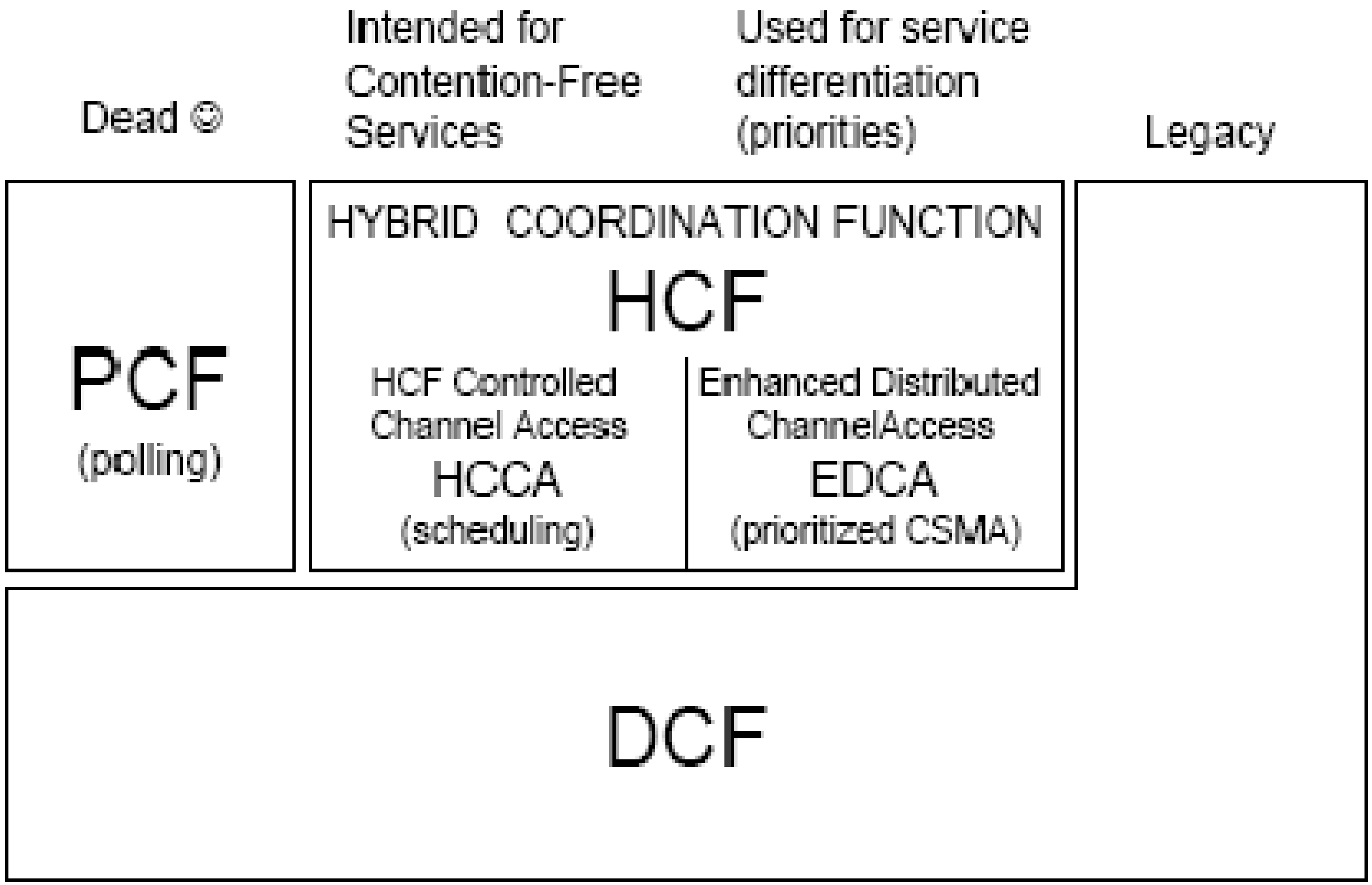
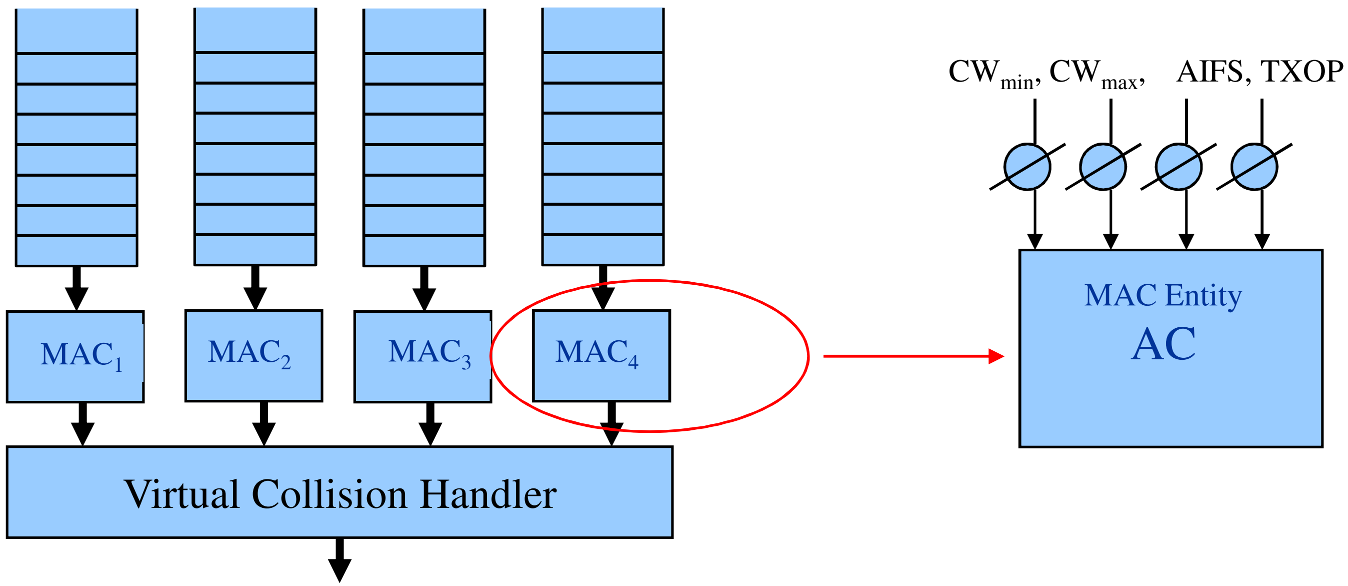
PART 8
IEEE 802.11 Extensions

QoS Support

802.11 MAC evolution
(802.11e, finalized in dicember 2005)



Multiple Queues

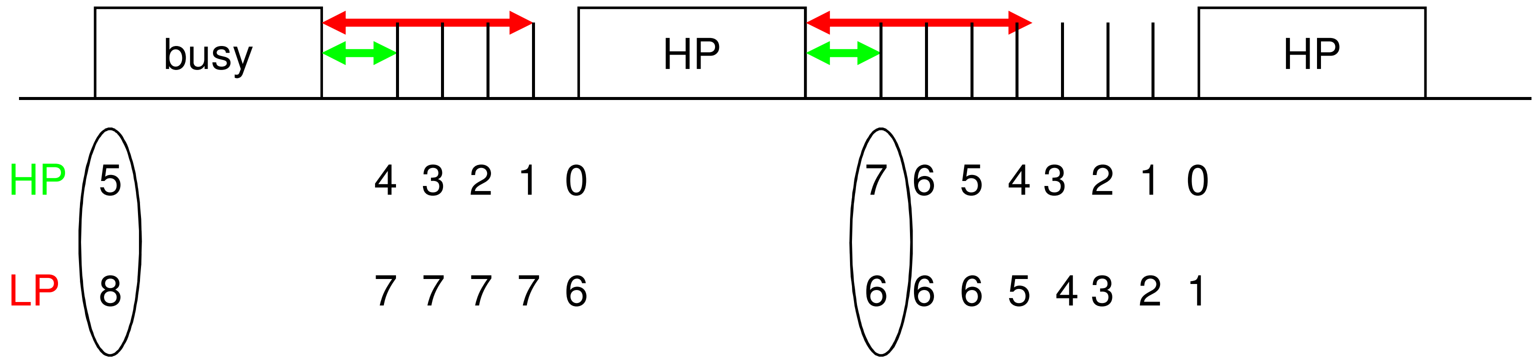


- ➔ **4 Access Categories**
  - ⇨ Mapping the 8 priority levels provided by 802.1p
  - ⇨ Different channel access probability through different access parameters
- ➔ **Independently operated as multiple MAC**
  - ⇨ Queues in the same station can (virtually) collide!

Distributed Prioritization: channel accesses

➔ **More channel accesses to High Priority stations reducing the backoff expiration times**

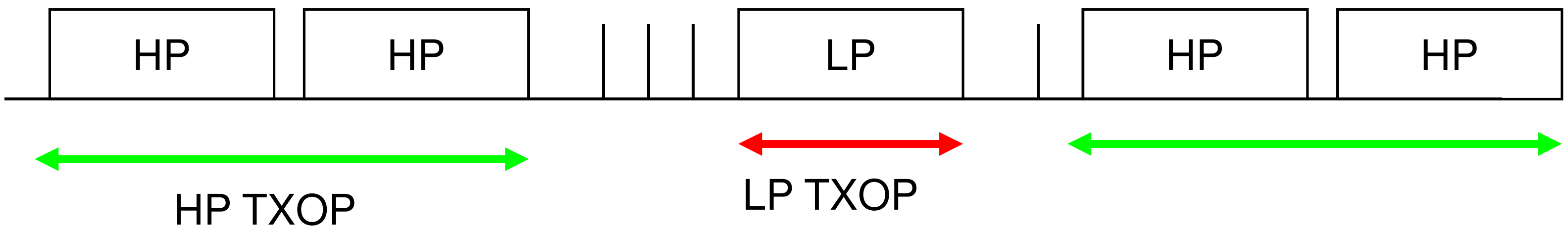
- ⇨ By giving probabilistically lower backoff counters (CWmin, CWmax)
- ⇨ By giving deterministically lower backoff resume times (AIFS)



N.B. Tunable CWmin can also be used for performance optimizations as a function of the network load!!

Distributed Prioritization: transmission grants

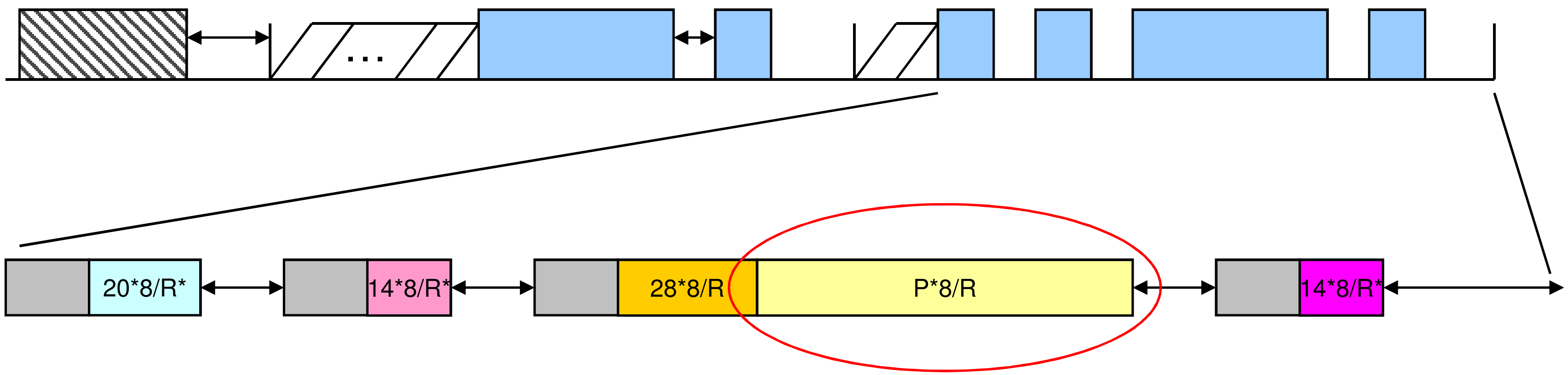
- **Given the channel access probability, we can also differentiate the number of packet transmissions allowed for the stations which wins the contention**
- **More transmissions opportunities back-to-back to High Priority stations**
  - Channel grants not on MSDU basis, but in terms of "channel holding times"



TXOP not only for throughput repartition, but also for efficiency improvements!

802.11: Old MAC and New PHYs..

➔ **In standard DCF, channel accesses are *packet oriented*: each MSDU transmission requires a different access**



• Channel wastes are due to both PHY layer constraints and MAC operations:

SIFS, DIFS, SlotTime, Preamble, TX rates R and R*

RTS, CTS, ACK, # of bk slots, Collision Probability

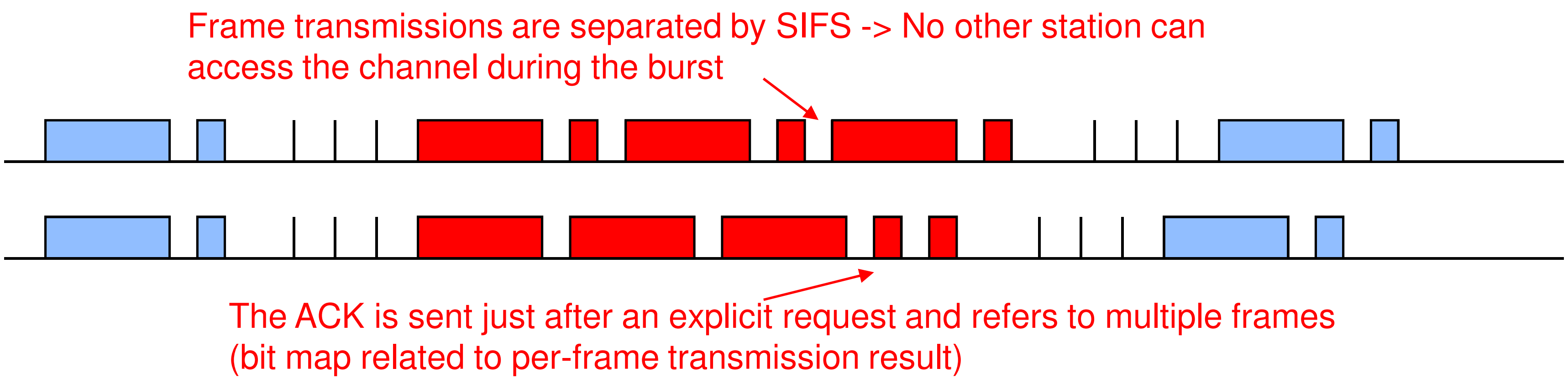
•New PHYs allow higher TX rates..

Overheads are not reduced proportionally

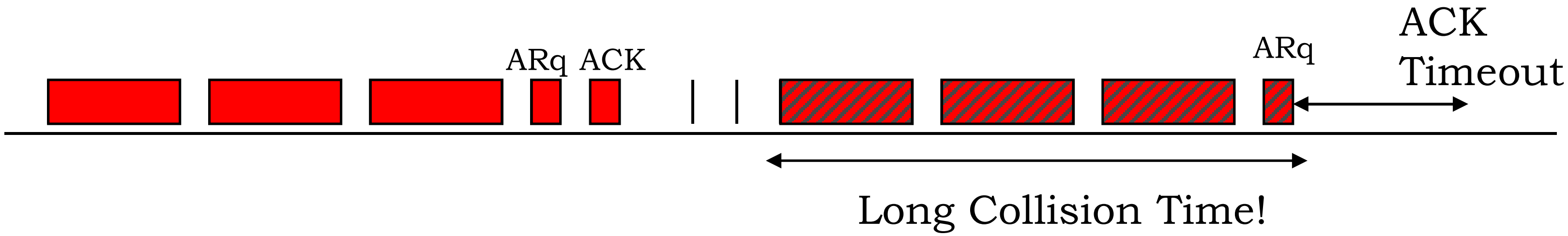
802.11e transmission extensions

- **Key idea: the system efficiency improves by maximizing the payload transmission in each channel access (since overheads are reduced proportionally reduced)**
  - But maximum payload size is limited to 2304 bytes!

- **TXOP & BACK:**
  - Perform multiple transmissions in burst in each channel access
  - Acknowledge more packet transmissions with a cumulative ACK

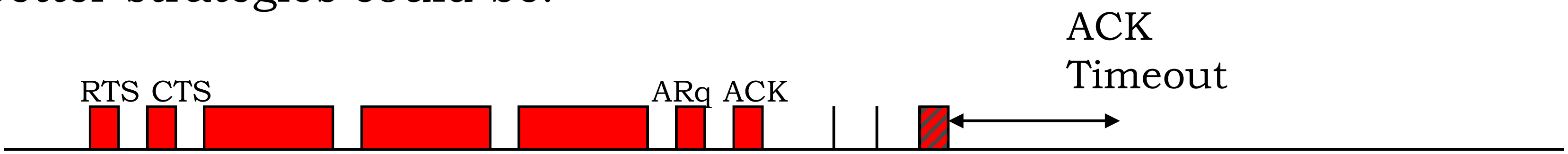


ACK Aggregation: does it work?

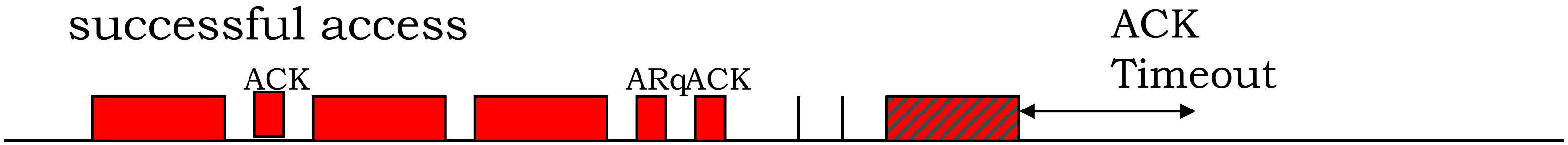


Collisions are revealed only after the transmission of the ACK Request (ARq) frame -> Collision times increase significantly.

Since only the Head Of Burst frame is subject to possible collisions, better strategies could be:

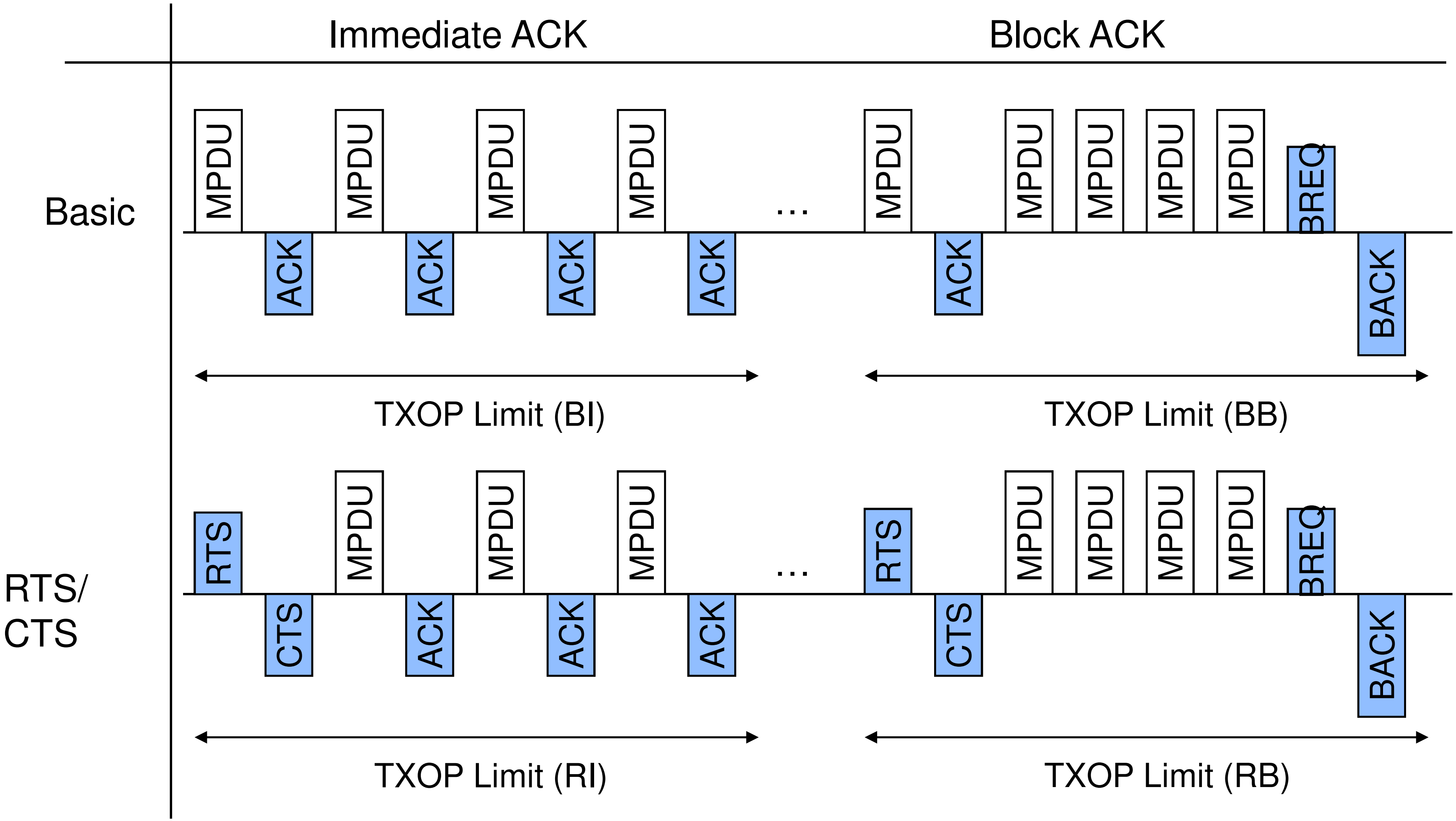


a) Preliminary RTS/CTS exchange in order to confirm the successful access



b) Explicit ACK for the first Data Frame before start the TX burst

Different Access and ACK policies

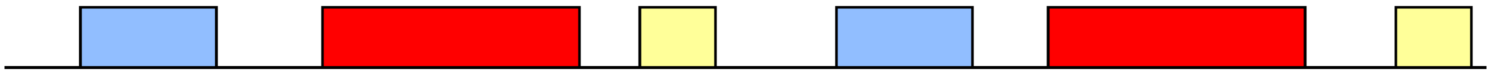


More on TXOP..

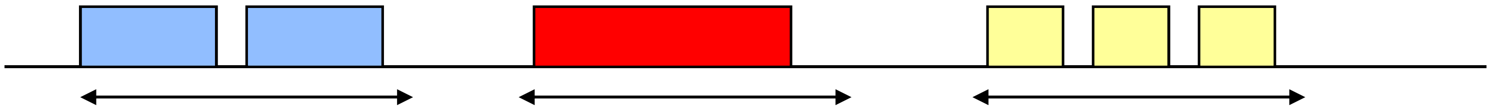
Basically, limit the channel holding times of the competing stations in presence of delay-sensitive traffic

However, TXOP implications are much deeper..

The channel access is managed with a completely different perspective
The access unit is not the MSDU (as in standard DCF), but a temporal interval -> temporary channel-service establishment *with higher efficiencies*



DCF

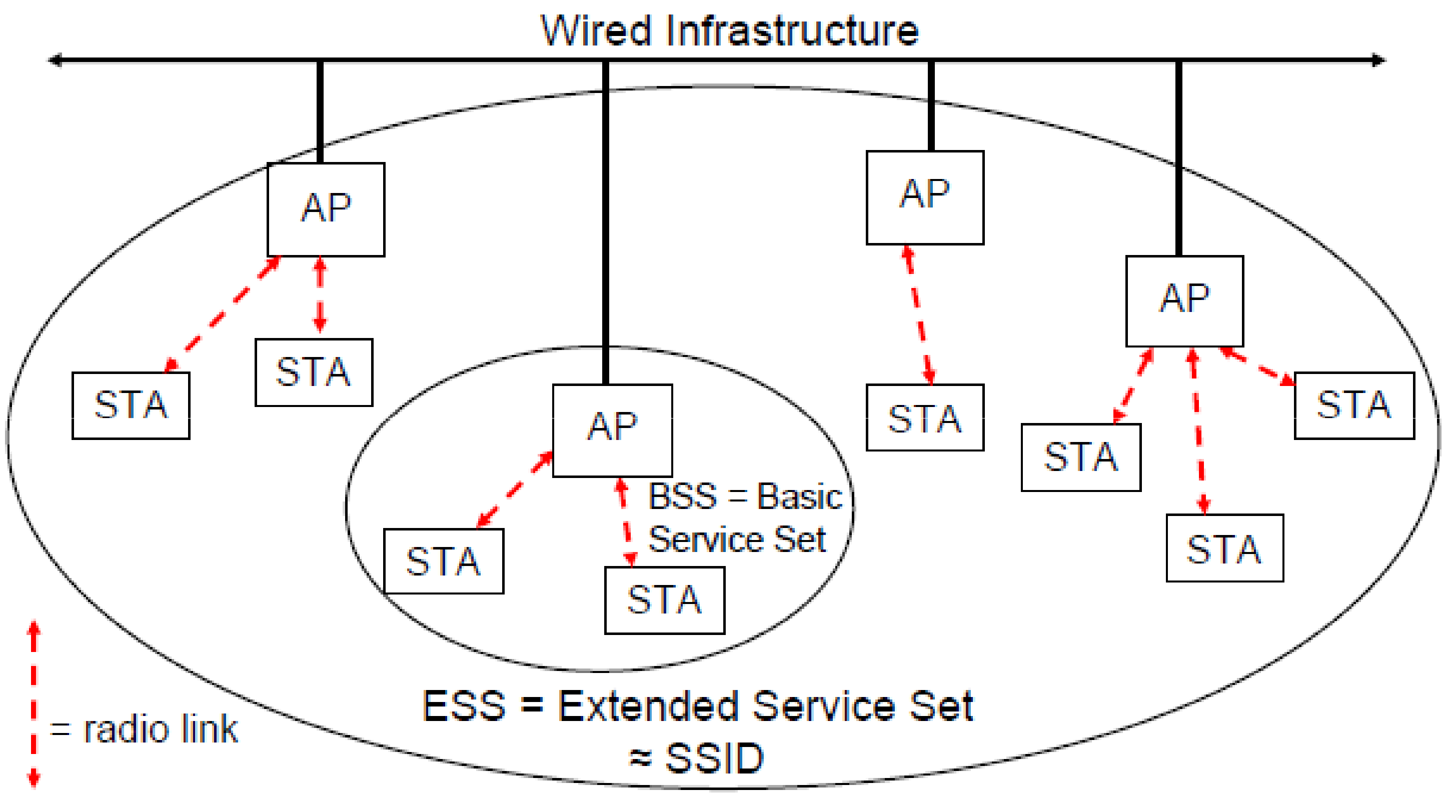


DCF + TXOP

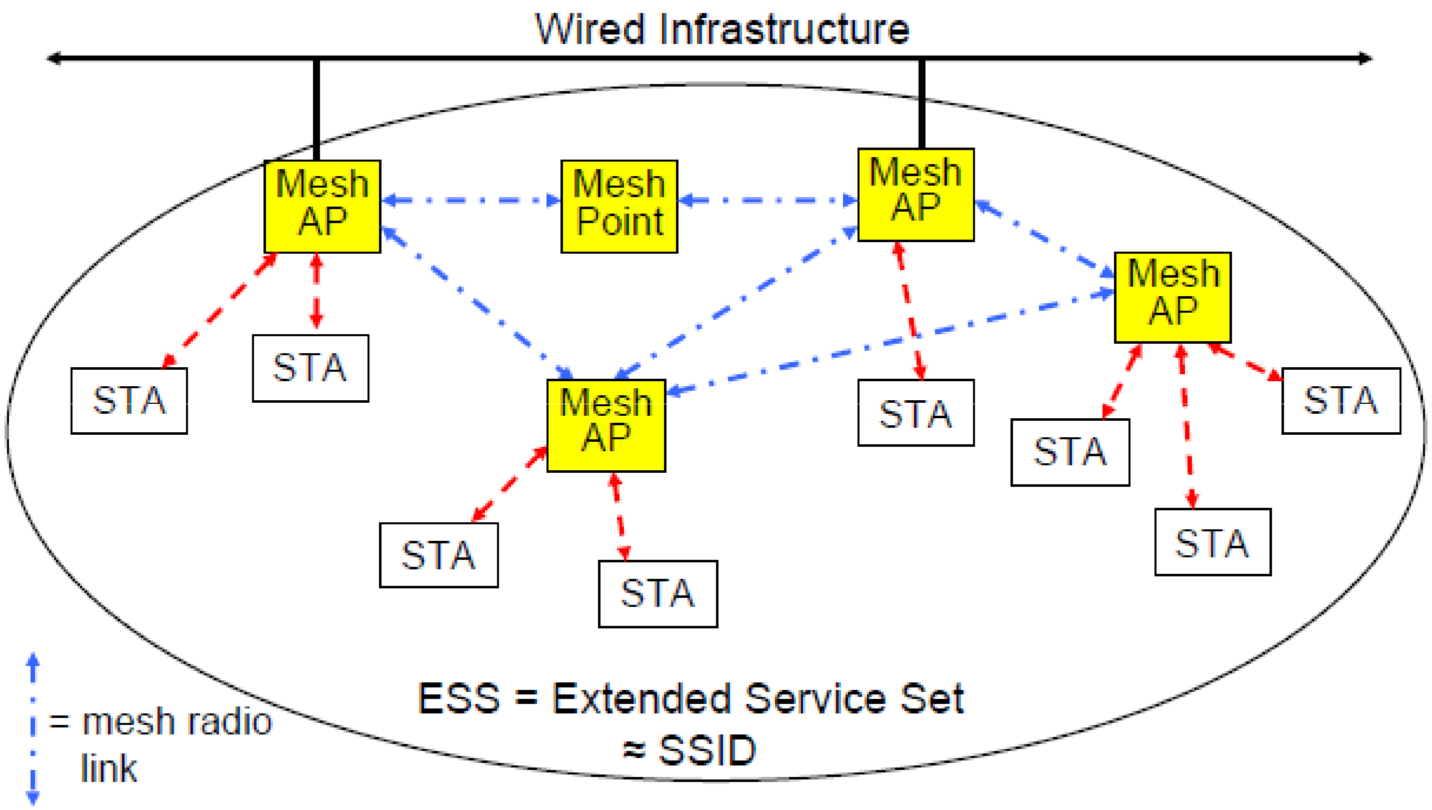
802.11e can natively provide temporal fairness via TXOP!

Mesh Networks

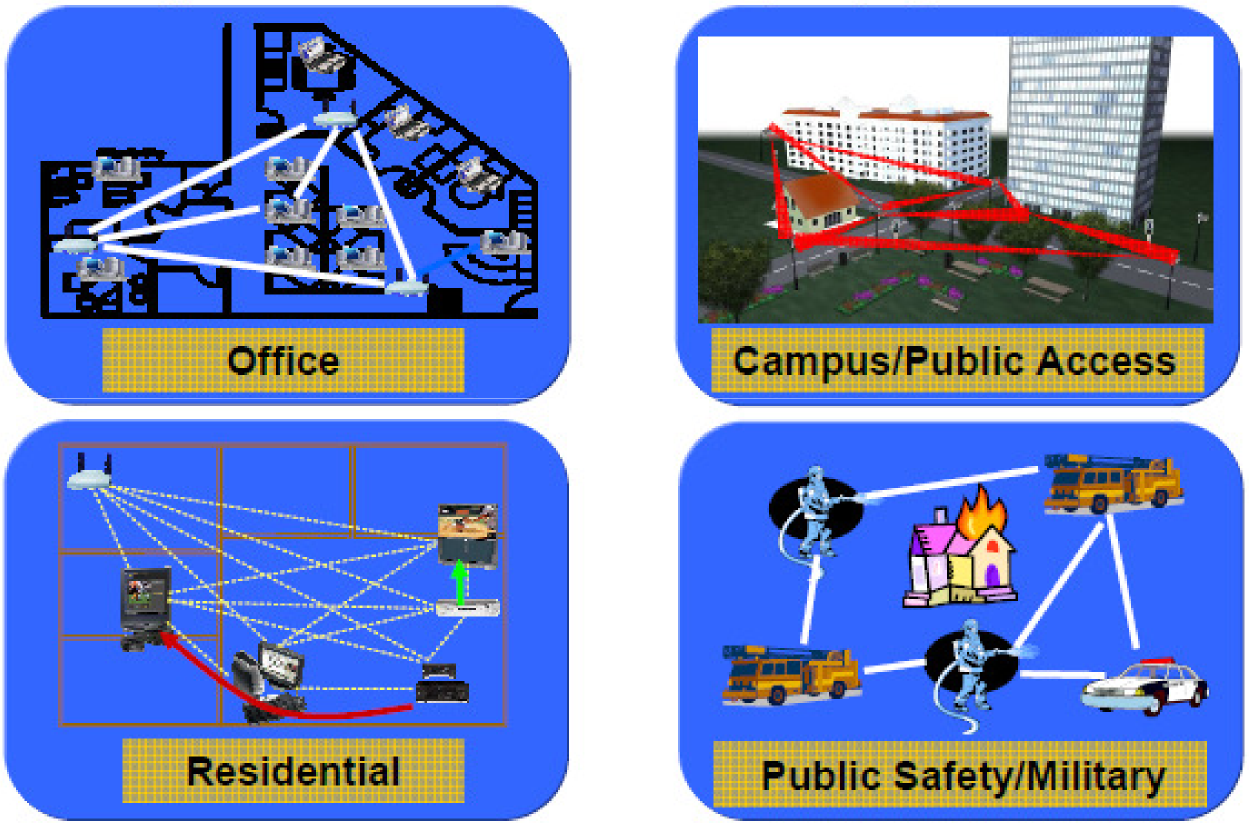
WLAN Extended Infrastructure



Unwire the WLAN with Mesh!



Deployment Scenarios



Birth of Mesh Networks (end of 90’)

- ➔ **Community-owned Wireless Networks (CWN)**
  - ⇨ Seattle Wireless; San Francisco Wireless; NYC Wireless
  - ⇨ … and tons of similar initiatives worldwide

- ➔ **CWN motto**
  - ⇨ NYASPTWYOMB
    - →Not Yet Another Service Provider To Whom You Owe Monthly Bill
  - ⇨ from Seattle Wireless FAQ:
    - →**The point of our CWN is to** create a local network infrastructure that replaces the local loop **that is, right now, owned by the telcos and other large corporations. [...]** The network isn't competing with the Internet, it is working in conjunction with the Internet to supplement ways for you to better use connectivity.

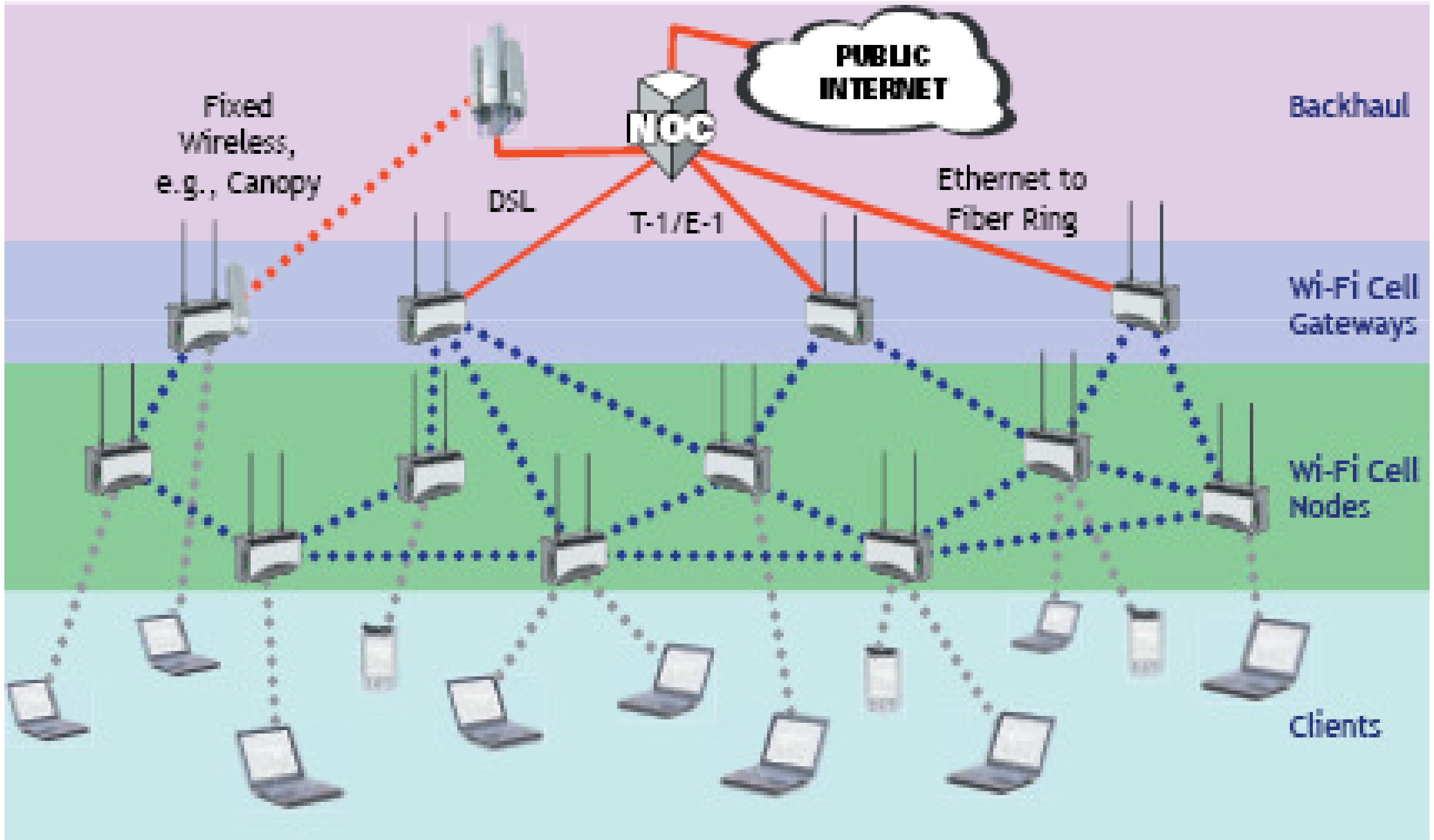
CWN deployment

- **802.11-based <u>very</u> cheap equipments**
  - ⇨ Antennas, APs, cards
  - ⇨ Often based on own-built antennas
- **802.11 for both client access and inter-AP connectivity**
- **Open-source routing solutions**
- **“How to set-up your own node” – instructions available!**

CWN bias in lessons learned: people involved <u>ARE</u> experts; Management burden (frequency planning, configuration, etc) completely unaccounted by CWN-ers (management and trouble-shooting = …a lot of fun…)

Proprietary mesh: Extended access network

Source: Tropos Networks



Hierarchical structure; wireless backhaul not necessarily 802.11 (e.g. 802.16)

Standardization: 802.11s

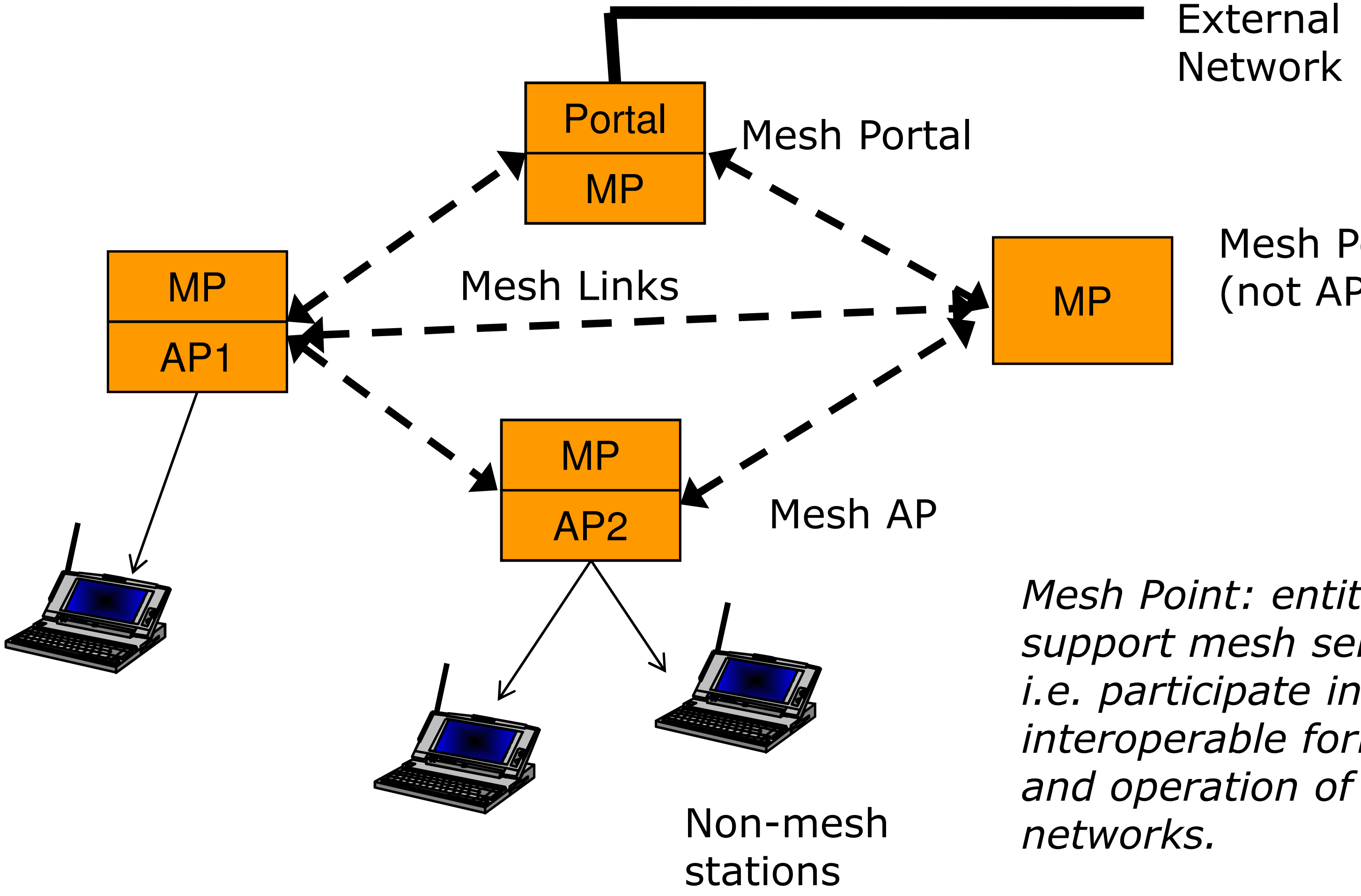
- ➔ **Mesh have been <u>officially</u> recognized as a possible/likely 802.11 extension**

- ➔ **802.11s PAR (Proposed Authorization Request)**
  - ⇨ Draft PAR: September 17, 2003
  - ⇨ PAR applications: June 24, 2004
  - ⇨ Draft Amendment to STANDARD [FOR] Information Technology-Telecommunications and information exchange between systems-Local and Metropolitan networks-Specific requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: <u>IEEE 802.11 ESS Mesh</u>.

802.11s entering into play

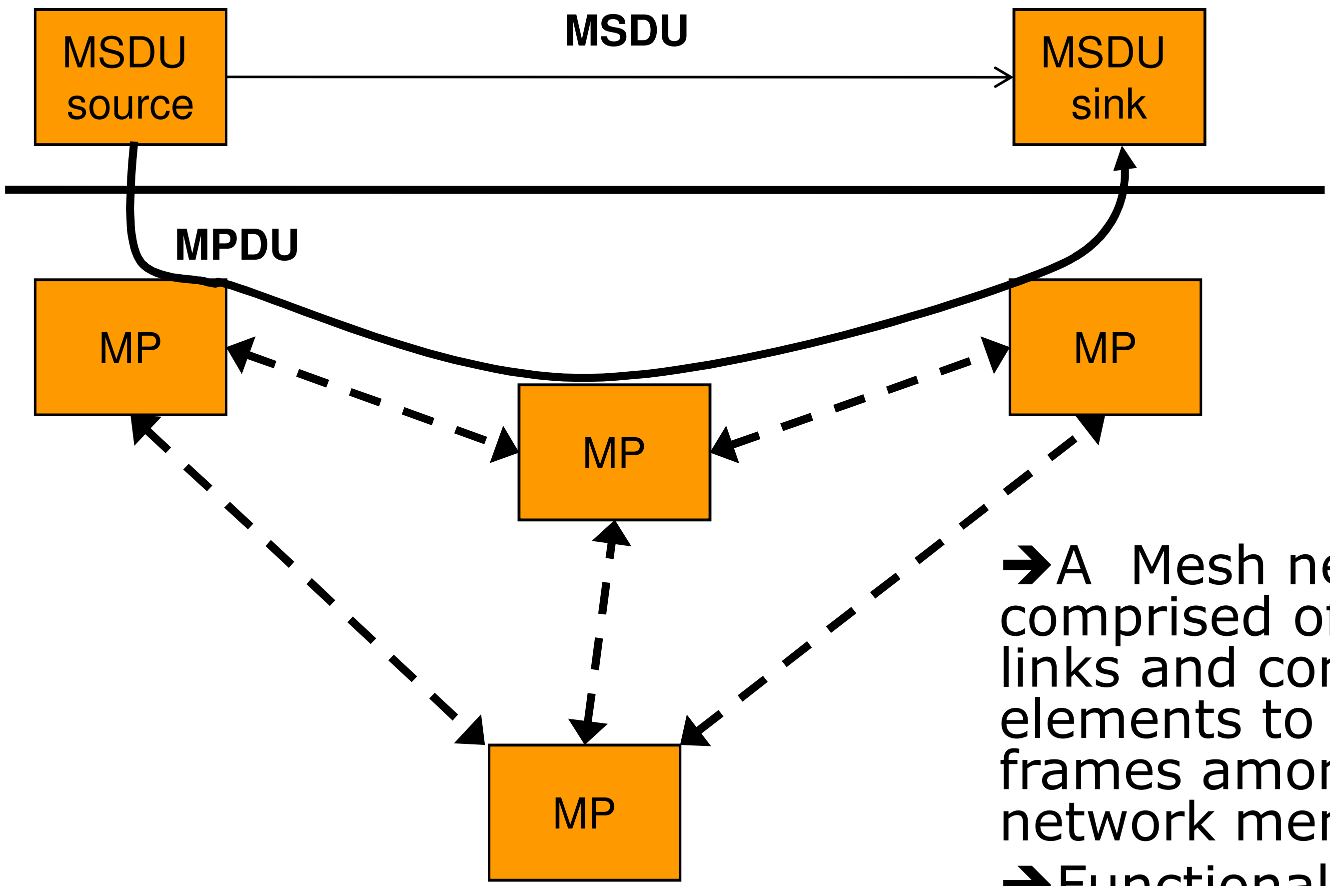
- **QUOTING FROM 802.11S PAR:**
- **802.11s scope:**
  - **To develop an IEEE 802.11 Extended Service Set (ESS) Mesh* with an IEEE 802.11 Wireless Distribution System (WDS)** using the IEEE 802.11 MAC/PHY layers **that supports both broadcast/multicast and unicast delivery over** self-configuring multi-hop topologies**.**
- **802.11s Purpose:**
  - **The IEEE 802.11-1999 (2003 edition) standard provides a four-address frame format for exchanging data packets between APs for the purpose of creating a Wireless Distribution System (WDS), but does not define how to configure or use a WDS. The purpose of the project is to** provide a protocol for auto-configuring paths between APs over self-configuring multi-hop topologies in a WDS **to support both broadcast/multicast and unicast traffic in an ESS Mesh** using the four-address frame format or an extension**.**

Network Vision



Mesh Point: entities that support mesh services, i.e. participate in interoperable formation and operation of mesh networks.

Mesh Network Model



➔A Mesh network is comprised of 802.11 links and control elements to forward frames among the network members;

➔Functionally equivalent to a broadcast Ethernet

Multi-hop Action Frame

- ➔A new management frame (type 00 – subtype 1111), including a mesh header, an action command and one or more vendor-specific information elements
- ➔Action examples:
  - ⇨Mesh peer management
  - ⇨Mesh link metric
  - ⇨Mesh path selection
  - ⇨Mesh interworking
  - ⇨Mesh resource coordination
  - ⇨Mesh security architecture

Mesh Topology: Discovery and Formation

➔MP Boot Sequence

1) Neighbor discovery
2) Channel selection
3) Link establishment
4) Local link state measurement
5) Path selection initialization
6) AP initialization (optional – if MAP)

Node States and Profiles

- ➔ **Each device supports one or more *profiles*.**
- ➔ **Each *profile* consists of**
  - ⇨ A Mesh ID: like SSID, e.g., “NCTU Mesh”
  - ⇨ A path selection protocol identifier: AODV, OLSR
  - ⇨ A path selection metric identifier: airtime cost

- ➔ **The neighbor state is one of**
  {Neighbor, Candidate_peer, Association_pending, Subordinate_link_down, Superordinate_link_down, Subordinate_link_up, Superordinate_link_up}

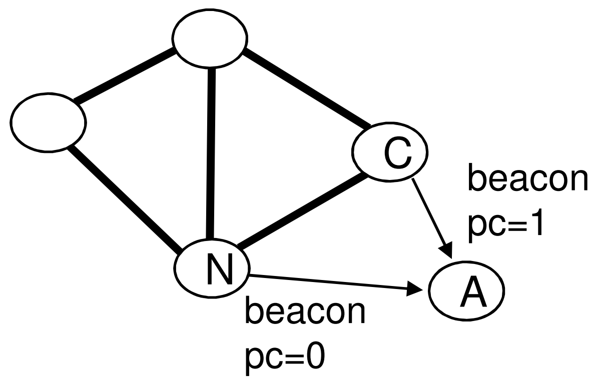
Neighbor Discovery

- ⇨ The following is executed for each profile in the order of user's preference. The first match is selected.
- ⇨ Passive (listen beacon) or Active (probe request) Scanning
- ⇨ Beacon/Probe Response frame contains:
  - **(1)** Mesh ID
  - **(2)** Active Protocol ID **(3)** Active Metric ID
  - **(4)** Peer Capacity: # of additional peer that can accommodate
- ⇨ If (1)~(3) are the same, ➔ *State := Neighbor*
- ⇨ If, in addition, (4) > 0, ➔ *State := Candidate_peer*
- ⇨ ***Example:***

  max_peer_capacity = 3

  C is a candidate_peer

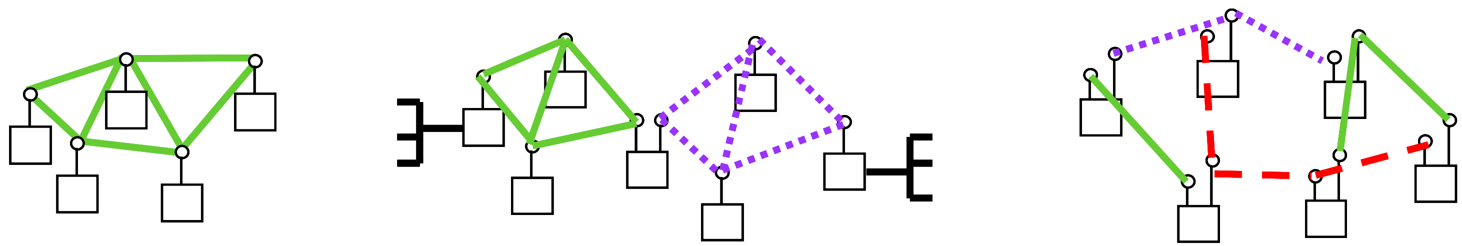
  N is not



Channel Selection

⇨ Two channel selection modes:

Simple unification mode (a) or *advanced mode* (b)(c).



(a) (b) (c)

⇨ *Simple Channel Unification Protocol*:

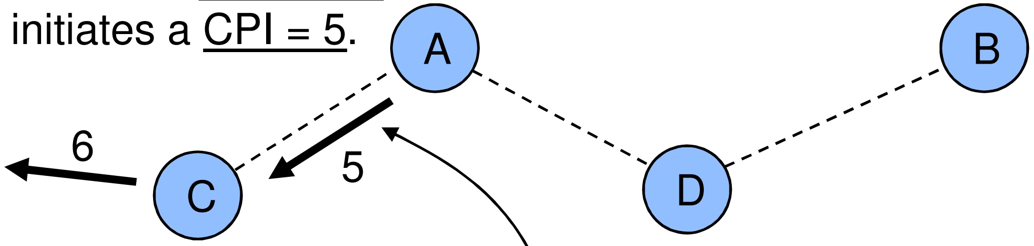
1. Use the *channel* in the 1st profile if no neighbor is found.
2. Use *channel precedence indicator* (a random number) to coalesce disjoint graphs and support channel switching for *dynamic channel selection*.

Figure from:
"802.11 TGs Simple Efficient Extensible Mesh (SEE-Mesh) Proposal", IEEE 802.11-05/0562r0

⇨ *Example:*

1. MP A is turned on.
   No neighbor is found.
   It switches on channel 1
   and initiates a CPI = 5.

2. MP B is turned on.
   No neighbor is found.
   It switches on channel 2
   and initiates a CPI = 8.



3. MP C is turned on.
   Find neighbor MP A.
   It switches on channel 1 as MP A
   and sets CPI to the same as MP A.

4. MP D is turned on.
   Find neighbor MP A and MP B.
   Because MP B has the higher CPI,
   MP C switches on channel 2 as MP B.

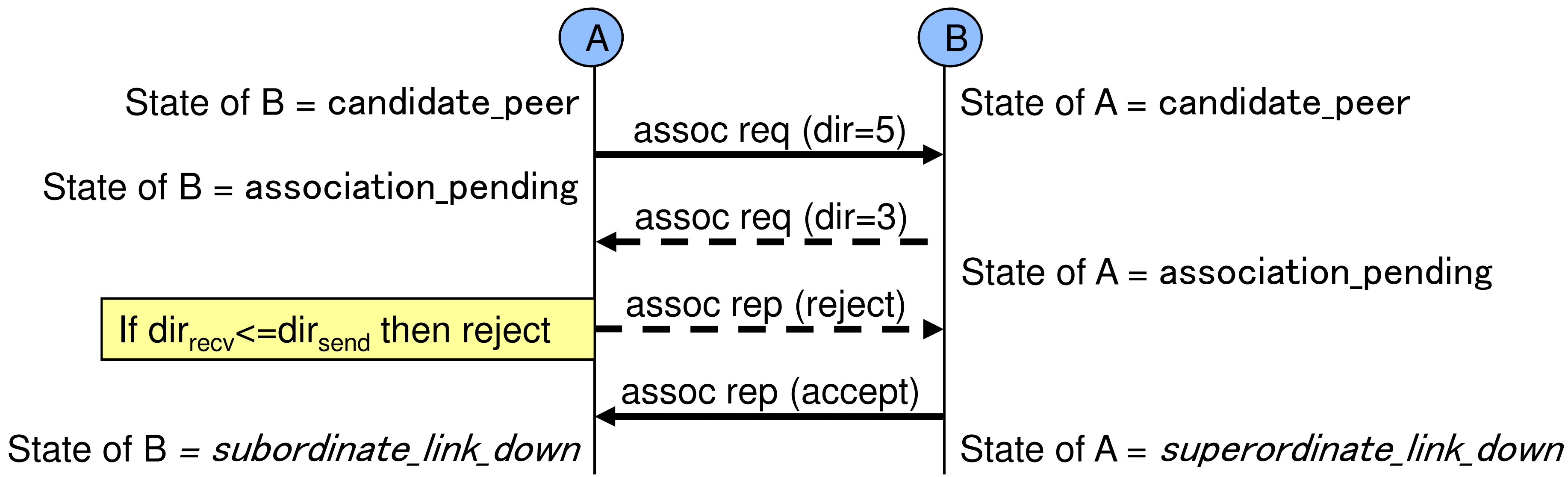
5. MP A discovers a higher CPI on channel 2.
   It sets a *channel switch wait timer* and
   broadcasts a *channel cluster switch announcement*.

6. MP C receives the *channel cluster switch announcement*
   and knows that it needs to switch to channel 2.
   It also forwards the *channel cluster switch announcement.*

7. When the timer expires, MP A and MP C switch to channel 2
   simultaneously.

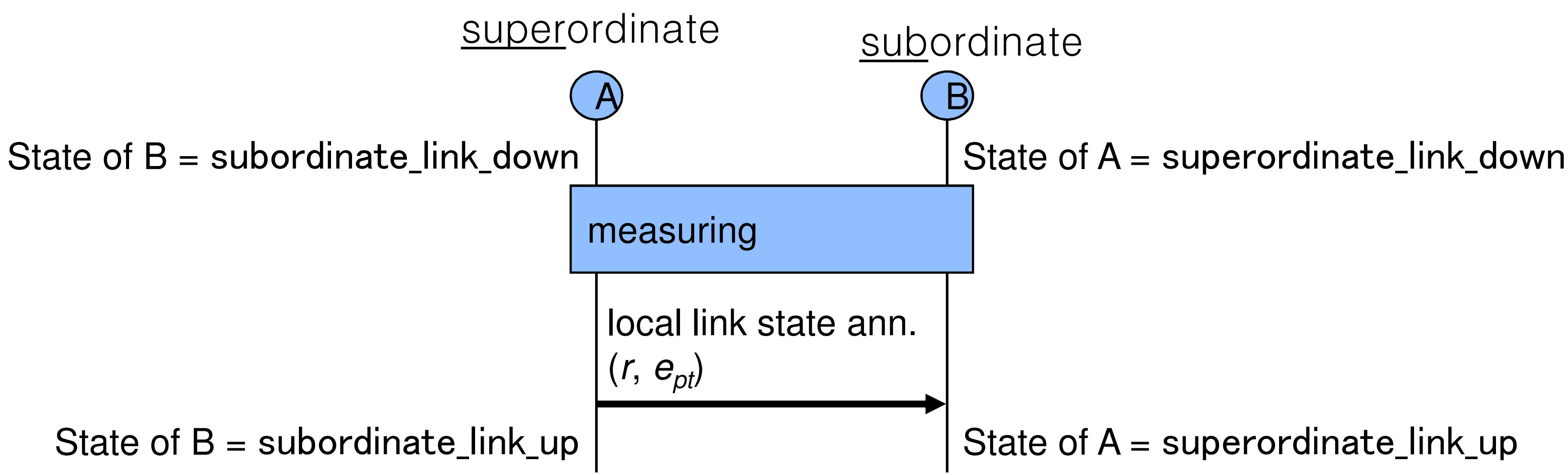
Link Establishment

- ⇨ A MP selects from its candidate_peers to establish peer links with based on measurement of signal quality, until the *maximum number of peers* is established.
- ⇨ Use *association request* and *association reply* frame to establish the link, and use *directionality field* (a random number) to break two concurrent associations.
- ⇨ *Example:*



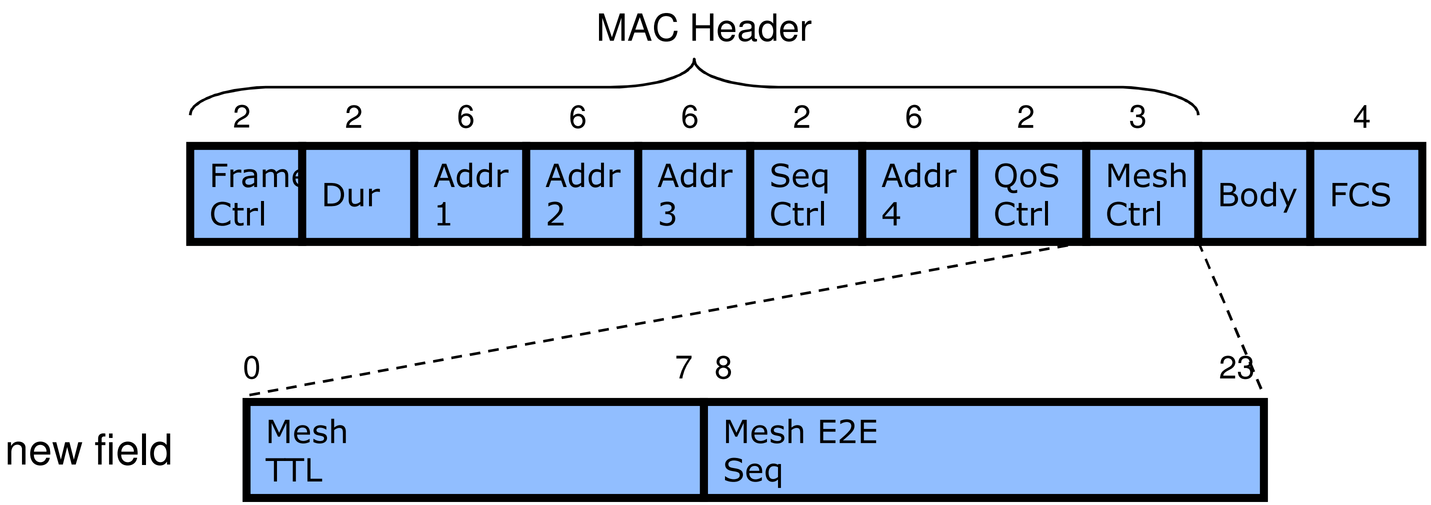
Local Link State Measurement

- ⇨ The *superordinate* node is responsible for measuring the link quality. And then it sends a *local link state announcement* frame to the *subordinate* node.
- ⇨ The measuring parameters may be:
  - → r : current bit rate in use (modulation mode)
  - → e_{pt} : packet error rate at the current bit rate
- ⇨ *Example:*

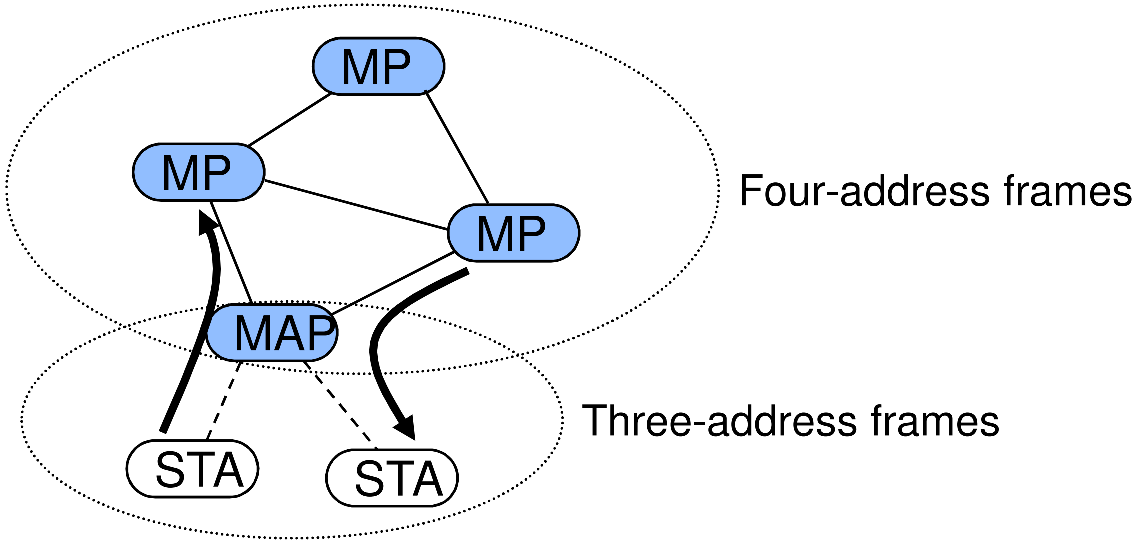


Data Message Forwarding

- ⇨ MSDU Ordering
  - → *Mesh E2E Sequence Number*
  - → Use a *buffer* to re-order the frame
  - → Use a *timer* to avoid *indefinitely waiting*
- ⇨ Eliminates possibility of infinite loops
  - → *Mesh TTL*



⇨ Translation between four-address frames and three-address frames

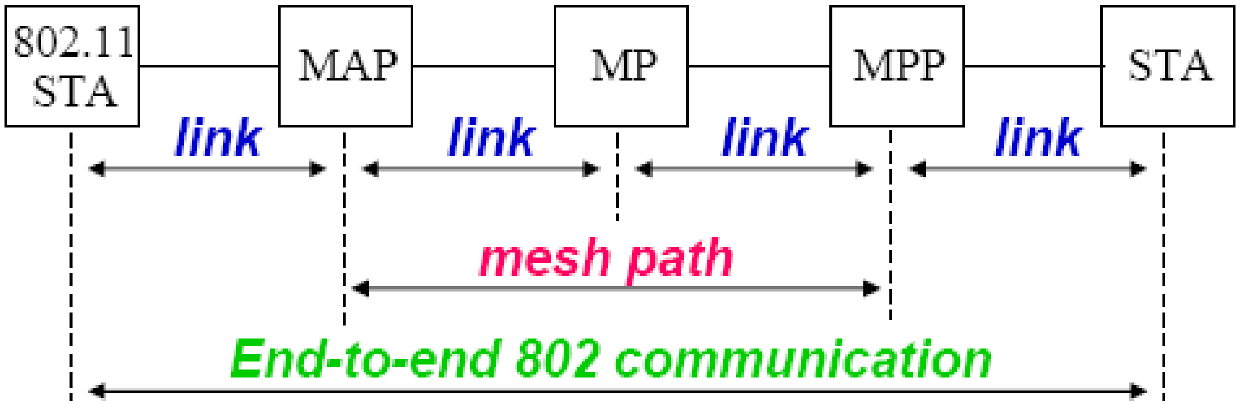


	ToDS	FromDS	Addr1	Addr2	Addr3	Addr4
<u>Frames in Mesh</u>	1	1	RA	TA	DA	SA
Frames to AP in BSS	1	0	BSSID	SA	DA	N/A
Frames from AP in BSS	0	1	DA	BSSID	SA	N/A

Address Mapping Principle

➔ The ordering of the addresses should be from the innermost to the outermost "connections"

- ⇨ *Address 1 & 2 for endpoints of a link between RX and TX*
- ⇨ *Address 3 & 4 for endpoints of a mesh path between a destination and a source MP,* including MPPs and MAPs
- ⇨ *Address 5 & 6 for endpoints of an (end-to-end) 802 communication*



Address Extension (AE)

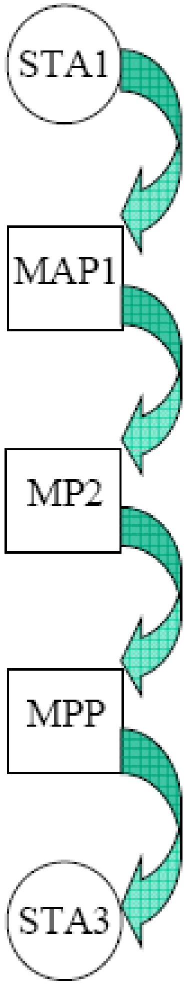
To DS	From DS	AE Flag	Address 1	Address 2	Address 3	Address 4	Address 5	Address 6
0	0	0	RA=DA	TA=SA	BSSID	N/A	N/P*	N/P
0	1	0	RA=DA	TA=BSSID	SA	N/A	N/P	N/P
1	0	0	RA=BSSID	TA=SA	DA	N/A	N/P	N/P
1	1	0	RA	TA	DA	SA	N/P	N/P
1	1	1	RA	TA	Mesh DA	Mesh SA	DA	SA

** N/P = Not Present*

11s MAC Header (up to Mesh TTL field)	Address 5	Address 6	Frame Body	FCS

When the AE flag = 0, all fields have their existing meaning, and there exist no "Address 5" and "Address 6" fields – this assures compatibility with existing hardware and/or firmware.

Example: 802.11 STA to external STA



Address 1	Address 2	Address 3	Address 4
MAP1	STA1	STA3	N/A

Address 1	Address 2	Address 3	Address 4	Address 5*	Address 6*
MP2	MAP1	MPP	MAP1	STA3	STA1

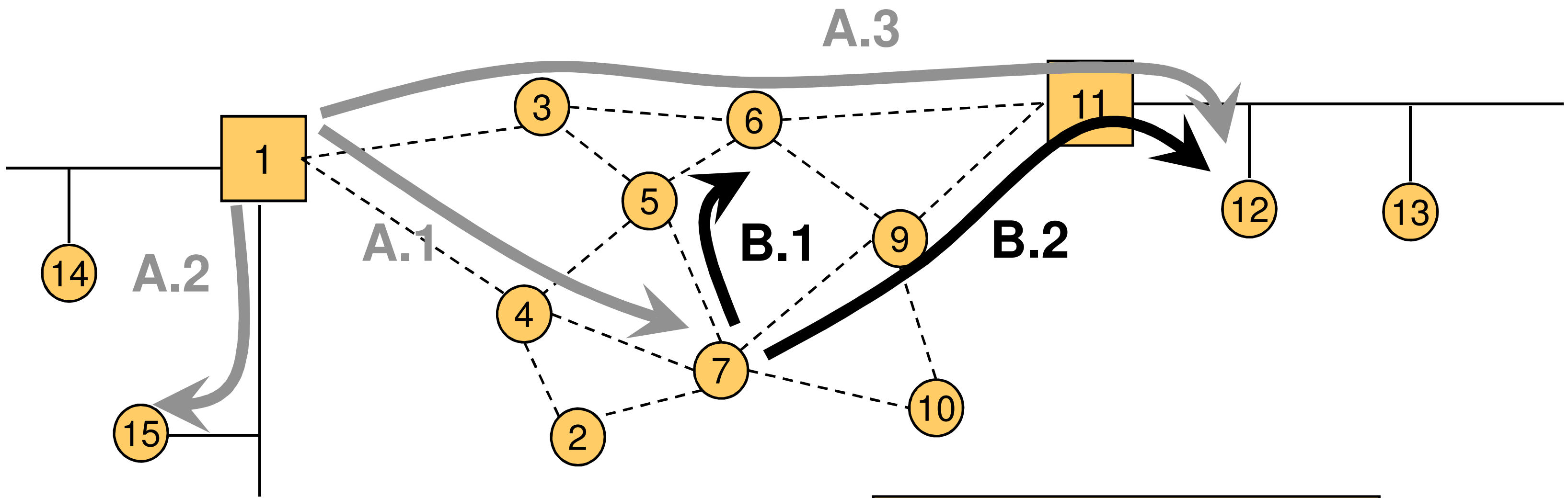
Address 1	Address 2	Address 3	Address 4	Address 5	Address 6
MPP	MP2	MPP	MAP1	STA3	STA1

DA	SA
STA3	MPP**

Non-802.11 (i.e., Ethernet) frame

** Intermediate MPs (here MP2) don't have to process these fields.*
*** Ethernet address of MPP's interface to a wired network*

Interworking: Packet Forwarding



Destination inside or outside the Mesh?

outside → Portal(s) forward the message

inside → Use path to the destination

Interworking: MP view

1. **Determine if the destination is inside or outside of the Mesh**
   a. Leverage layer-2 mesh path discovery
2. **For a destination inside the Mesh,**
   a. Use layer-2 mesh path discovery/forwarding
3. **For a destination outside the Mesh,**
   a. Identify the “right” portal, and deliver packets via unicast
   b. If not known, deliver to all mesh portals

802.11s Path Selection and Forwarding Overview

Giuseppe Bianchi, Ilenia Tinnirello

Mandatory and Alternative Path Selection Protocols

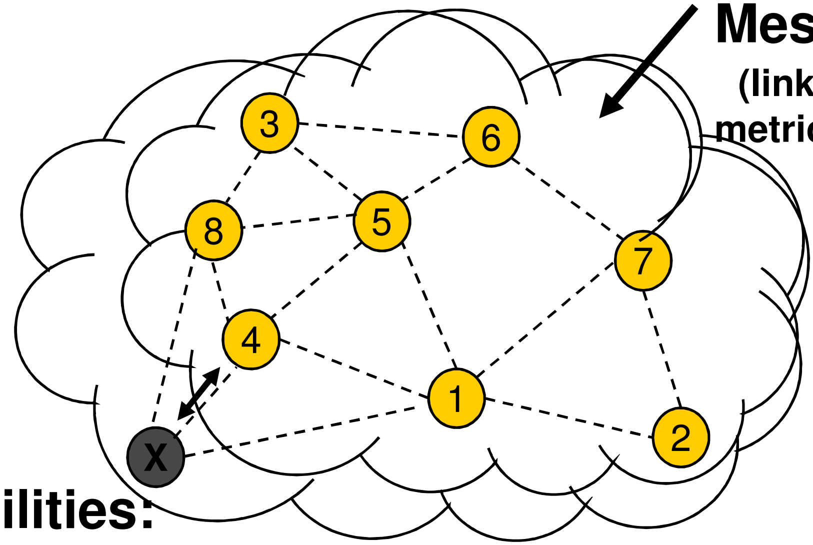
- **All implementations support mandatory protocol and metric**
  - ***Any vendor may implement any protocol and/or metric*** within the framework
  - Only one protocol/metric will be active on a particular link at a time
  - A particular mesh will have only one active protocol
- **Mesh Points use the WLAN Mesh Capability IE to indicate which protocol is in use**
- **MIB objects provide a standard management interface to the mandatory and alternative path selection protocols**
- **A mesh that is using other than mandatory protocol is not required to change its protocol when a new MP joins**
  - Algorithm to coordinate such a reconfiguration is out of scope

Example

1. **Mesh Point *X* discovers Mesh (WLANMesh_Home) with Profile (link state, airtime metric)**
2. **Mesh Point *X* associates / authenticates with neighbors in the mesh, since it is capable of supporting the Profile**
3. **Mesh Point *X* begins participating in link state path selection and data forwarding protocol**

Mesh Identifier:
WLANMesh_Home

Mesh Profile:
(link state, airtime metric)



Capabilities:
Path Selection: distance vector, link state
Metrics: airtime, latency

One active protocol/metric in one mesh, but allow for alternative protocols/ metrics in different meshes

Hybrid Wireless Mesh Protocol (HWMP)

Default Path Selection for Interoperability

- **Combines the flexibility of on-demand route discovery with the option for efficient proactive routing to a mesh portal**
  - Supports any path selection metric (QoS, load balancing, power-aware, etc)
    - Simple mandatory metric based on airtime as default, with support for other metrics
- **Foundation is Radio Metric AODV (RM-AODV)**
  - Based on basic mandatory features of AODV (RFC 3561)
  - Extensions to identify best-metric path with arbitrary path metrics
  - By default, RM-AODV used to discover routes to destinations in the mesh on-demand
- **Additional pro-active, tree based routing**
  - If a Root portal is present, a distance vector routing tree is built and maintained
  - Tree based routing is efficient for hierarchical networks
  - Tree based routing avoids unnecessary discovery flooding during discovery and recovery
- **HWMP resource demands vary with Mesh functionality**
  - Makes it suitable for implementation on a variety of different devices under consideration in TGs usage models from CE devices to APs and servers

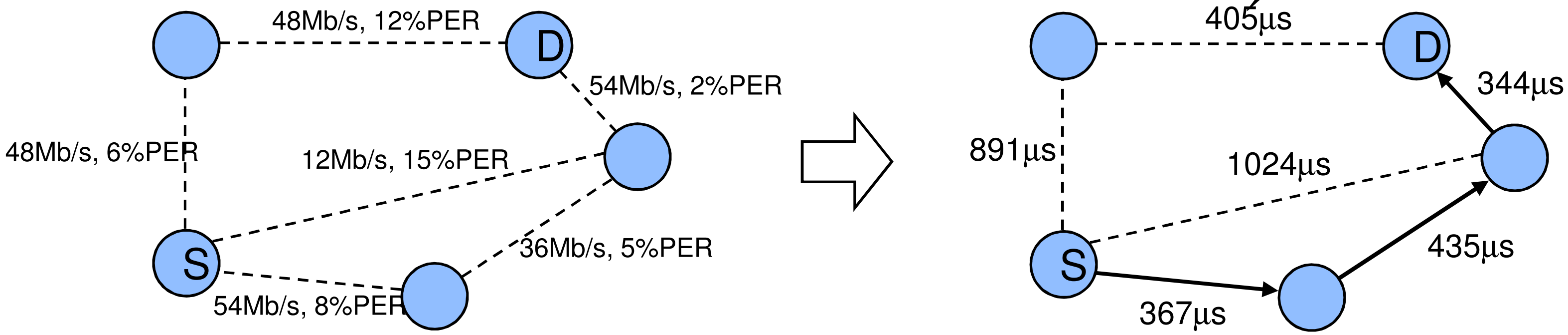
Path Selection Metric – Airtime Cost

⇨ Airtime cost reflects the amount of *channel resources* (time) consumed by transmitting the frame.

$$c_a = \left[O_{ca} + O_p + \frac{B_t}{r} \right] \frac{1}{1 - e_{pt}}$$

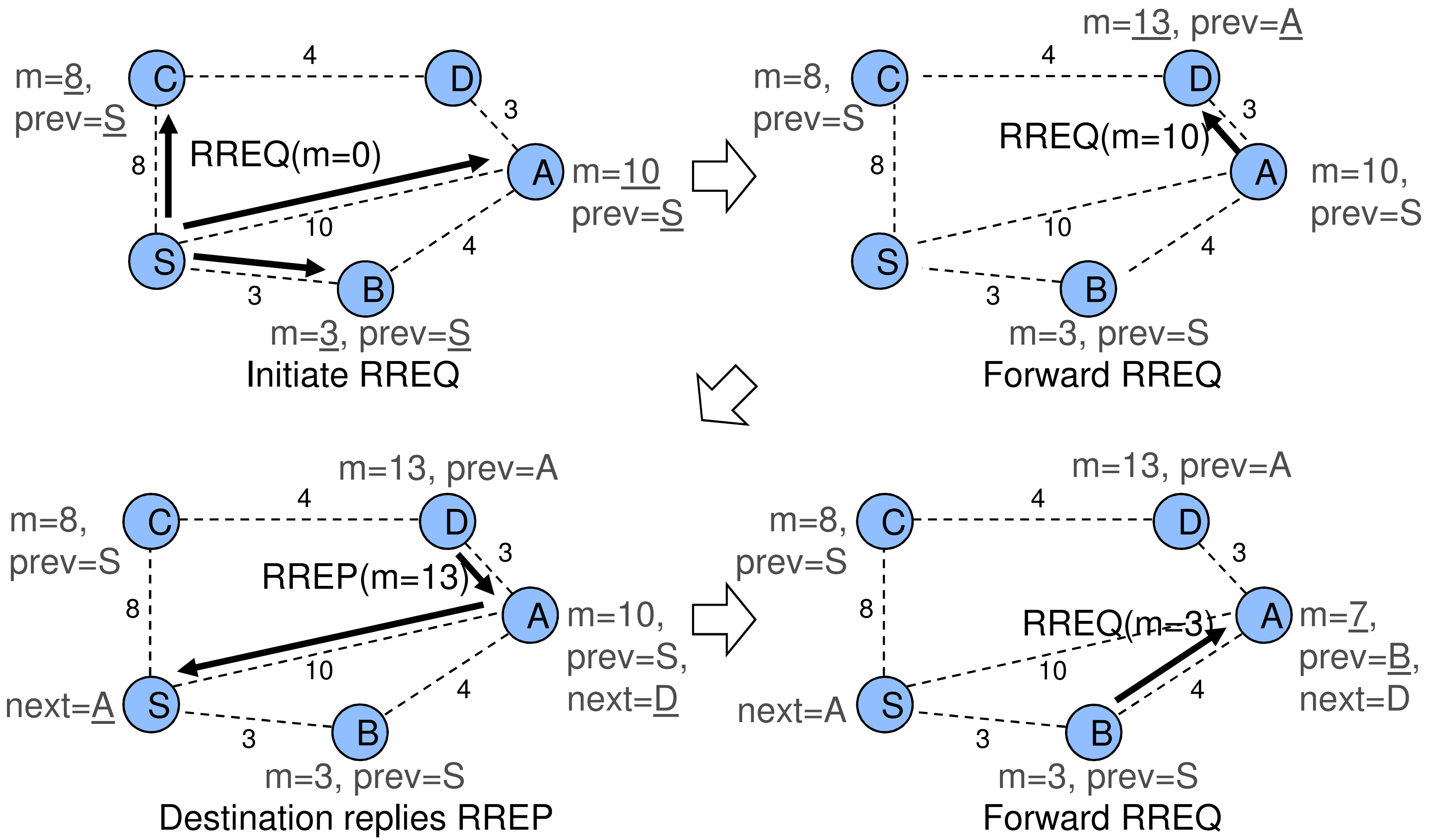
Parameter	Value (802.11a)	Value (802.11b)	Description
O_{ca}	75µs	335µs	Channel access overhead
O_p	110µs	364µs	Protocol overhead
B_t	8224	8224	Number of bits in test frame

(75+110+ 8224/48)* (1/0.88) = 404.6 us

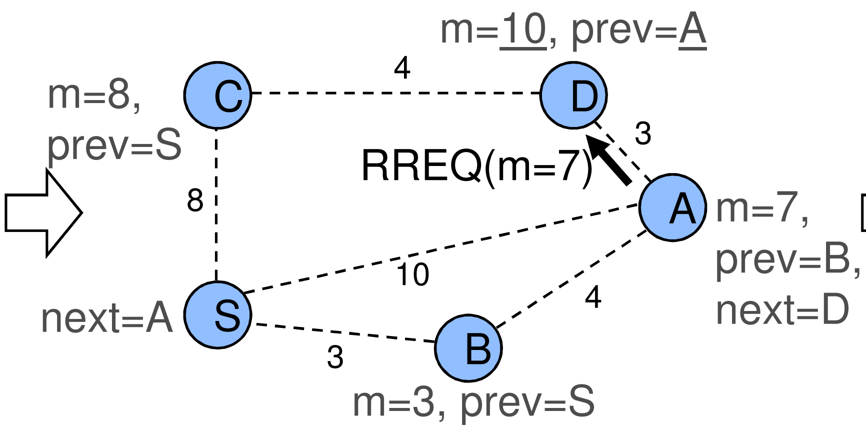


Path Selection Protocol – RMAODV

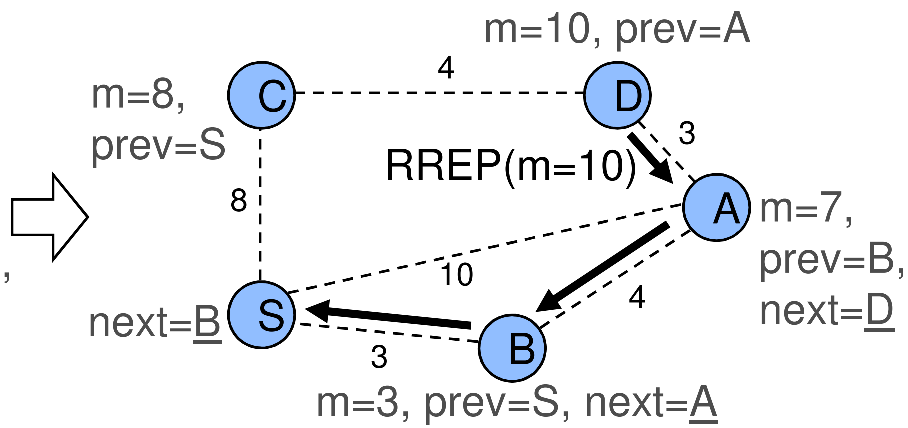
⇨ *Example:*



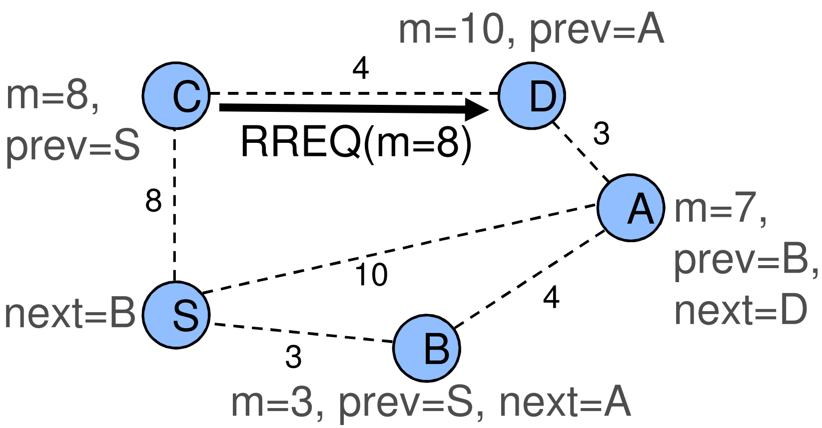
⇨ *Example (cont.):*



Forward RREQ with better metric



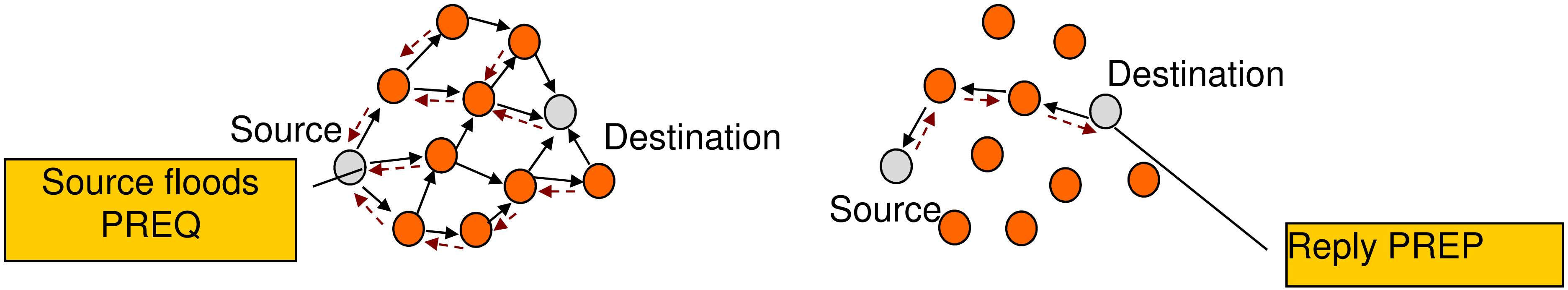
Reply RREP with better metric



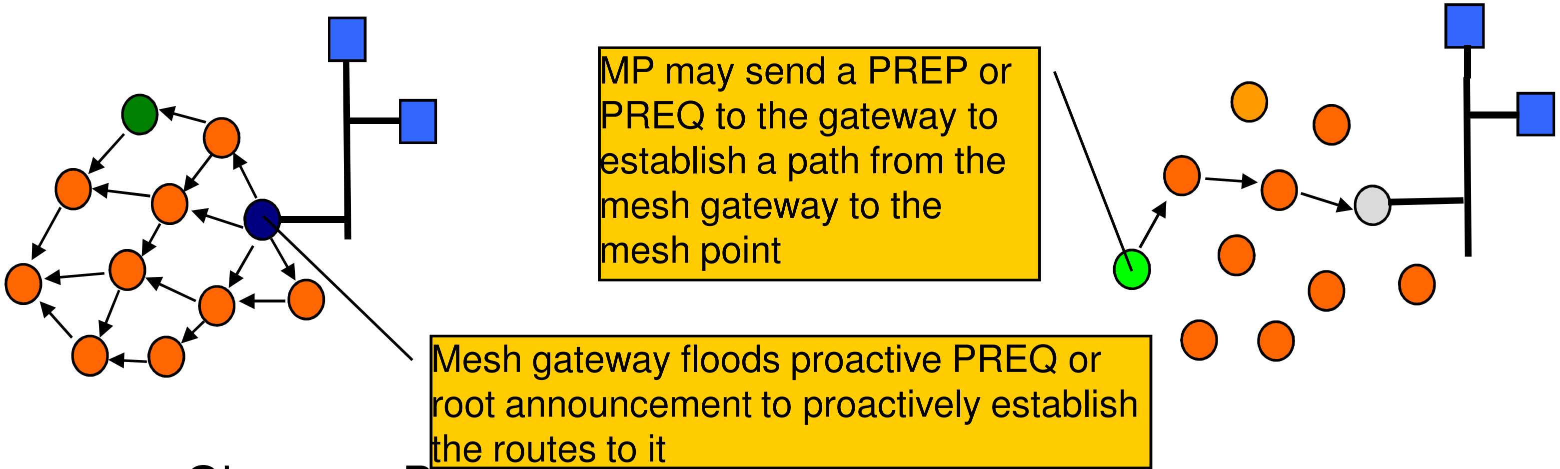
Forward RREQ. But the destination do not reply because the metric is no better.

Why Hybrid?

➔ **On-demand: Use route request/route reply to discover the route on-demand (reduce routing overhead)**



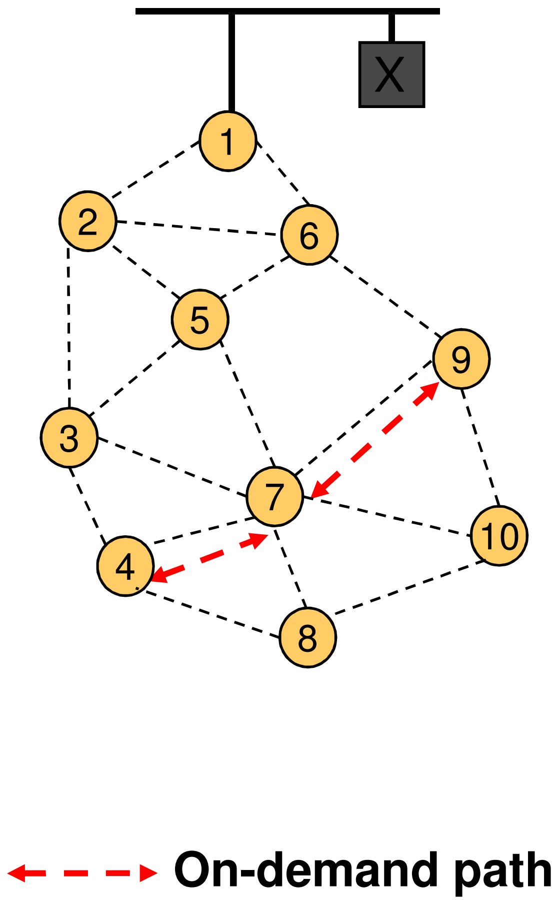
➔ **Proactive: Gateway proactively announce itself to establish route to reach it (reduce route discovery delay)**



HWMP Example #1: No Root, Destination Inside the Mesh

Example: MP 4 wants to communicate with MP 9

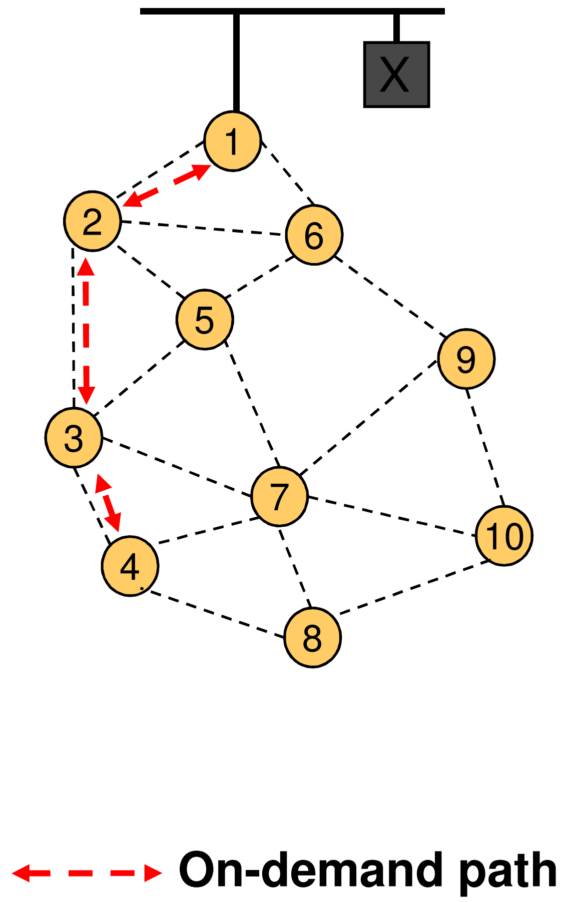
1. MP 4 first checks its local forwarding table for an active forwarding entry to MP 9
2. If no active path exists, MP 4 sends a RREQ to discover the best path to MP 9
3. MP 9 replies to the RREQ with a RREP to establish a bi-directional path for data forwarding
4. MP 4 begins data communication with MP 9



HWMP Example #2: Non-Root Portal(s), Destination Outside the Mesh

<u>Example: MP 4 wants to communicate with X</u>

1. MP 4 first checks its local forwarding table for an active forwarding entry to X
2. If no active path exists, MP 4 sends a RREQ to discover the best path to X
3. When no RREP received, MP 4 assumes X is outside the mesh and sends messages destined to X to Mesh Portal(s) for interworking
   - ⇨Learned via IE in beacons, probe response
4. MP 1 forwards messages to other LAN segments according to locally implemented interworking

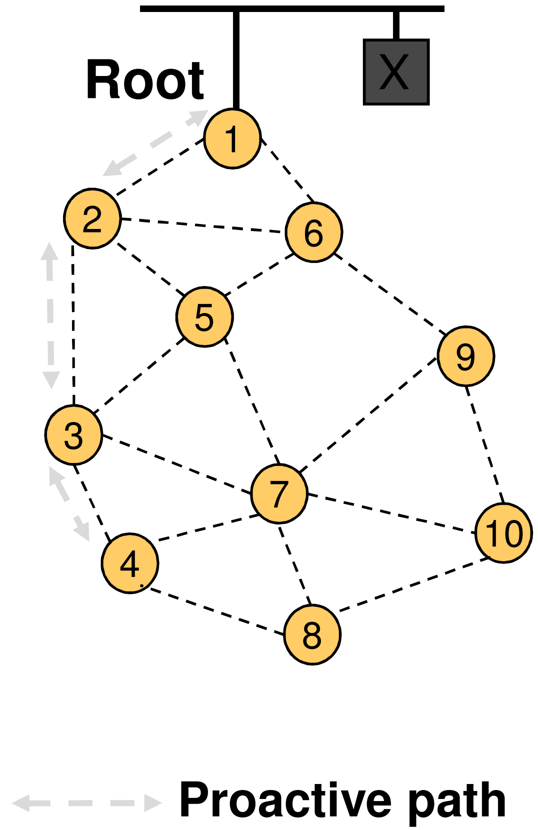


HWMP Example #3: Root Portal, Destination Outside the Mesh

<u>Example: MP 4 wants to communicate with X</u>

1. MP 4 first checks its local forwarding table for an active forwarding entry to X
2. If no active path exists, MP 4 may immediately forward the message on the proactive path toward the Root MP 1
3. When MP 1 receives the message, if it does not have an active forwarding entry to X it may assume the destination is outside the mesh and forward on other LAN segments according to locally implemented interworking

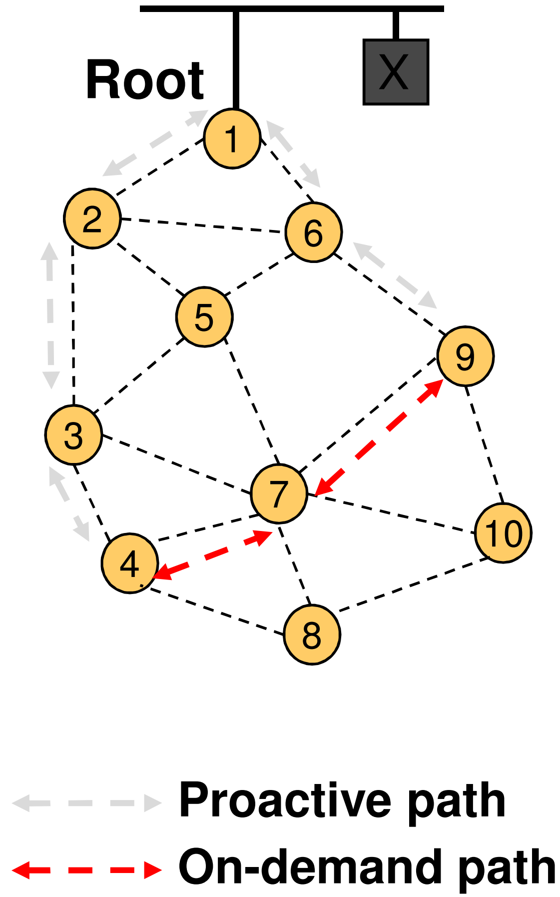
Note: No broadcast discovery required when destination is outside of the mesh



HWMP Example #4: With Root, Destination Inside the Mesh

Example: MP 4 wants to communicate with MP 9

1. MP 4 first checks its local forwarding table for an active forwarding entry to MP 9
2. If no active path exists, MP 4 *may* immediately forward the message on the proactive path toward the Root MP 1
3. When MP 1 receives the message, it flags the message as "intra-mesh" and forwards on the proactive path to MP 9
4. When MP 9 receives the message, it *may* issue an on-demand RREQ to MP 4 to establish the best intra-mesh MP-to-MP path for future messages



802.11s MAC Enhancements Overview

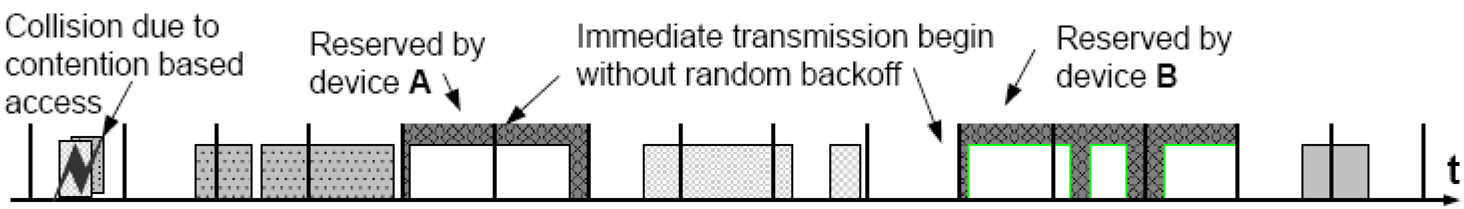
802.11e MAC Enhancements

- ➔ **EDCA as the basis for the .11s media access mechanism**
  - ⇨ Re-use of latest MAC enhancement from 802.11
  - ⇨ Compatibility with legacy devices
  - ⇨ Interaction of forwarding and BSS traffic
    - – Handling of multi-hop mesh traffic and single-hop BSS traffic within one device impacts network performance
      - » Dependent on system fairness and prioritization policies
      - » Treated as an implementation choice

- ➔ **MAC Enhancement for mesh**
  - ⇨ Mesh Deterministic Access (MDA)
  - ⇨ Intra-mesh Congestion Control
    - – Simple hop-by-hop congestion control mechanism implemented at each MP
  - ⇨ Common Channel Framework (Optional)
    - – Support for multi-channel MAC operation

Mesh Deterministic Access (MDA)

- ➔MAC Enhancement based on a reservation protocol
  - ➔Setup request/setup reply
  - ➔MD AOP advertisement
- ➔QoS support in large scale distributed Mesh Networks
- ➔Synchronized operation, reduced contention



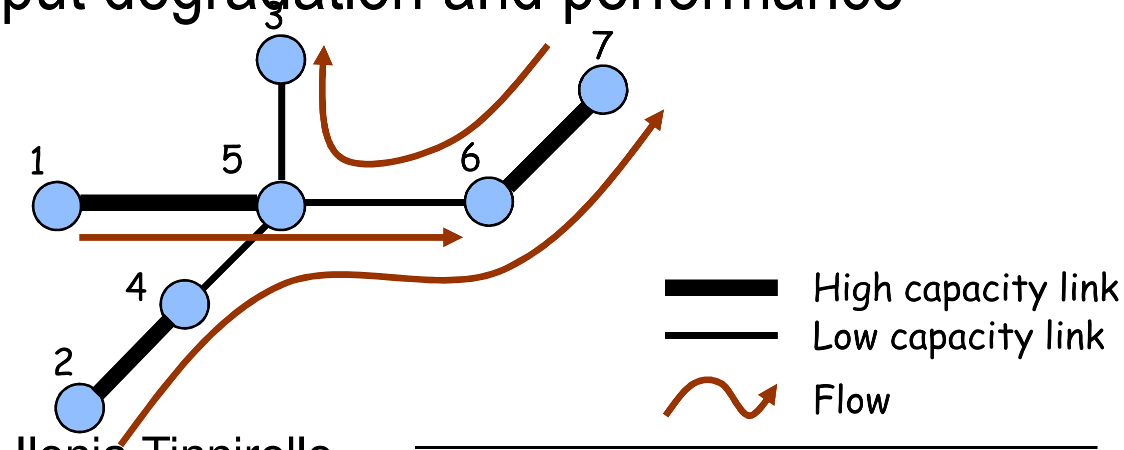
Need for Congestion Control

➔ **Mesh characteristics**

- ⇨ Heterogeneous link capacities along the path of a flow
- ⇨ Traffic aggregation: Multi-hop flows sharing intermediate links

➔ **Issues with the 11/11e MAC for mesh:**

- ⇨ Nodes blindly transmit as many packets as possible, regardless of how many reach the destination
- ⇨ Results in throughput degradation and performance inefficiency



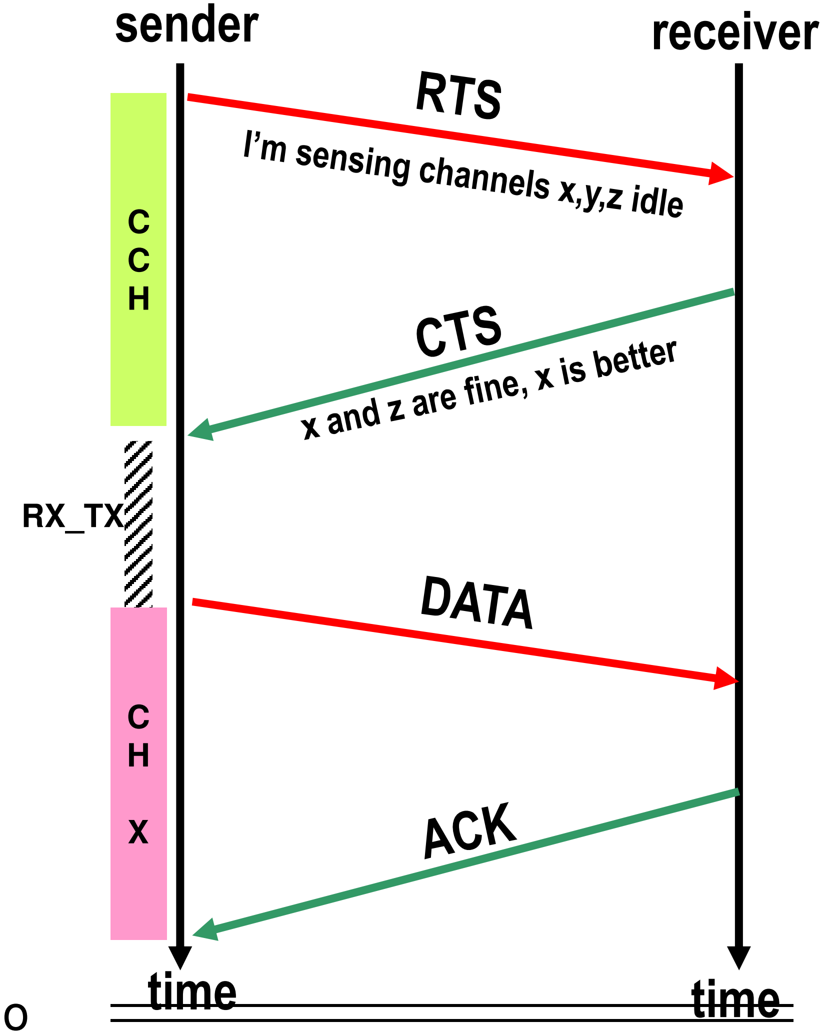
Intra-Mesh Congestion Control Mechanisms

- ➔ **Local congestion monitoring *(informative)***
  - ⇨ Each node actively monitors local channel utilization
  - ⇨ If congestion detected, notifies previous-hop neighbors and/or the neighborhood
- ➔ **Congestion control signaling**
  - ⇨ Congestion Control Request (unicast)
  - ⇨ Congestion Control Response (unicast)
  - ⇨ Neighborhood Congestion Announcement (broadcast)
- ➔ **Local rate control *(informative)***
  - ⇨ Each node that receives either a unicast or broadcast congestion notification message should adjust its traffic generation rate accordingly
  - ⇨ Rate control (and signaling) on per-AC basis – e.g., data traffic rate may be adjusted without affecting voice traffic
  - ⇨ Example: MAPs may adjust BSS EDCA parameters to alleviate congestion due to associated STAs

Multi Radio

Multiple Radio MAC

- ➔ **Taking dinamicity in the MAC: multi-channel MAC**
  - →**[Nasipuri, Zhuang, Das, 1999]; [Jain, Das, Nasipuri, 2001]**
  - →**[Tseng, Wu, Lin, 2001]**
  - →**[Hung, Law, Leon-Garcia, 2002]**
- ➔ **Multiple channels available**
- ➔ **DATA transmitted on channel selected via (modified) RTS/CTS handshake**
  - ⇨ RTS/CTS handshake on Common Control (signalling) Channel

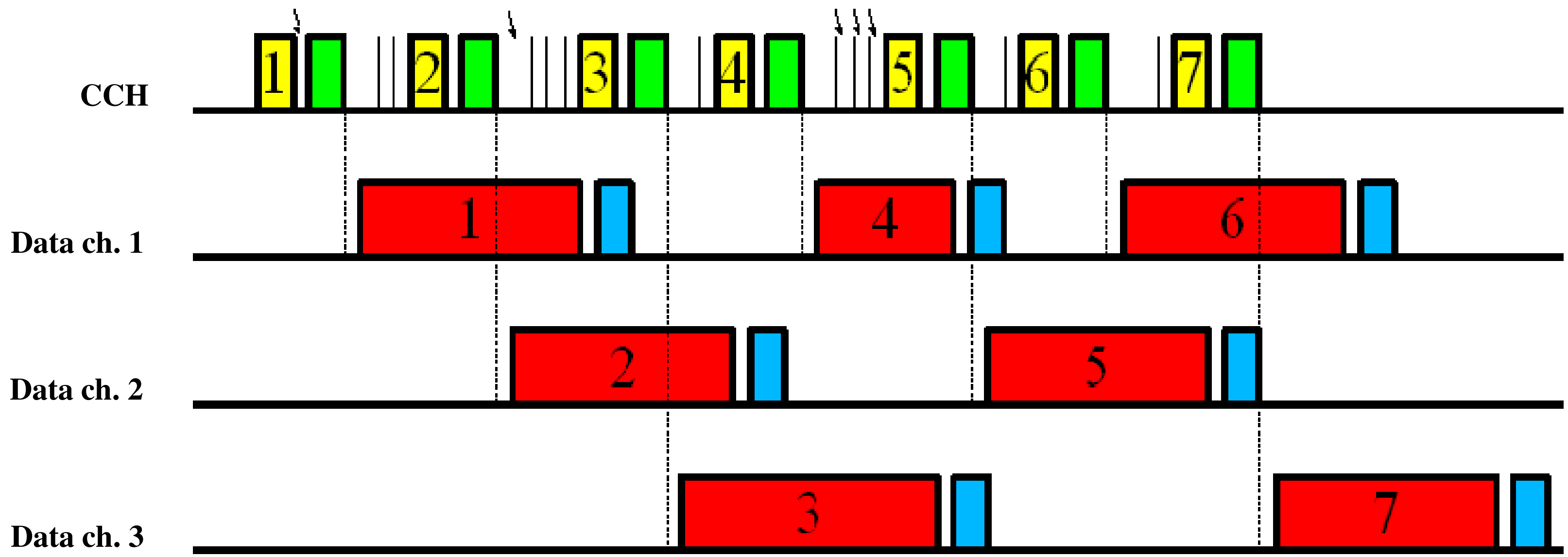


Implementation issues

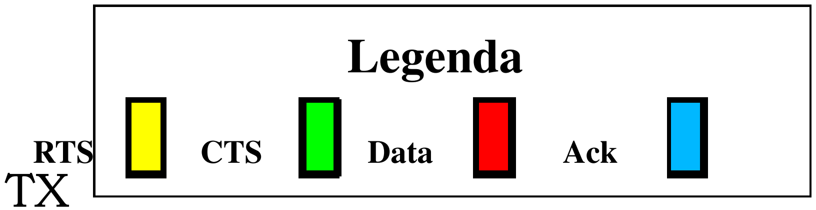
- ➔ **Implementation transparent to MAC**
  - →Multichannel handshake coded into PLCP header
    - » [Technical report in italian project FIRB-PRIMO]
  - →MAC sees a unique channel

- ➔ **Technical issues**
  - ⇨ Multi-channel carrier sense
    - →Hard with commercial components…
  - ⇨ Timing constraints for channel switching
    - →Again, many products do not support required timing

Multi Channel MAC

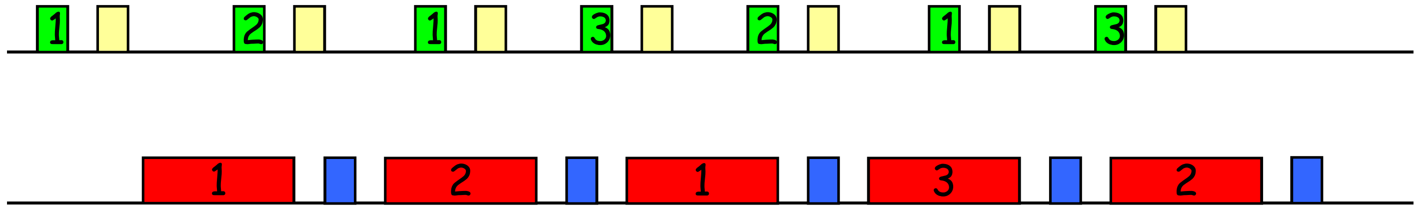


- ⇨ Legacy RTS/CTS handshake
  - →On control channel, only
- ⇨ Limited exploitation of parallel TX
  - →Approach not exploited to its full capabilities
  - →Channel separation wastes capacity
- ⇨ Tradeoffs required
  - →How much bandwidth to (bottleneck) signalling channel?

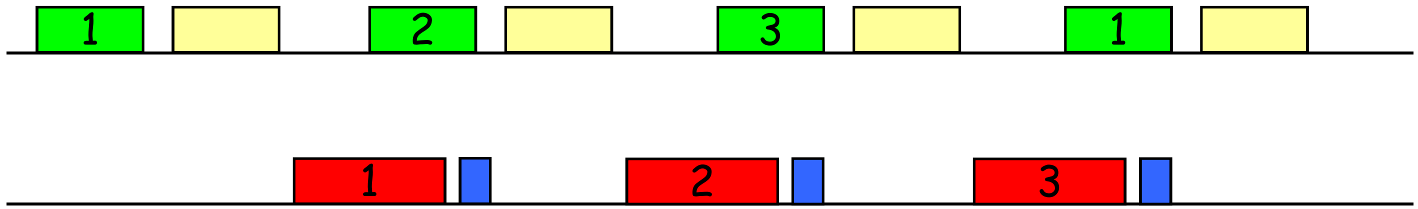


Rate optimization

Control channel data rate cannot be arbitrarily low, in order to avoid data channel wastes



fully utilized data channel



Resource wastes due to lack of reservations