Wireless Mesh Networks

Based on:

- G. R. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann, B. Walke: *IEEE 802.11s: The WLAN Mesh Standard*. IEEE Wireless Communications, Feb. 2010, pp. 104-111
- The IEEE 802.11-2012 Standard

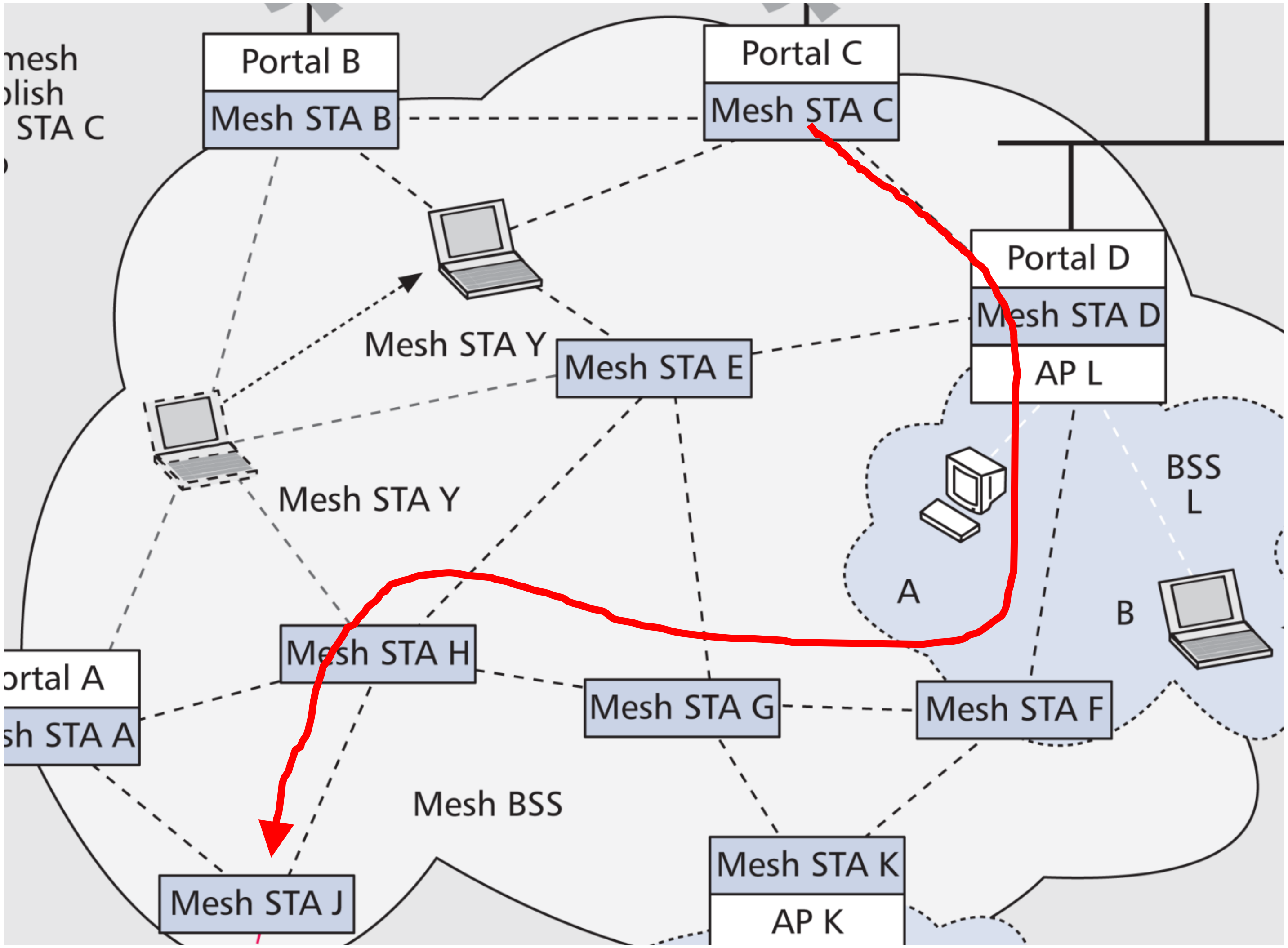
Mesh Networks: General concepts

- Most of the previously considered wireless networks are infrastructure based:
  - Access points and the Ethernet for WiFi (ESS)
  - Base Stations for GSM, UMTS, LTE (and WiMAX)
- We also have considered **a single-hop** ad hoc (IBSS) network with no infrastructure.
- The mesh networks are **multi-hop** wireless networks with no infrastructure required.
- **Two methods** to build a multi-hop network in which packets are transferred using:
  - The Layer 3 mechanism (the IP-layer based network)
  - The Layer 2 mechanism (the link layer based networks)

Mesh Networks in Wikipedia

Example of a **multi-hop wireless network**:

- The stations (STAs) form a mesh
- Packets are being forwarded in a number of hops, e.g. from **STA C to STA J through STAs D, F, G and H**



Connecting Network Segments

- Data Link Layer devices are typically designed to form **single-hop** systems or **network segments**:
  - Ethernet IEEE 802.3 standard operates with only two MAC addresses: source and destination
- To connect network segments at the Data Link Layer a **bridge** is required
  - The IEEE 802.1d standard specifies bridges for the Ethernet networks.
- A **network bridge**:
  - connects multiple network segments at the data link layer
  - allows managing traffic between network segments.

From single-hop to multi-hop WLANs

- Non-mesh 802.11 WLANs rely on wired networks to carry out bridging functions.
- Dependency on wired infrastructure is costly and inflexible, as WLAN coverage cannot be extended beyond the wired infrastructure.
- Centralized structures work inefficiently with new applications, such as wireless gaming, requiring peer-to-peer connectivity.
- A fixed topology inhibits stations from choosing a better path for communication.
- The **Wireless Mesh System** (WMS) allows bridging/routing between wireless segments without relying on the wired infrastructure.

IP-based Wireless Mesh Networks (WMN)

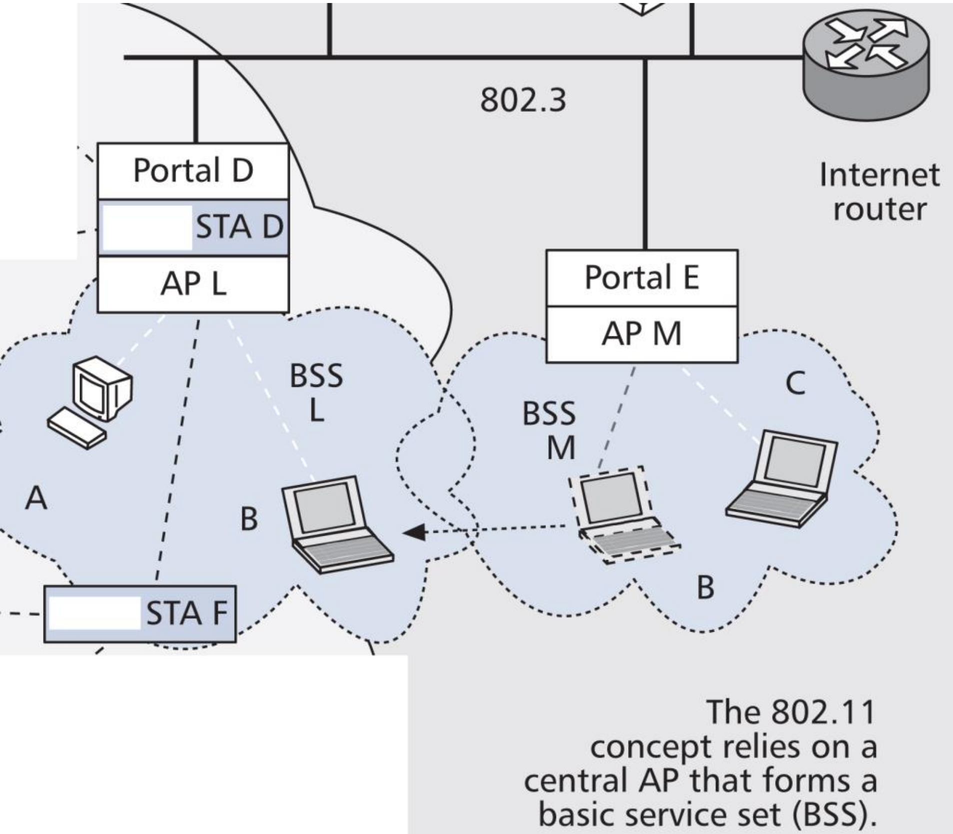
- Most of **existing WMNs** rely on the **IP layer** to enable multi-hop communication.
- The **ad hoc routing protocols have been** developed by the Internet Engineering Task Force's (IETF's) :

  Mobile Ad Hoc Networks (MANET) rfc2501
- MANETs rely on **indirect measurements** of the radio environment
  - the IP-layer has no knowledge of radio.
- The MAC layer has adequate knowledge of its radio neighbourhood but
  - 802.11 does not specify the interfaces that the IP layer needs

Mesh BSS in IEEE 802.11-2012

- The Wireless Mesh Networks (WMN) are described in the current IEEE 802.11 standard which includes the previous **IEEE 802.11s** amendment.
- The standard defines the **Mesh BSS** (MBSS: clause 4.3.15)
- The **MBSS** is a Wireless Mesh Network with **routing capabilities at the MAC layer.**
- MAC-address based **routing** is called **path selection** to differentiate it from conventional **IP routing**.
- An MBSS is a LAN consisting of autonomous STAs.
- Inside the MBSS, all STAs establish wireless links with neighbour STAs to mutually exchange messages.
- From the data delivery point of view, it appears as if all STAs in a MBSS are directly connected at the MAC layer even if the STAs are not within range of each other.

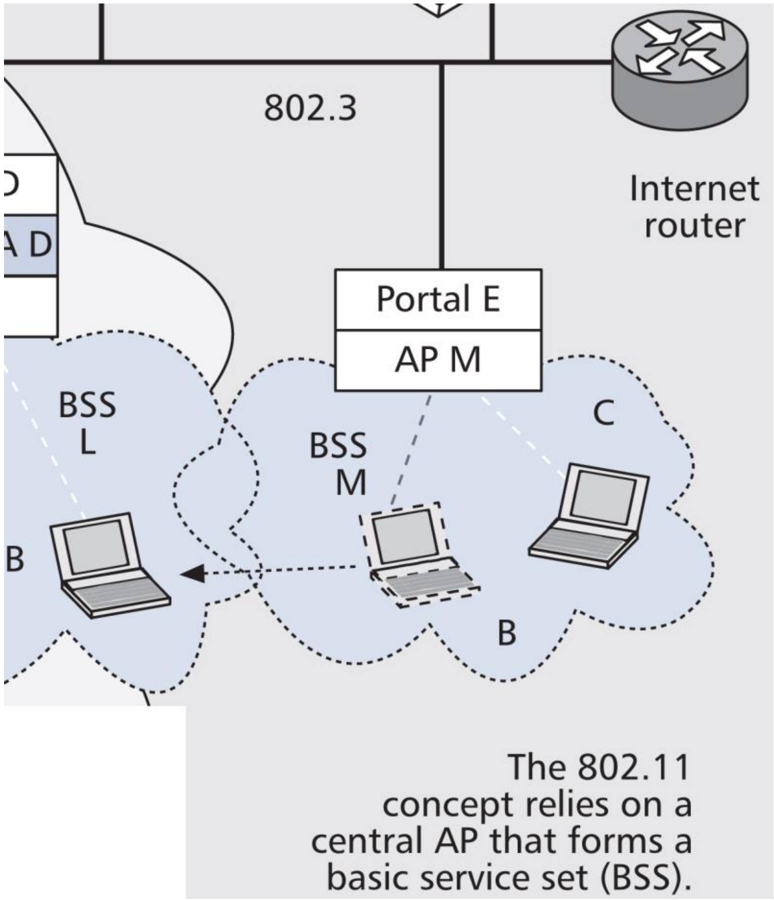
The 802.11 Network Design - Revision



- Two BSSs with APs M and L form an ESS through the connection to the 802.3 network
- It is shown that the station B moves from the BSS M to the BSS L

- A station (STA) is the entity in an 802.11 network.
- The most elementary 802.11 network, called a **basic service set** (BSS), can be formed using two stations.
- If a station provides the **integration service** to the other stations, this station is referred to as an **access point** (AP).
- If an AP is present in a BSS, it is referred to as an **infrastructure BSS**.
- To join an infrastructure BSS, a station associates with the AP.

BSS and an Access Point in 802.11



- The AP M is part of the infrastructure and provides stations B and C with access to the **distribution system** (DS).
- The DS provides the services that are necessary to communicate with devices outside the station's own BSS.
- The DS allows APs to unite multiple BSSs to form an **extended service set** (ESS).
- Within an ESS, stations can **roam** from one BSS to another.
- Ethernet (802.3) is typically used as the **distribution system medium** (DSM) on which the DS relies.
- In practice, APs collocate with the so called **portals** that provide the integration of WLANs with non-802.11 networks.

MAC Addressing

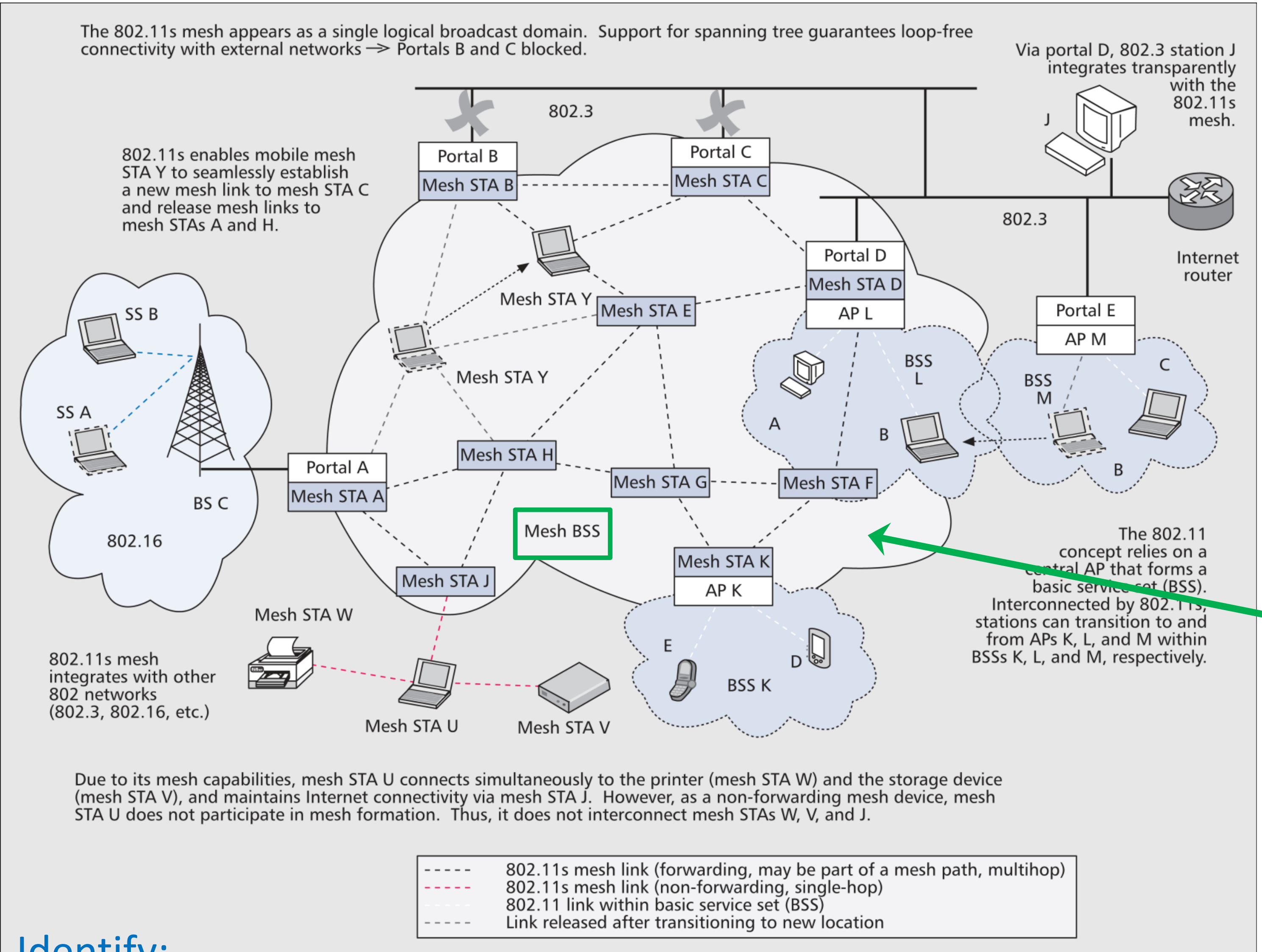
- The 802.11 frame format provides **four fields** necessary for addressing over multiple intermediate devices:

2 octets	2 octets	6 octets	6 octets	6 octets	2 octets	6 octets	2 octets	4 octets	0–7955 octets	4 octets
Frame control	Duration/ID	Address 1	Address 2	Address 3	Sequence control	Address 4	QoS control	HT control	Body	FCS

- There are four 48-bit (6-byte) address fields in the MAC frame format that indicate:
  - the basic service set identification (BSSID) identifies the AP
  - source address (SA) identifies the originator of the frame (Initial hop)
  - destination address (DA) identifies the final recipient(s)
  - transmitting STA address (TA) identifies the immediate transmitter of the frame
  - receiving STA address (RA) identifies the immediate recipient of the frame
- Certain frames may contain only some of the address fields.
- SA and DA remain unchanged in a concatenated set of multiple wireless hops.
- The transmitting and receiving station addresses, which denote the stations that actually forwarded the frame, change with every hop.

Wireless Mesh Network Architecture: Interworking

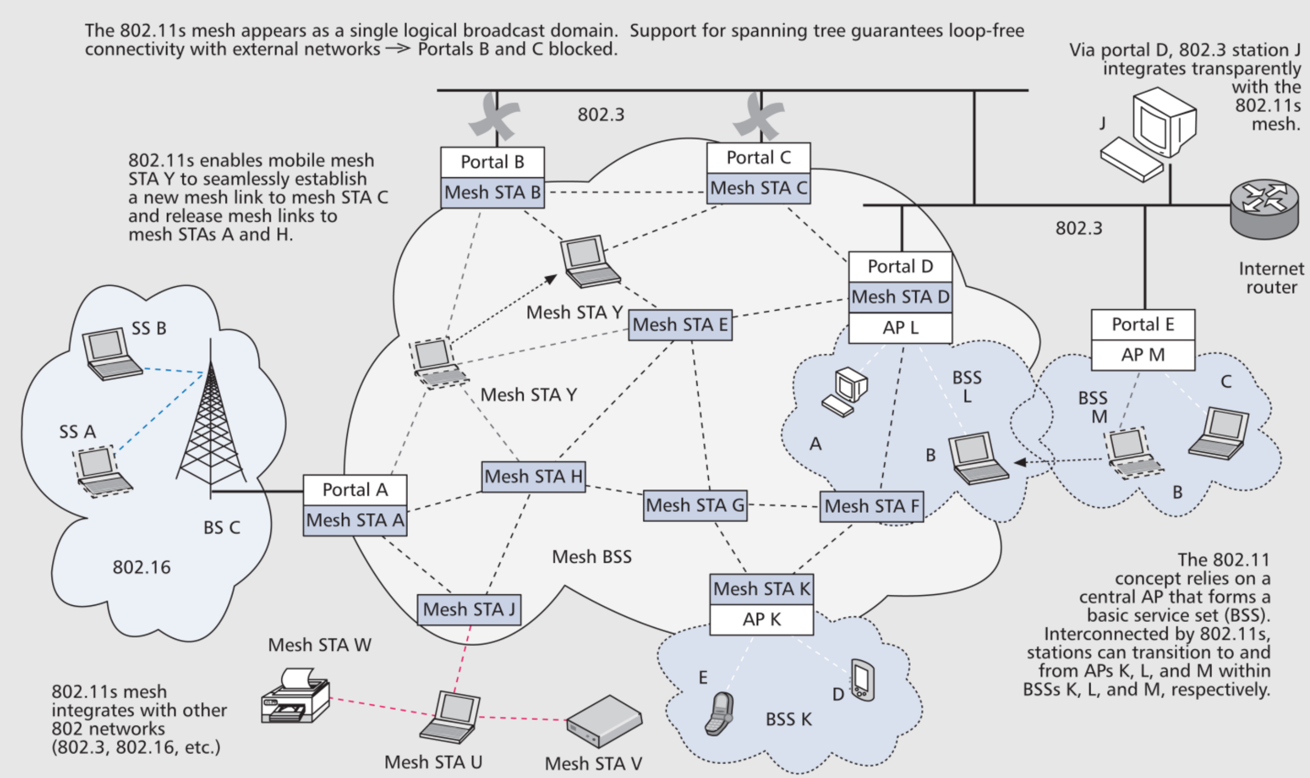
802.11s mesh = MBSS



- For seamless integration, the MBSS appears as a **single Ethernet segment** to the outside:
- portals C and B are blocked
- The MBSS implements a **single broadcast domain** and thus integrates seamlessly with other 802 networks.

Identify:

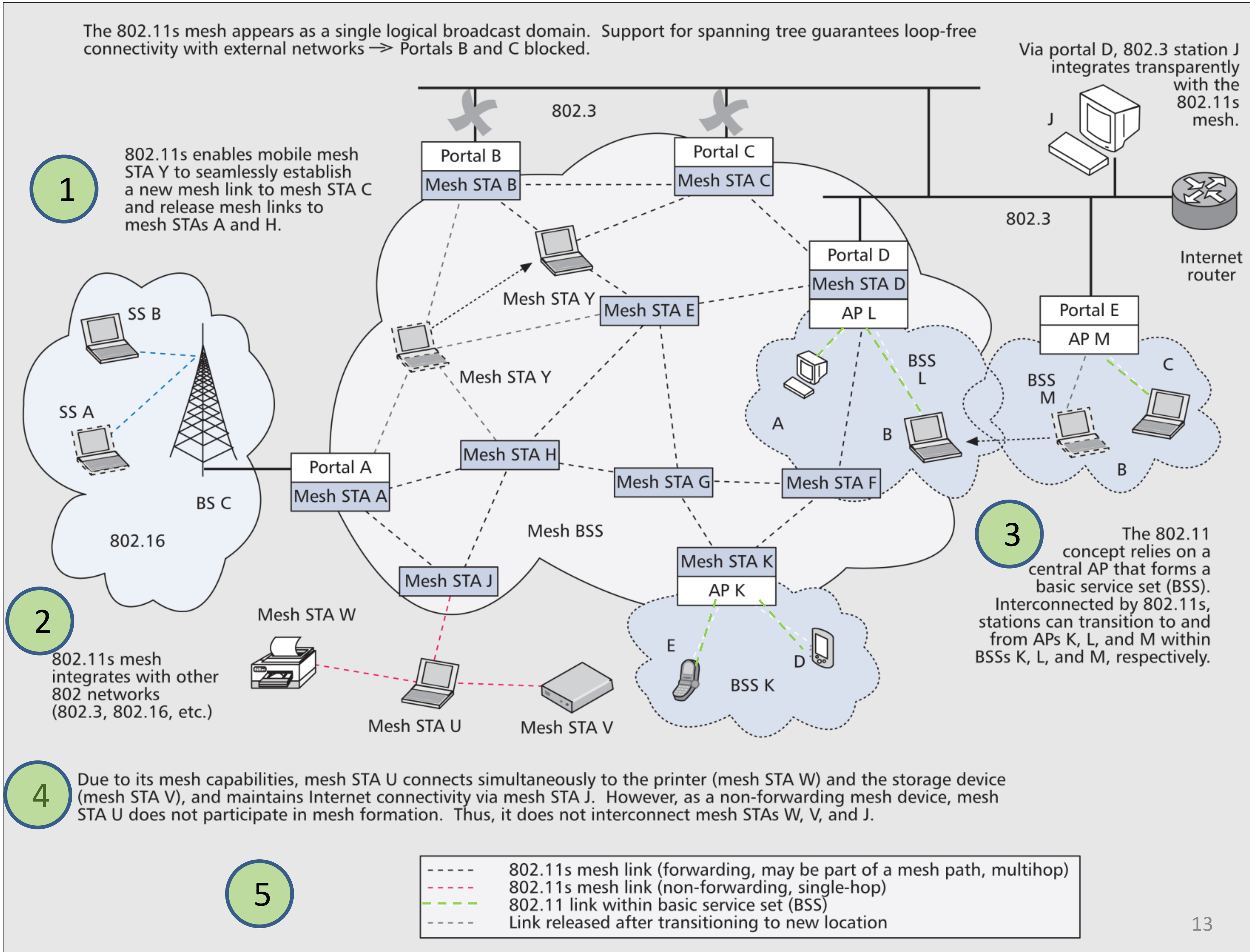
MBSS, non-mesh BSSs, WiMAX (802.16) network, an Ethernet network



Interworking (2)

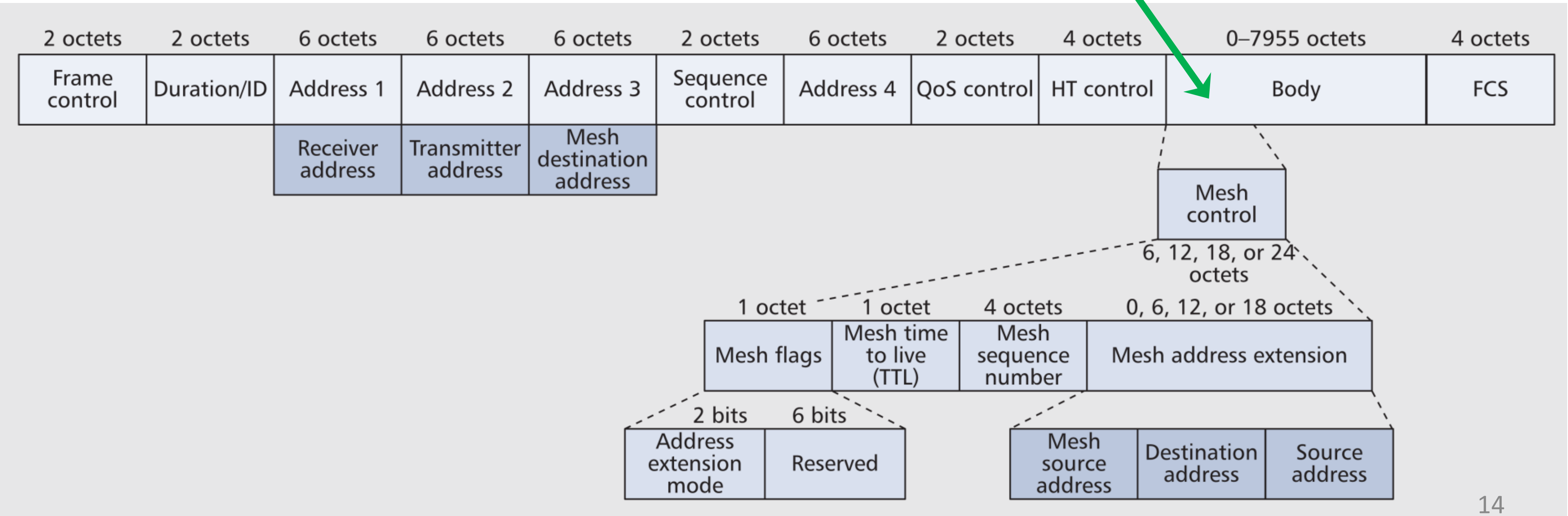
- 802.11s supports transparent delivery of uni-, multi-, and broadcast frames to destinations inside and outside of the MBSS

- Devices that form the mesh are called **mesh stations** (mesh STAs).
- Mesh stations forward frames wirelessly but do not communicate directly with non-mesh stations, e.g. with A, B, C in BSS L and M and with D, E in BSS K but through co-located Access Points.
- A mesh station may be collocated with other 802.11 entities e.g. Portals A, B, C, D, Access Points AP K, L.
- An Ethernet station J (not the mesh STA J) can communicate with MBSS transparently through the Portal D.

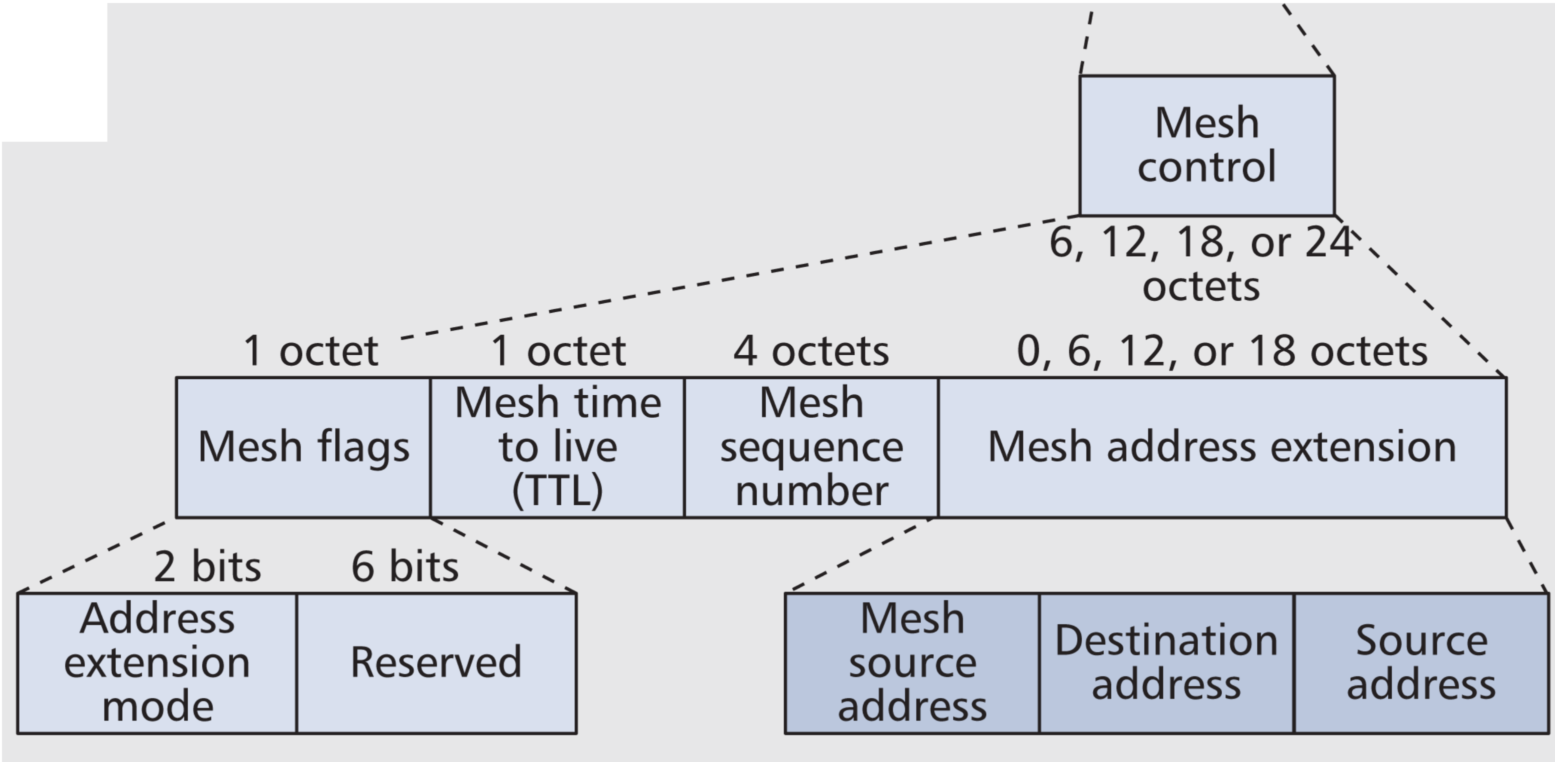

The 802.11s mesh appears as a single logical broadcast domain. Support for spanning tree guarantees loop-free connectivity with external networks → Portals B and C blocked.
Via portal D, 802.3 station J integrates transparently with the 802.11s mesh.
J
Internet router
802.3
802.3
1
802.11s enables mobile mesh STA Y to seamlessly establish a new mesh link to mesh STA C and release mesh links to mesh STAs A and H.
Portal B
Mesh STA B
Portal C
Mesh STA C
Portal D
Mesh STA D
AP L
Portal E
AP M
Mesh STA Y
Mesh STA Y
Mesh STA E
Mesh STA H
Mesh STA G
Mesh STA F
Portal A
Mesh STA A
Mesh STA J
Mesh STA K
AP K
Mesh BSS
BSS L
BSS M
BSS K
A
B
C
B
E
D
SS B
SS A
BS C
802.16
2
802.11s mesh integrates with other 802 networks (802.3, 802.16, etc.)
Mesh STA W
Mesh STA U
Mesh STA V
3
The 802.11 concept relies on a central AP that forms a basic service set (BSS). Interconnected by 802.11s, stations can transition to and from APs K, L, and M within BSSs K, L, and M, respectively.
4
Due to its mesh capabilities, mesh STA U connects simultaneously to the printer (mesh STA W) and the storage device (mesh STA V), and maintains Internet connectivity via mesh STA J. However, as a non-forwarding mesh device, mesh STA U does not participate in mesh formation. Thus, it does not interconnect mesh STAs W, V, and J.
5
802.11s mesh link (forwarding, may be part of a mesh path, multihop)
802.11s mesh link (non-forwarding, single-hop)
802.11 link within basic service set (BSS)
Link released after transitioning to new location

802.11s Frame Structure

- 802.11 categorizes frames as data, control, or management.
- Data frames carry higher-layer data.
- Control frames are used for acknowledgments and reservations.
- Devices use management frames to set up, organize, and maintain a WLAN and the local link.
- To provide for multi-hop, 802.11s extends data and management frames by an additional **mesh control field**
- The mesh flags field indicates the presence of additional MAC addresses in the mesh control field.



Mesh control



The mesh control field consists of:

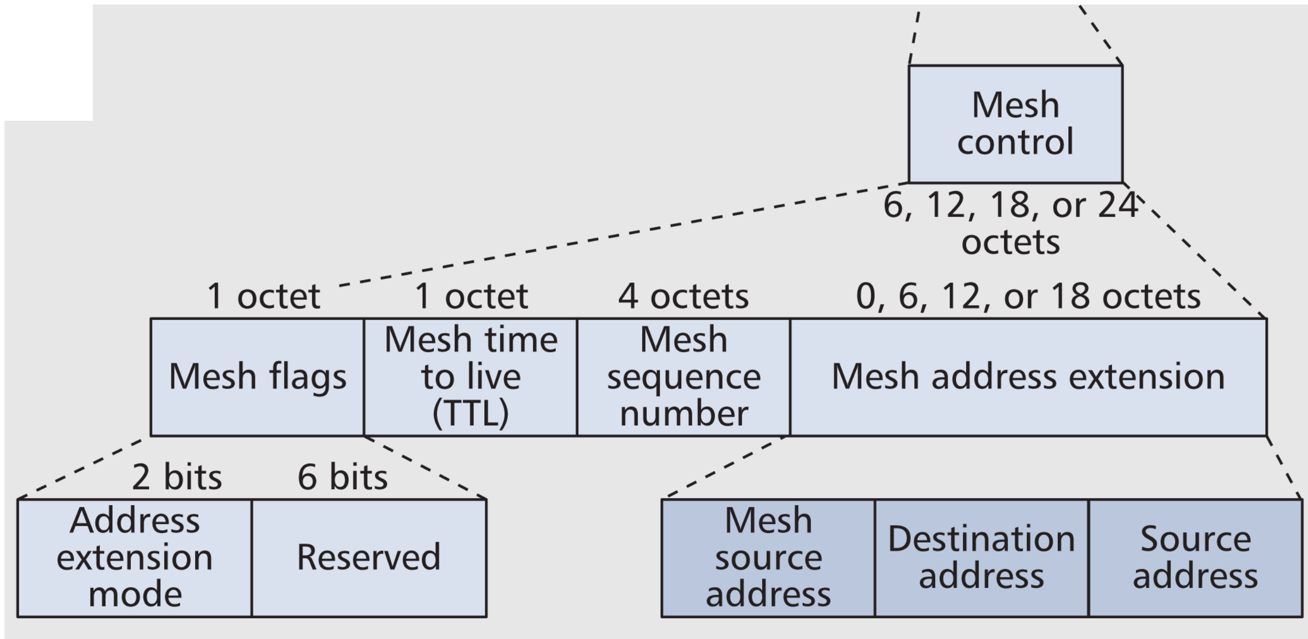
- a mesh time to live (TTL) field,
- a mesh sequence number,
- a mesh flags field,
- a mesh address extension field (optional)

- The TTL and sequence number fields are used to prevent the frames from looping forever.

When mesh stations communicate over a single hop, their frames do not carry the mesh control field.

The six address scheme

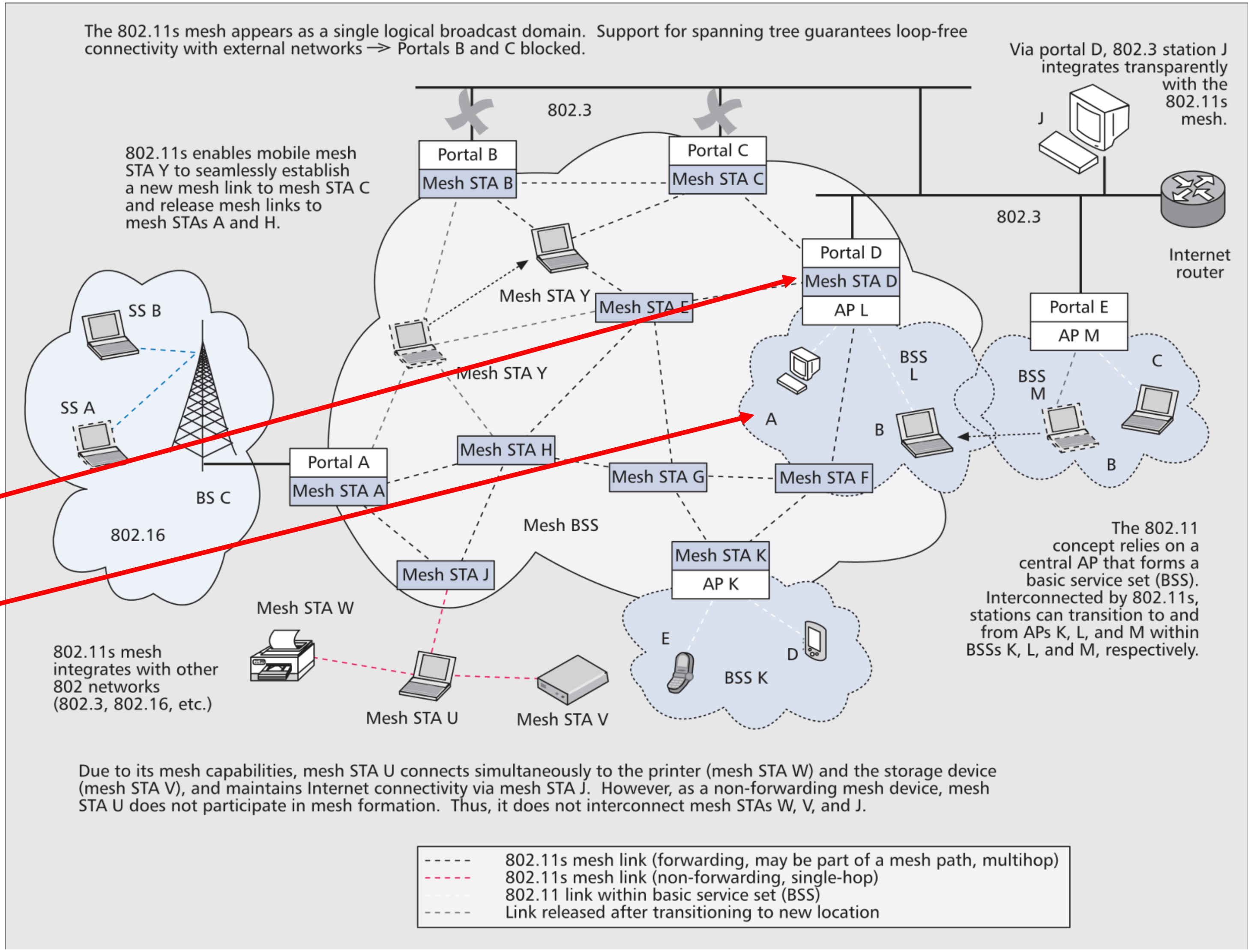
- The mesh frame structure allows for the addition of up to three addresses:



- Non-mesh management frames have three addresses only.
- Hence, in the case of multi-hop mesh management frames, address 4 is included in the mesh control field rather than in the standard frame header.
- The six address scheme provides support for:
  - **proxied stations** and
  - tree-based **path selection**.

Proxied Entities

- Up to **six address fields** in a mesh frame,
- Used when the source and destination of the frame are not part of the mesh, but are **proxied** by mesh stations
- In the example mesh station D proxies non-mesh stations A, B, and C.
- Informing other mesh stations of its proxied devices, mesh station D diverts to itself all frames destined for A, B, or C.



The six address scheme allows for the proxied entities to be identified as the final destination beyond the intermediate destination D.

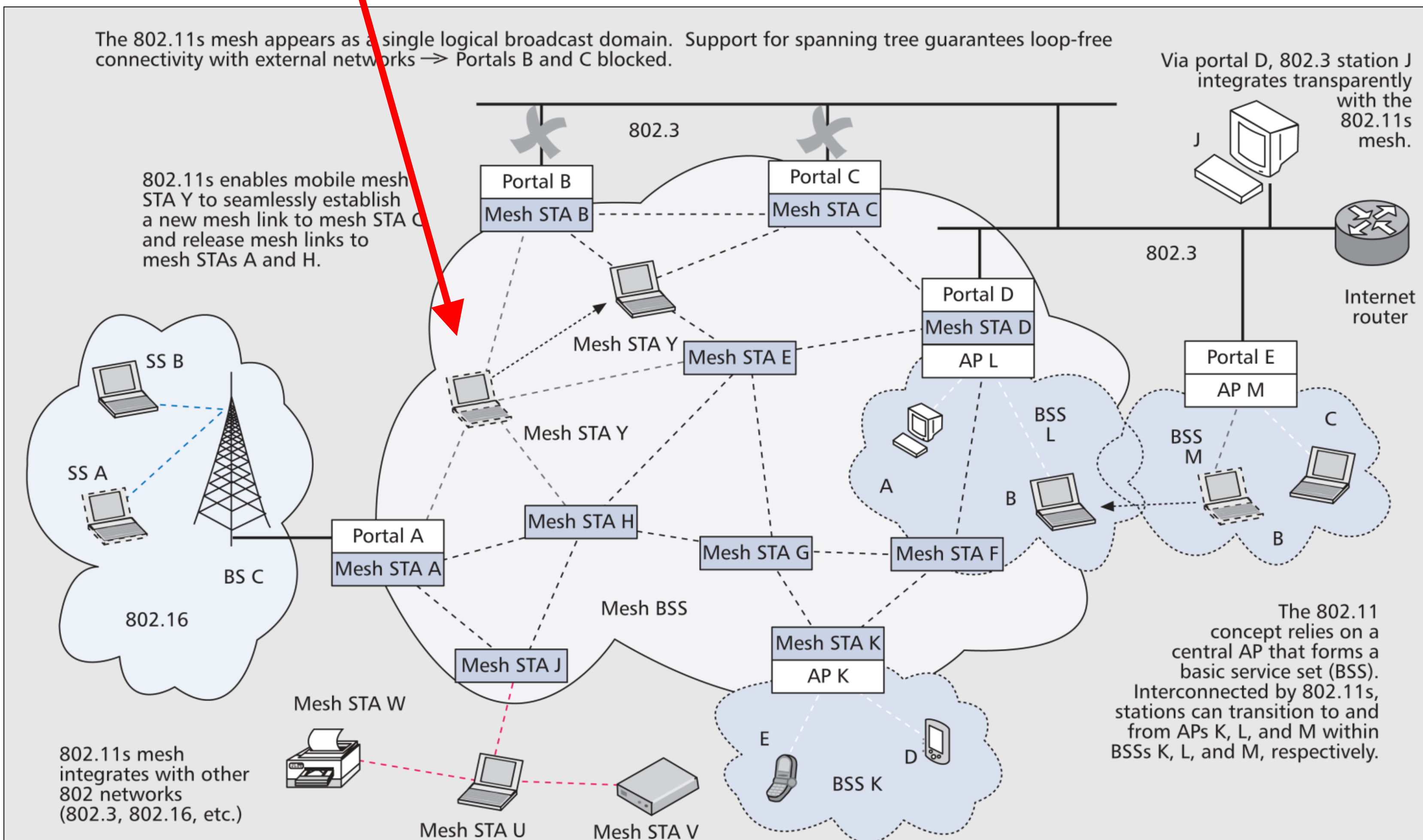
Mesh Formation and Management

- An **AP's beacon** frame helps the non-mesh stations to detect a BSS and learn about its settings
- Similarly, the **mesh station's beacon** carries information about the mesh and helps other mesh stations detect and join the mesh.
- Mesh stations detect each other based on:
  - **passive scanning** (observation of beacon frames) or
  - **active scanning** (probe frame transmission).

Beacon and Probe Frames

- The mesh-specific beacon and probe frames contain
  - a **Mesh ID** (the name of a mesh),
  - a **configuration element** that advertises the mesh services,
  - **parameters** supported by the transmitting mesh station.
- This functionality enables mesh stations to search for **suitable peers** (e.g., other mesh stations that use the same path selection protocol and metric).
- Once such a candidate peer has been identified, a mesh station uses the **Mesh Peer Link Management protocol** to establish a peer link with another mesh station.

- Even when the physical link breaks, mesh stations may keep the peer link status to allow for quick reconnection.
- The mesh STA Y may re-establish connection with mesh STA A or H as soon as it moves in range again.



Path Selection Metric

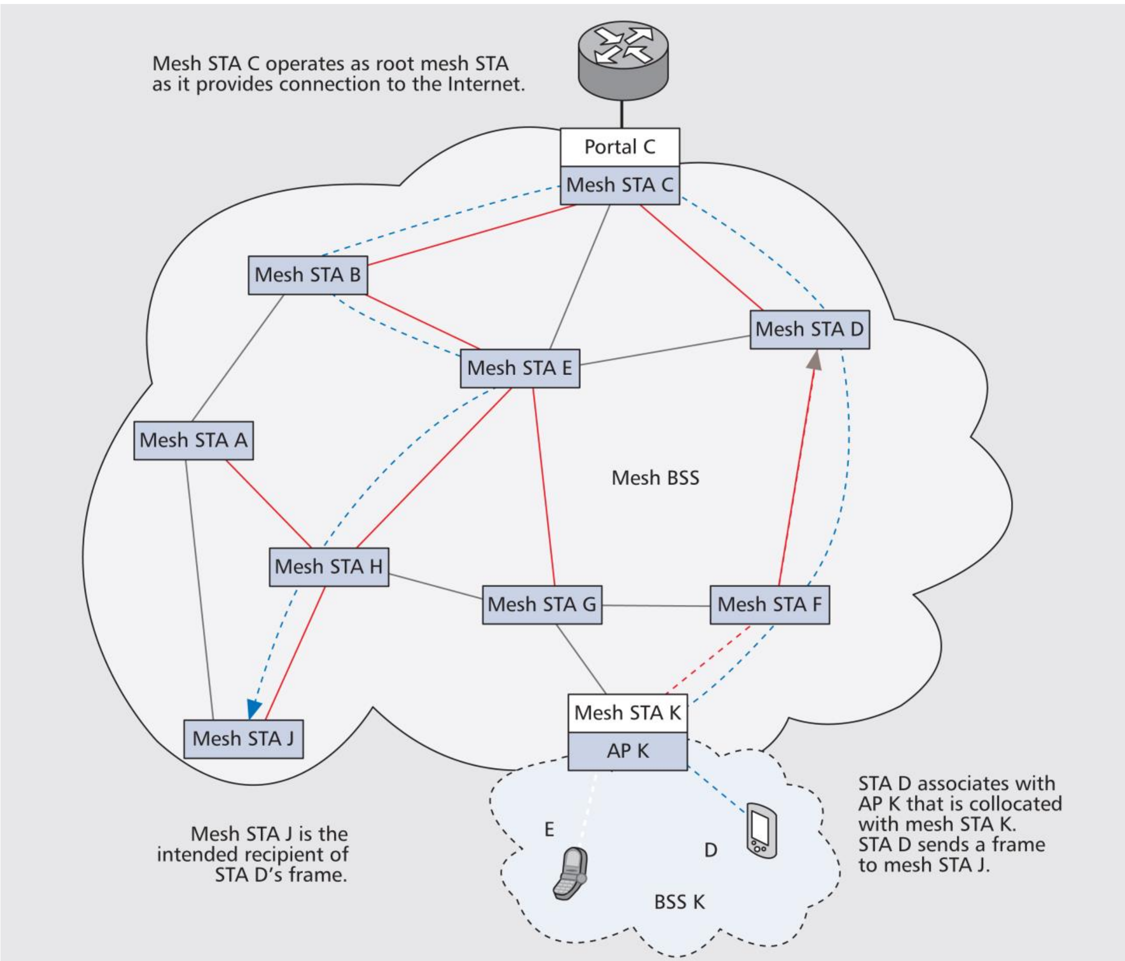
- Within a mesh, all mesh stations use the same
  - **path metric** and
  - **path selection protocol**.
- For both, 802.11s defines a mandatory default scheme.
- Because of its extensible framework, they can be replaced by other solutions.
- The default **airtime metric** indicates a link's overall cost for a **test frame of 1kB** size taking into account
  - data rate,
  - overhead, and
  - frame error rate

Path Selection Protocol

- The default path selection protocol, is the **Hybrid Wireless Mesh Protocol** (HWMP),
- This protocol describes two concurrent modes:
  - a **proactive** tree-oriented path selection mode
  - an **on demand** distributed path selection mode, (derived from the Ad Hoc On Demand Distance Vector (AODV) protocol).

Proactive Path Selection

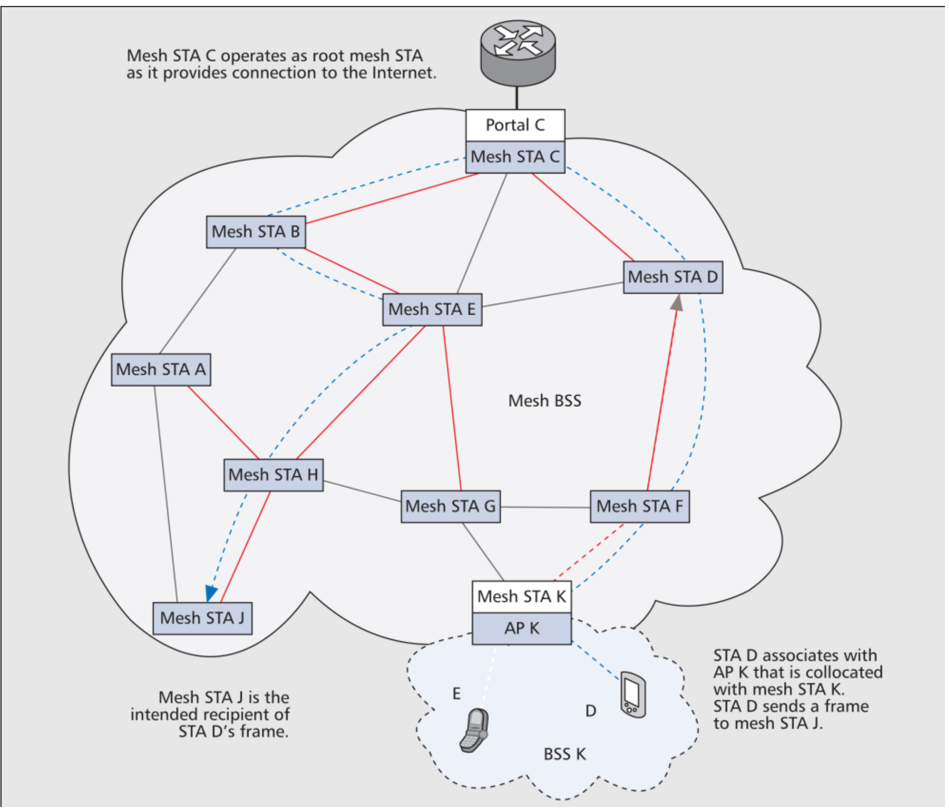
- The extension to six addresses allows for **proactive routing/path selection**.
- Proactive routing divides a path into two distinct routes to simplify path selection.



- Only mesh station C that provides Internet connection, maintains paths to all mesh stations.
- When a non-mesh station D sends frames to a mesh station J
  - the frames enter the mesh at mesh STA K,
  - traverse to mesh STA C (the first route), and
  - from there to mesh station J (the second route).

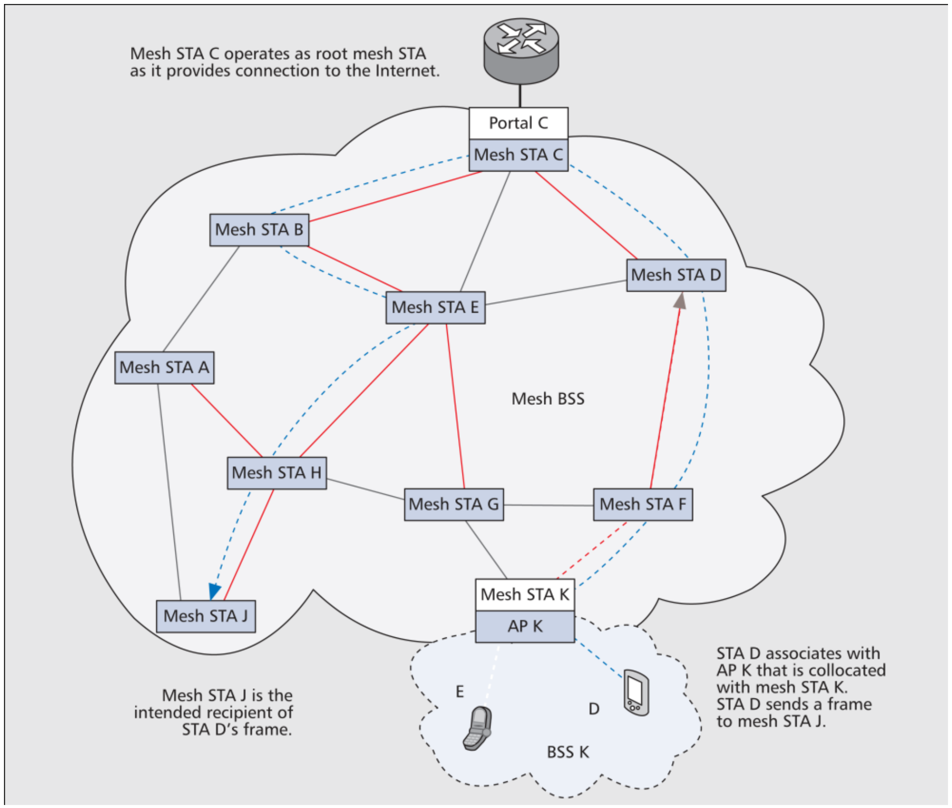
More on Proactive Mode

- The **proactive mode** requires a mesh station to be configured as a **root mesh station** typically collocated with a **portal**.



- The **root mesh station** constantly propagates routing messages that
  - either establish and maintain paths to all mesh stations in the mesh, or
  - simply enable mesh stations to initiate a path to it (red lines in Fig).
- Mesh STA K uses the root mesh STA C to establish an initial path (dotted line) to mesh STA J.

AODV: Ad hoc On demand Distance Vector



- Once the path is established using the proactive mode,
- mesh stations may use the AODV part of HWMP to avoid the indirection via the root mesh station.
- In the example, K could discover a shorter path (links marked in grey) via G and H to forward STA D's frames to the destination mesh STA J.

More Path Selection options

- Mesh stations also rely on AODV when a root mesh station is unavailable.
- When no path setup messages are propagated proactively, however, the initial path setup is delayed.
- To allow for even simpler configuration, vendors may opt not to implement HWMP (Hybrid Wireless Mesh Protocol) at all.
- As an example, a battery-limited handheld device may refrain from frame forwarding to minimize power consumption.
- Accordingly, it does not propagate path information and behaves like an end station.
- However, the device is still able to request the frame forwarding service from neighbouring mesh stations.

Power Management

- All beacon frames provide a time reference that is used for synchronization and power saving.
- Power-saving mesh stations are either in light-sleep or deep-sleep mode.
- Being in **light-sleep mode**, a mesh station switches to full power whenever a neighbour, or the mesh station itself is expected to transmit a beacon frame.
- In **deep-sleep mode** a mesh station solely wakes up for its own beacon frame transmissions.
- The mesh station can be informed of buffered traffic during the awake period that follows the beacon.

Medium Access Control in 802.11s

- For medium access, mesh stations implement the **mesh coordination function** (MCF).
- For the **mandatory part**, MCF relies on the contention-based protocol known as **Enhanced Distributed Channel Access** (EDCA), which is an improved variant of the basic 802.11 **distributed coordination function** (DCF).

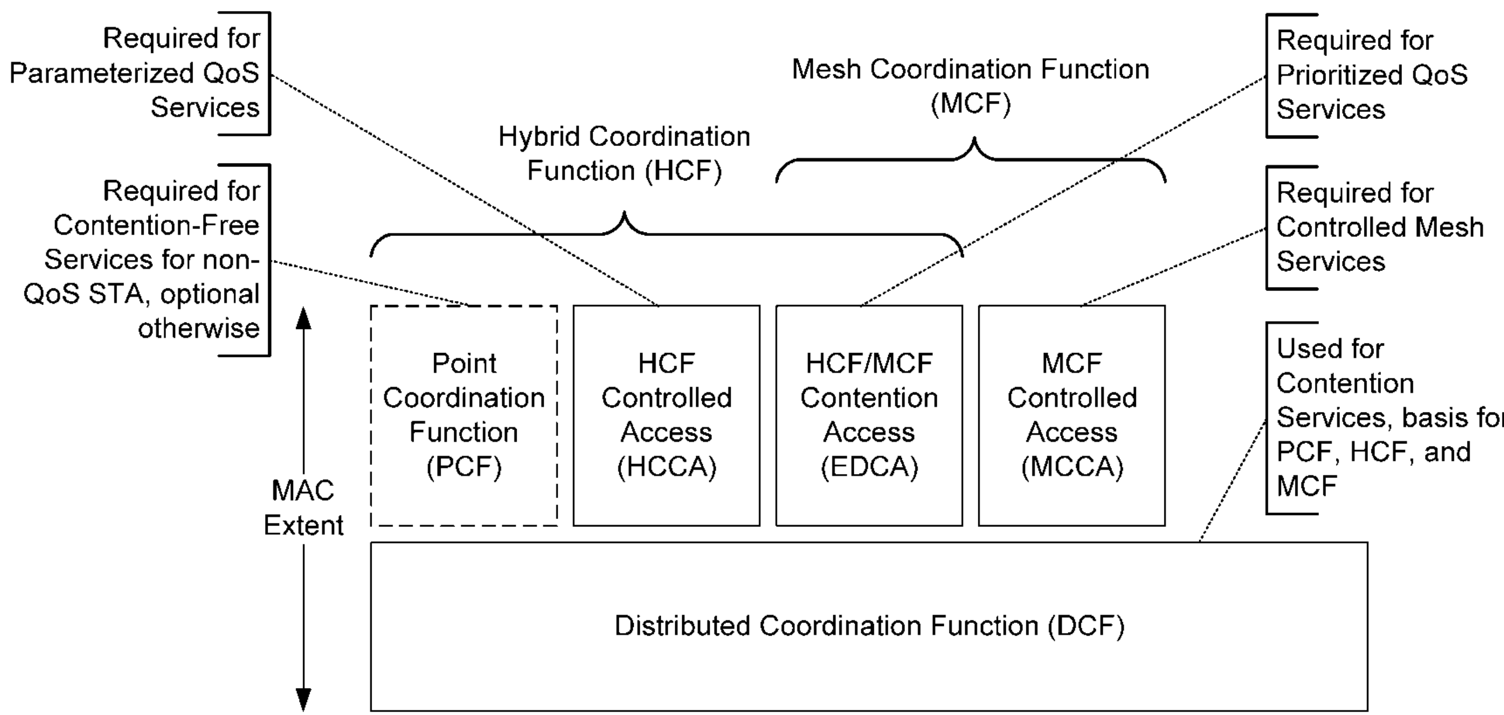


Figure 9-1—MAC architecture

Enhanced Distributed Channel Access

- Using DCF, a station transmits a **single frame** of arbitrary length.
- With EDCA, a station may transmit **multiple frames** whose total transmission duration may not exceed the so-called **transmission opportunity** (TXOP) limit.
- The intended receiver acknowledges any successful frame reception.
- EDCA also differentiates four traffic categories with different priorities in medium access and thereby allows for limited support of quality of service (QoS).

Mesh Coordinated Channel Access (1)

- To enhance QoS, MCF describes an **optional medium access** protocol called **Mesh Coordinated Channel Access** (MCCA).
- It is a distributed reservation protocol that allows mesh stations to avoid frame collisions.
- With MCCA, mesh stations reserve TXOPs (transmission opportunities times) called MCCA opportunities (MCCAOPs).
- An MCCAOP has a precise start time and duration measured in slots of 32 μs.
- To negotiate an MCCAOP, a mesh station sends an MCCA setup request message to the intended receiver.
- Once established, the mesh stations advertise the MCCAOP via the beacon frames.

Mesh Coordinated Channel Access (2)

- Since mesh stations outside the beacon reception range could conflict with the existing MCCAOPs, mesh stations also include their neighbours' MCCAOP reservations in the beacon frame.
- At the beginning of an MCCA reservation, mesh stations other than the **MCCAOP owner** refrain from channel access.
- In a presence of stations that do not support MCC A, the owner of the MCCAOP uses standard EDCA to access the medium, and does not have priority over such stations.
- After an MCCA transmission ends, mesh stations use again EDCA for medium contention.

Congestion Control

- Access in 802.11 relies on carrier sensing.
- At a mesh's edge, mesh stations have fewer neighbours and therefore observe an idle wireless medium more often than mesh stations located in the core of the mesh.
- Consequently, edge mesh stations have a higher probability to transmit.
- When core mesh stations congest, they cannot carry the aggregated traffic and drop frames.
- This is costly as the mesh frame has already traversed several hops to reach the congested mesh station.
- The optional 802.11s **congestion control** concept uses a management frame to indicate the expected duration of congestion and to request a neighbour mesh station to slow down.

Security in 802.11s

- With 802.11s, mesh stations perform the **Simultaneous Authentication of Equals** (SAE) algorithm.
- Besides mutual authentication, SAE provides **two mesh stations** with a **pairwise master key** (PMK) that they use to encrypt their frame.
- As its name indicates, SAE does not rely on a keying hierarchy like traditional 802.11 encryption.
- Instead, it implements a distributed approach that both mesh stations may initiate simultaneously.
- Because of the pairwise encryption, **each link is independently secured**.
- As a consequence, 802.11s does not provide end-to-end encryption.
- Since broadcast traffic must reach all authenticated peers, a mesh station is required to update its broadcast traffic key with every new peering it establishes.

802.11s Implementations

Find out about

- the OLPC project
- open80211s

as two examples of the implementation of the 802.11s mesh networks