
    - …
    - dot11RSNAConfigDLCGroupTable
- MAC Attributes
  - MAC GROUPS
    - dot11OperationTable
    - …
    - dot11ResourceInfoTable
- PHY Attributes
  - PHY GROUPS
    - dot11PhyOperationTable
    - …
    - dot11TransmitBeamformingConfigTable



BroadBand Forum TR-181

- TR-181 defines version 2 of the TR-069 Device data model (Device:2)
  - Applicable to all types of TR-069-enabled devices.
  - Obsoletes both Device:1 and InternetGatewayDevice:1 specifications
- Based on TR-069 / CWMP (CPE WAN Management Protocol)
  - https://www.broadband-forum.org/cwmp.php
  - TR-069 is an soap/HTTP based protocol for transmission of XMLbased descriptions of management models between CPE and ACS
- The TR-069 Management Data Model Schema is specified in TR-106.
  - TR-069 Data Models are xml documents that are “schema-like”, that describe the management objects and parameters used for particular use cases.
- TR-181 provides a compact set of IEEE 802.11 specific attributes for configuration
  - Only a small subset of the attributes in IEEE 802.11
- TR-181 adds to each of the elements of the Wi-Fi model a rich set of attributes for monitoring/accounting/statistics.

TR-181 Wi-Fi Model


Device.WiFi
Device.WiFi.Radio.{i}
Device.WiFi.Radio.{i}.Stats
Device.WiFi.NeighboringWiFiDiagnostic
Device.WiFi.NeighboringWiFiDiagnostic.Results.{i}
WiFi.SSID.{i}
WiFi.SSID.{i}.Stats
WiFi.EndPoint.{i}.
WiFi.EndPoint.{i}.Stats
WiFi.EndPoint.{i}.Securtiy
WiFi.EndPoint.{i}.Profile.{i}
WiFi.EndPoint.{i}.Profile.{i}.Security
WiFi.EndPoint.{i}.WPS
WiFi.EndPoint.{i}.AC.{i}
WiFi.EndPoint.{i}.AC.{i}.Stats
WiFi.AccessPoint.{i}
WiFi.AccessPoint.{i}. Security
WiFi.AccessPoint.{i}. Accounting
WiFi.AccessPoint.{i}.WPS
WiFi.AccessPoint.{i}. AssociatedDevises.{i}
WiFi.AccessPoint.{i}. AssociatedDevises.{i}.Stats
WiFi.AccessPoint.{i}.AC.{i}
WiFi.AccessPoint.{i}.AC. {i}.Stats

- TR-181 supports two kinds of devices: APs and (nonAP) STAs (Endpoints)
- A Wi-Fi device consists out of 1..n radio interfaces, 1..n SSIDs and 1..n AccessPoints or EndPoints

CableLabs amendments to TR-181

- WR-SP-WiFi-MGMT-I05-141201.pdf is CableLabs' most relevant specification for OAM of Wi-Fi interfaces.
- CableLabs builds management of Wi-Fi on top of TR-069 approaches by
  - adopting the TR-181 device model for Wi-Fi
  - amending the device model by vendor specific extensions for missing functions
    - RadiusClient
    - Interworking Service
    - Passpoint
    - ClientSessions
    - ClientState
    - ApNeighborStats
    - AccessControlFilter
  - defining a compatible SNMP MIB to enable backward-compatibility to the legacy provisioning and management systems in the cable environment

IETF CAPWAP

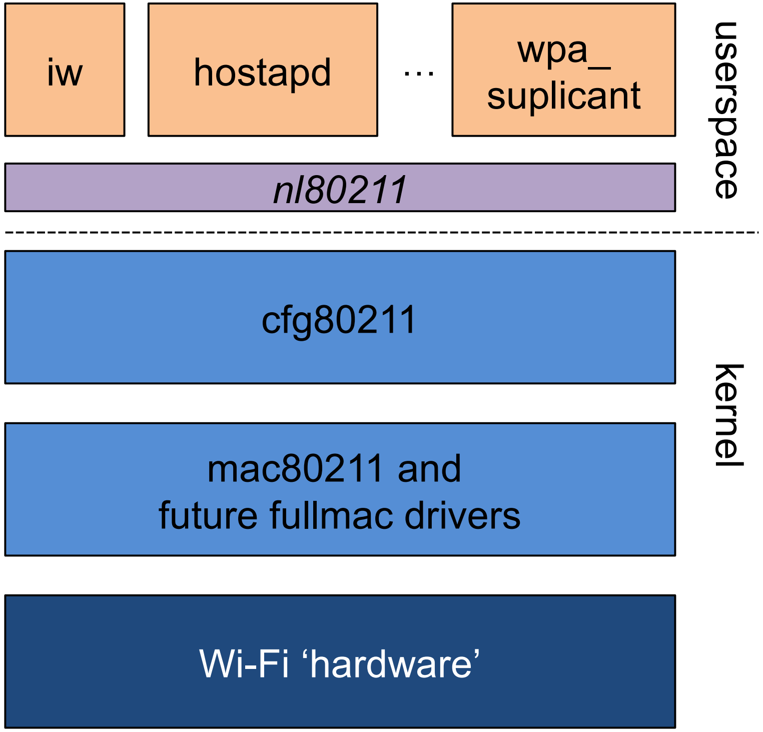
- CAPWAP (Control And Provisioning of Wireless Access Points) specifies interface between a wireless termination point (WTP) and an access controller (AC)
- Supports different architectural models with various possibilities to locate functions either in WTB or AC

```
+-+         wireless frames        +-+
| |--------------------------------| |
| |              +-+               | |
| |--------------| |---------------| |
| |wireless PHY/ | |     CAPWAP    | |
| | MAC sublayer | |               | |
+-+              +-+               +-+
STA              WTP                AC

Split MAC CAPWAP Architecture
```

```
+-+wireless frames +-+ 802.3 frames +-+
| |----------------| |--------------| |
| |                | |              | |
| |----------------| |--------------| |
| |wireless PHY/   | |    CAPWAP    | |
| | MAC sublayer   | |              | |
+-+                +-+              +-+
STA                WTP               AC

Local MAC CAPWAP Architecture
```

- RFC 5415 defines Control And Provisioning of Wireless Access Points (CAPWAP) Protocol
- RFC 5416 provides Binding of CAPWAP for IEEE 802.11, i.e. management model
- RFC 7494 amends RFC5416 for more recent 802.11 standards and deployment scenarios
  - RFC7494: IEEE 802.11 Medium Access Control (MAC) Profile for Control and Provisioning of Wireless Access Points (CAPWAP)

LINUX Wireless Wi-Fi driver architecture



- nl80211 has become de-facto standard for Wi-Fi configuration in LINUX
  - Defines a comprehensive list of controls, commands and attributes for Wi-Fi
  - Communicates by netlink (RFC3549) with kernel
- cfg80211 provides unified interface into kernel drivers
- Two variants for implementation of MAC
  - softmac or fullmac

Wi-Fi OAM specification ‘nl80211.h’

```
#ifndef __LINUX_NL80211_H
#define __LINUX_NL80211_H
/*
 * 802.11 netlink interface public header
 *
 * Copyright 2006-2010 Johannes Berg <johannes@sipsolutions.net>
 * Copyright 2008 Michael Wu <flamingice@sourmilk.net>
 * Copyright 2008 Luis Carlos Cobo <luisca@cozybit.com>
 * Copyright 2008 Michael Buesch <m@bues.ch>
 * Copyright 2008, 2009 Luis R. Rodriguez <lrodriguez@atheros.com>
 * Copyright 2008 Jouni Malinen <jouni.malinen@atheros.com>
 * Copyright 2008 Colin McCabe <colin@cozybit.com>
 *
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 *
 * THE SOFTWARE IS PROVIDED "AS IS" AND THE AUTHOR DISCLAIMS ALL WARRANTIES
 * WITH REGARD TO THIS SOFTWARE INCLUDING ALL IMPLIED WARRANTIES OF
 * MERCHANTABILITY AND FITNESS. IN NO EVENT SHALL THE AUTHOR BE LIABLE FOR
 * ANY SPECIAL, DIRECT, INDIRECT, OR CONSEQUENTIAL DAMAGES OR ANY DAMAGES
 * WHATSOEVER RESULTING FROM LOSS OF USE, DATA OR PROFITS, WHETHER IN AN
 * ACTION OF CONTRACT, NEGLIGENCE OR OTHER TORTIOUS ACTION, ARISING OUT OF
 * OR IN CONNECTION WITH THE USE OR PERFORMANCE OF THIS SOFTWARE.
 *
 */

#include <linux/types.h>

#define NL80211_GENL_NAME "nl80211"

/**
 * DOC: Station handling
 *
 * Stations are added per interface, but a special case exists with VLAN
 * interfaces. When a station is bound to an AP interface, it may be moved
 * into a VLAN identified by a VLAN interface index (%NL80211_ATTR_STA_VLAN).
 * The station is still assumed to belong to the AP interface it was added
 * to.
 *
```
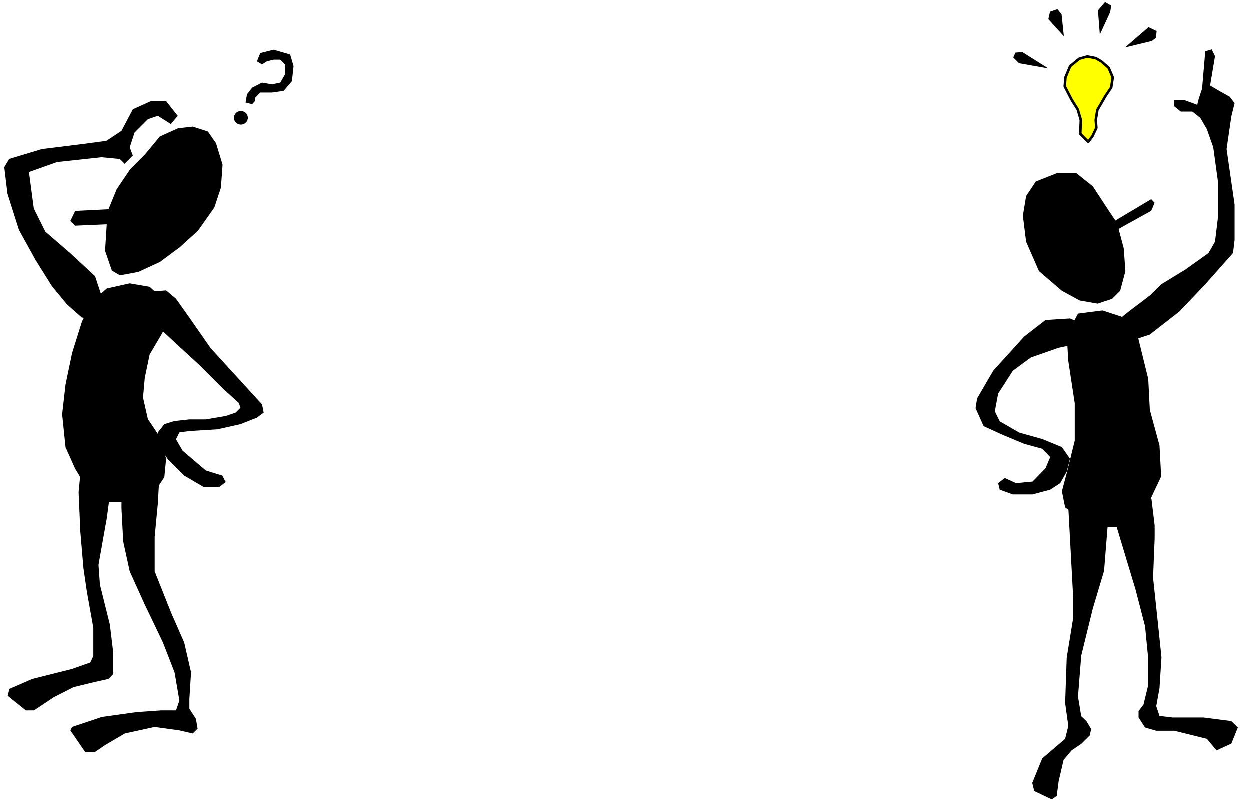

- http://git.kernel.org/cgit/linux/kernel/git/linville/wireless.git/tree/include/uapi/linux/nl80211.h?id=HEAD
- nl80211.h defines
  - 120 commands
  - about 600 attributes and controls
- nl80211.h is allowing access to most of the PHY, MAC and SME parameters of a Wi-Fi radio interface
- Scope similar to IEEE 802.11 SNMP MIB

WLAN IEEE 802.11

END OF PART 2

Questions and answers



Questions…

Medium Access Functions

1) Why does collision detection with immediate termination of transmission usually not work in wireless?
2) What means are used by IEEE 802.11 to avoid collisions?
3) What does SIFS mean, and for which frame is it used?
4) What is the difference between random backoff and exponential backoff?
5) How is virtual carrier sensing done?
6) When does a receiver respond with an ACK to a received frame?
7) What is the issue of the hidden station problem?
8) Which procedure is used to mitigate the hidden station problem?
9) Which message is used by a receiver to respond to a ‘Request To Send’?
10) When is it beneficial to fragment the transmission of a long frame?

More questions…

Mac Layer Management

1) What does MLME stand for?
2) What are the two main functions of the MAC layer Systems Management?
3) What is the purpose of the Timer Synchronization Function?
4) Please shortly outline the role of the Delivery Traffic Indication Message for the power management in IEEE 802.11
5) Which sequence of MAC management procedures is necessary for the establishment of a connection in IEEE 802.11
6) What is the purpose of scanning?
7) What are beacons in IEEE 802.11?
8) Explain the difference between active scanning and passive scanning.
9) What stands 'GAS' in IEEE 802.11 for?
10) What is the purpose of ANQP in IEEE 802.11?
11) How is ANQP related to GAS?
12) What is the purpose of IEEE 802.11 association procedure?
13) What is a Reassociation in IEEE 802.11?
14) Please shortly explain the MAC procedures for handover from on AP to another AP of the same ESS.
15) What are the limitations of Layer 2 mobility management?

More questions…

Quality of Service

1) How does the Distributed Coordination Function (DCF) work?
2) What means EDCF, and what enhancement does it add to DCF?
3) What HCF stands for, and what previous coordination function has been replaced by it?
4) By which standard amendment was QoS support added to IEEE 802.11?
5) What main functions were added to 802.11 by 802.11e?
6) How many priority classes does WMM support?
7) What is WMM?
8) What are the QoS classes supported by WMM?
9) Through which method are traffic classes realized in 802.11e?
10) What does TSPEC mean, and for what is it used?

More questions…

Hotspot 2.0

1) What is the benefit of ‘Roaming’?
2) How is the access method for public Wi-Fi through opening a Web page called?
3) What is the main benefit of Hotspot 2.0?
4) What is ANQP used for Hotspot 2.0?
5) How can a station detect that an AP supports Hotspot 2.0?
6) What is the brand name of the Wi-Fi Alliance certification program for Hotspot 2.0?
7) In which release of Hotspot 2.0 was Online Sign-Up added?
8) What special server is needed for online signup support?
9) How many ESSs are required for online signup?
10) By which mean verifies the user the identity of the OSU provider?

More questions…

OAM for Wi-Fi

1) What kind of OAM interface specification does IEEE 802.11 provide?
2) What is the specification of the BroadBand Forum describing the management model for Wi-Fi?
3) Which protocol is used for carrying TR-181?
4) Which specification was adopted by CableLabs to define their extensions?
5) Which organization did ‘CAPWAP’ standardize?
6) Which architectural models are supported by CAPWAP?
7) What is Wireless Linux ‘nl80211’?
8) How does nl80211 communicate with its lower layer in the kernel?

Anything left for today?

See you again next week☺.