IEEE 802.1Q

Media Access Control Bridges and Virtual Bridged Local Area Networks

Patricia Thaler, Norman Finn, Don Fedyk,
János Farkas, Glenn Parsons, Eric Gray

Authors

János Farkas	janos.farkas@ericsson.com
Don Fedyk	donald.fedyk@alcatel-lucent.com
Norman Finn	nfinn@cisco.com
Eric Gray	eric.gray@ericsson.com
Michael David Johas Teener	mikejt@broadcom.com
Glenn Parsons	glenn.parsons@ericsson.com
Panagiotis Saltsidis	panagiotis.saltsidis@ericsson.com
Patricia Thaler	pthaler@broadcom.com

Presentation Objective

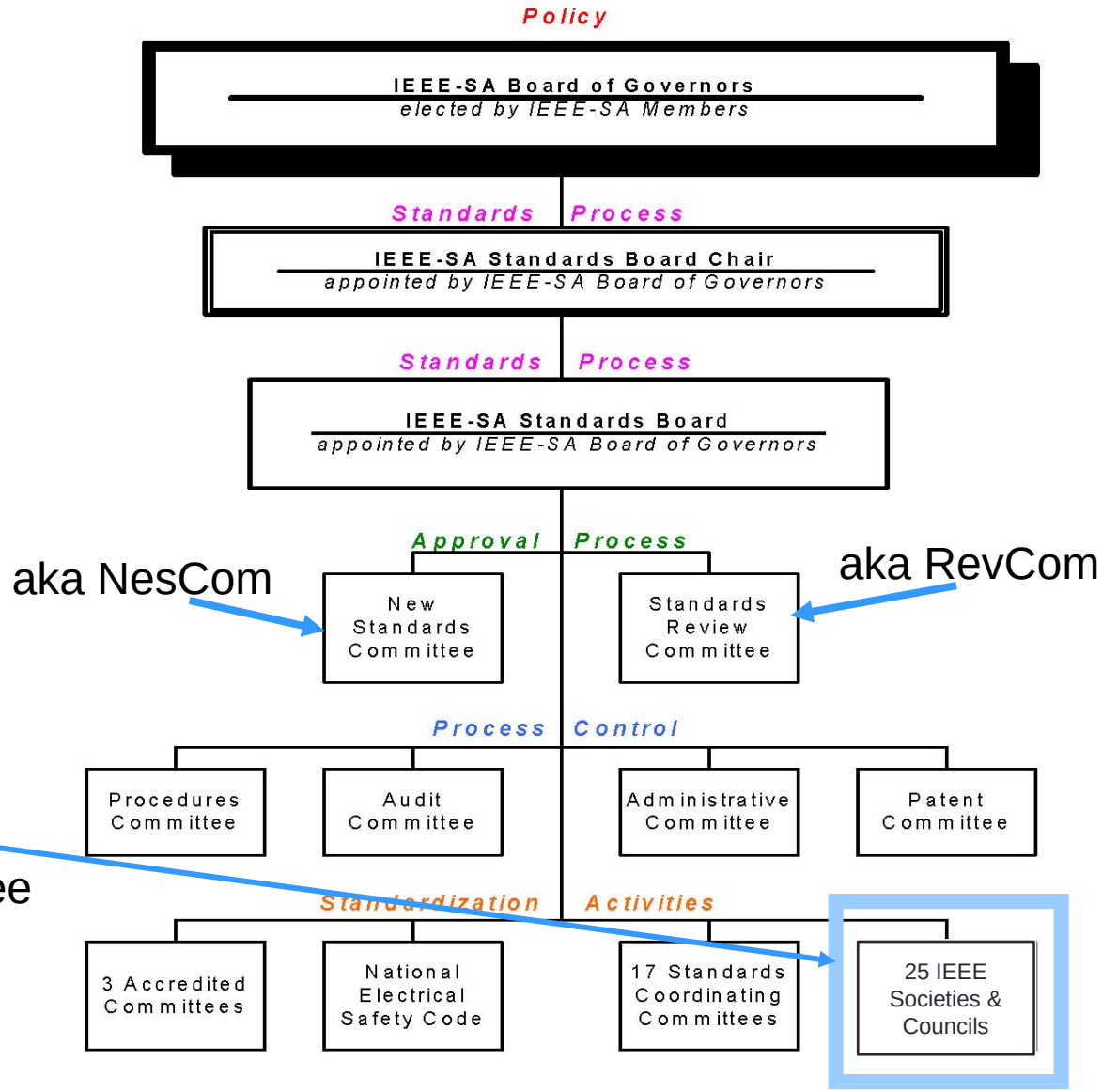
- Give an overview of the capabilities of today's 802.1Q
  - It is much more than spanning tree protocol and 4K VLANs
- A lot of topics covered → at a high level
- Overall capabilities are discussed but details are not covered

- Today's networks often involve a mixture of L3 routing and L2 bridging sometimes even in the same box
  - Understanding of today's L2 would be useful

Contents

IEEE 802.1 OVERVIEW

IEEE Standards Organization



IEEE 802 is here:
a standards committee
formed by the
Computer Society

IEEE 802 Organization

EXECUTIVE COMMITTEE (EC)

CHAIR
Paul Nikolich

Working Group/TAG Chairs

802.1 BRIDGING/ARCH Tony Jeffree	802.3 Ethernet David Law	802.11 WLAN Bruce Kraemer
802.15 WPAN Bob Heile	802.16 BWA Roger Marks	802.18 TAG Radio Regulatory Mike Lynch
802.19 Coexistence Steve Shellhammer	802.21 Media indep. handover Subir Das	802.22 WRAN Apurva Mody
802.24 Smart Grid TAG James Gilb	OmniRAN EC Study Group Max Riegel	

Hibernating WG Chairs
(non voting)

- 802.17 Resilent Packet Ring John Lemon
- 802.20 MBWA Radhakrishna Canchi

Appointed Officers

1st VICE CHAIR Pat Thaler	2nd VICE CHAIR James Gilb
EXECUTIVE SECY Jon Rosdahl	RECORDING SECY John D'Ambrosia
TREASURER Bob Grow	

Appointed Officers
(non voting)

MEETING MGR MEMBER EMERITUS Buzz Rigsbee	MEMBER EMERITUS Geoff Thompson

IEEE 802 is an open organization

IEEE 802.1 Task Groups

- **Interworking (IWK, Stephen Haddock)**
  - Internetworking among 802 LANs, MANs and other wide area networks
- **Time-Sensitive Networking (TSN, Michael David Johas Teener)**
  - Formerly called Audio Video Bridging (AVB) Task Group
  - Time-synchronized low latency streaming services through IEEE 802 networks
- **Data Center Bridging (DCB, Patricia Thaler)**
  - Enhancements to existing 802.1 bridge specifications to satisfy the requirements of protocols and applications in the data center, e.g.
- **Security (Mick Seaman)**
- **Maintenance (Glenn Parsons)**

IEEE 802.1 Standards

- The ones with capital letters, e.g. 802.1Q or 802.1AX are independent standards
- Amendments to these standards are identified by lower case letters e.g. 802.1ah, 802.1Qbg or 802.1AEbn
- Periodically the amendments get merged into a revision of the main standard, e.g. 802.1ah and 802.1Qay are now part of 802.1Q-2011
- 802.1Q can be considered as many individual standards (RFCs) integrated into a single document
  - Clauses 6 through 9 give a general overview of the 802.1Q bridge architecture
  - To get oriented on an additional area, it's best to read the Clause titled the "Principles of <area>"
  - Once oriented, references in the subclause of Clause 5 Conformance for the relevant device can be helpful

Before We Start

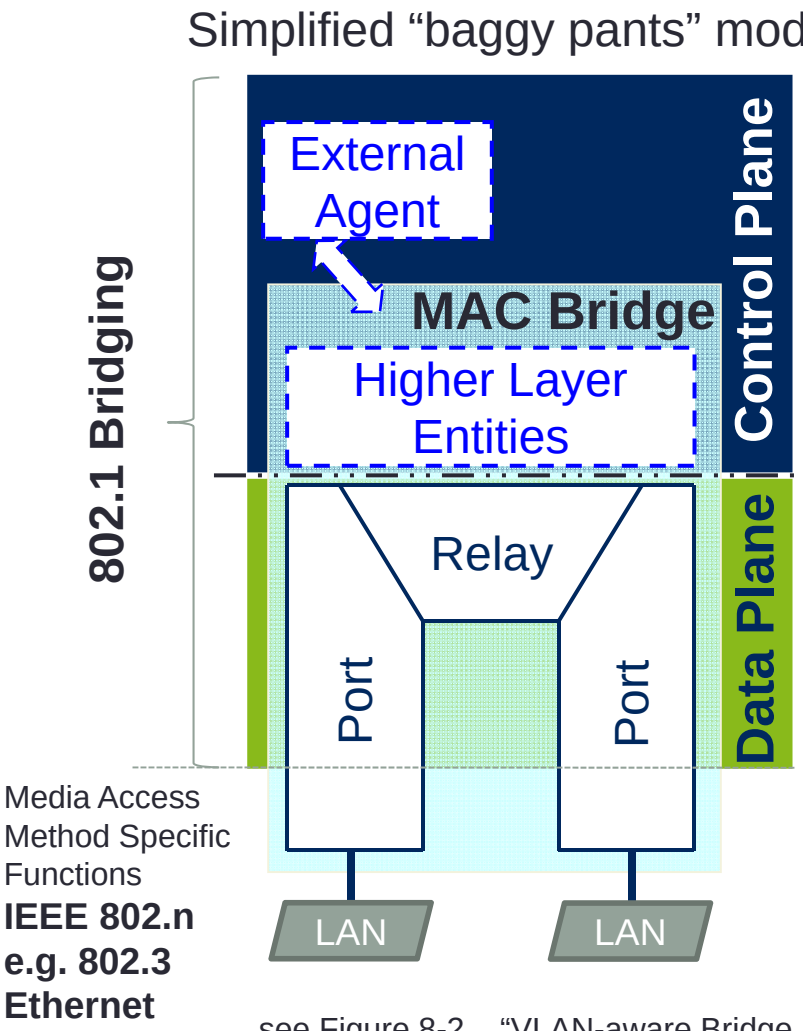
- Bridge forwarding is based on MAC addresses and virtual networks, i.e. Virtual LANs (VLAN)
- Context determines VLANs/MACs/Tags in the standard:
  - Customer: C-MAC, C-VLAN, C-tag
  - Service: S-VLAN, S-tag
  - Backbone: B-MAC, B-VLAN, B-tag
- It is possible to construct a hierarchy out of the virtual networks

BRIDGE ARCHITECTURE

Basic Principles

- MAC addresses are “identifier” addresses, not “location” addresses
  - *This is a major Layer 2 value, not a defect!*
- Bridge forwarding is based on
  - Destination MAC
  - VLAN ID (VID)
- Frame filtering for only forwarding to proper outbound ports(s)
  - Frame is forwarded to every port (except for reception port) within the frame's VLAN if it is not known where to send it
  - Filter (unnecessary) ports if it is known where to send the frame (e.g. frame is only forwarded towards the destination)
- Quality of Service (QoS) is implemented after the forwarding decision based on
  - Priority
  - Drop Eligibility
  - Time

Control Plane Separated from Data Plane



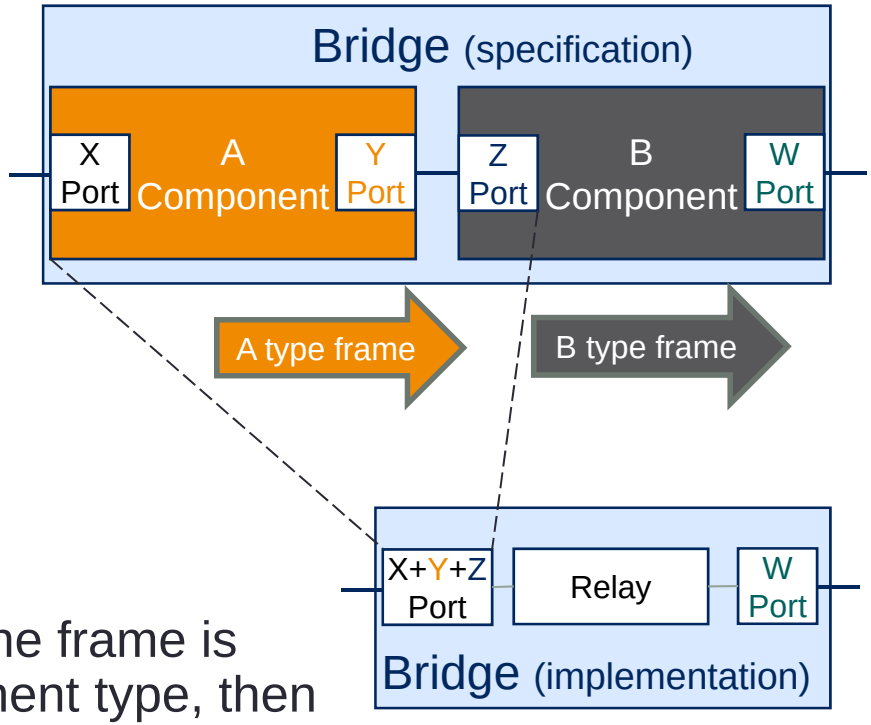
- Control protocols are implemented as Higher Layer Entities
- External Agent may provide control instead of the distributed protocols

- The data plane is comprised of
  - A MAC Relay and
  - At least two ports

see Figure 8-2 – “VLAN-aware Bridge architecture” of 802.1Q for more details

Bridge Components

- Used as a description language in the specs
- Specify the operation in distinct steps
- Different Component types for the different L2 virtual networks
- Ports have their own distinct type based on their role within a Component
- Key observation
  - When the outermost Ethertype of the frame is not the same as the bridge component type, then the frame is assigned a VLAN by the reception port



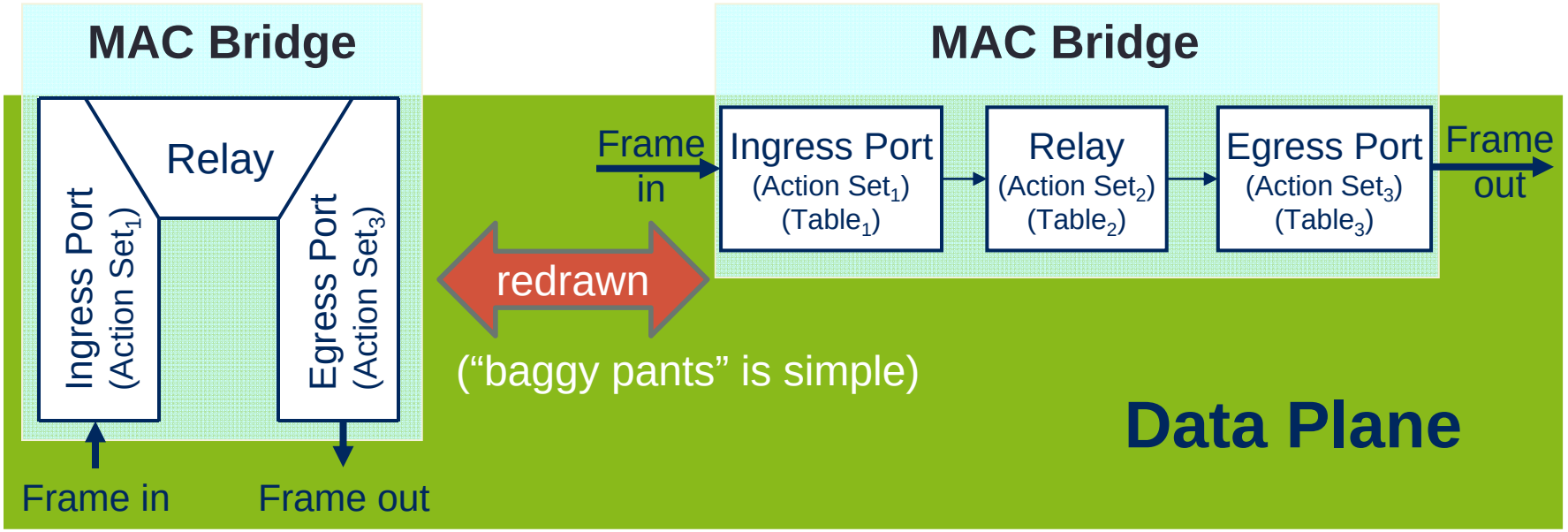
- Implementations are often based on a single MAC relay → a port may implement several functions
- Invented for humans to be able to talk about it, not for making it complex

DATA PLANE

Data Plane Today

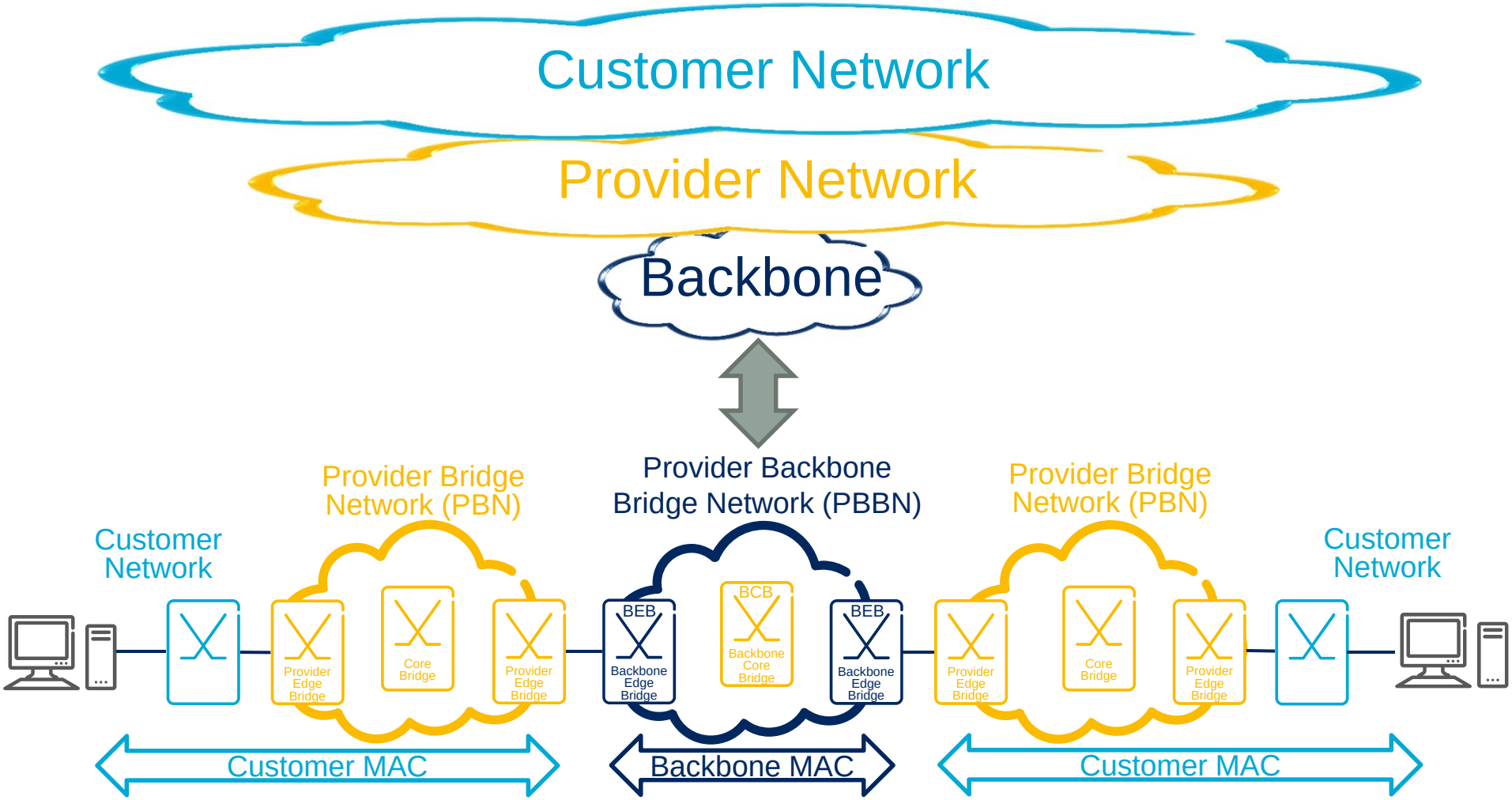
- 802.1Q today is 802.Q-2011 (Revision 2013 is ongoing)
  - Note that if the year is not given in the name of the standard, then it refers to the latest revision, e.g.
    today 802.1Q = 802.1Q-2011 and 802.1D = 802.1D-2004
- 802.1Q already involves
  - Q-in-Q = Provider Bridges (PB)
    [IEEE 802.1ad-2005]
  - MAC-in-MAC = Provider Backbone Bridges (PBB)
    [IEEE 802.1ah-2008]
- 802.1Qbg-2012 Edge Virtual Bridging (EVB) is also part of today's 802.1Q data plane (802.1Qbg not yet amended to 802.1Q)
- 802.1Q is not only about 12-bit C-VLANs any more

Data Plane Actions



- Ingress Port (Action Set_1)
  - Filtering (drop), (un)tagging, VID translation, de/en-capsulation
- Relay (Action Set_2)
  - Forwarding, filtering
- Egress Port (Action Set_3)
  - Filtering, (un)tagging, VID translation, de/en-capsulation, metering, queuing, transmission selection

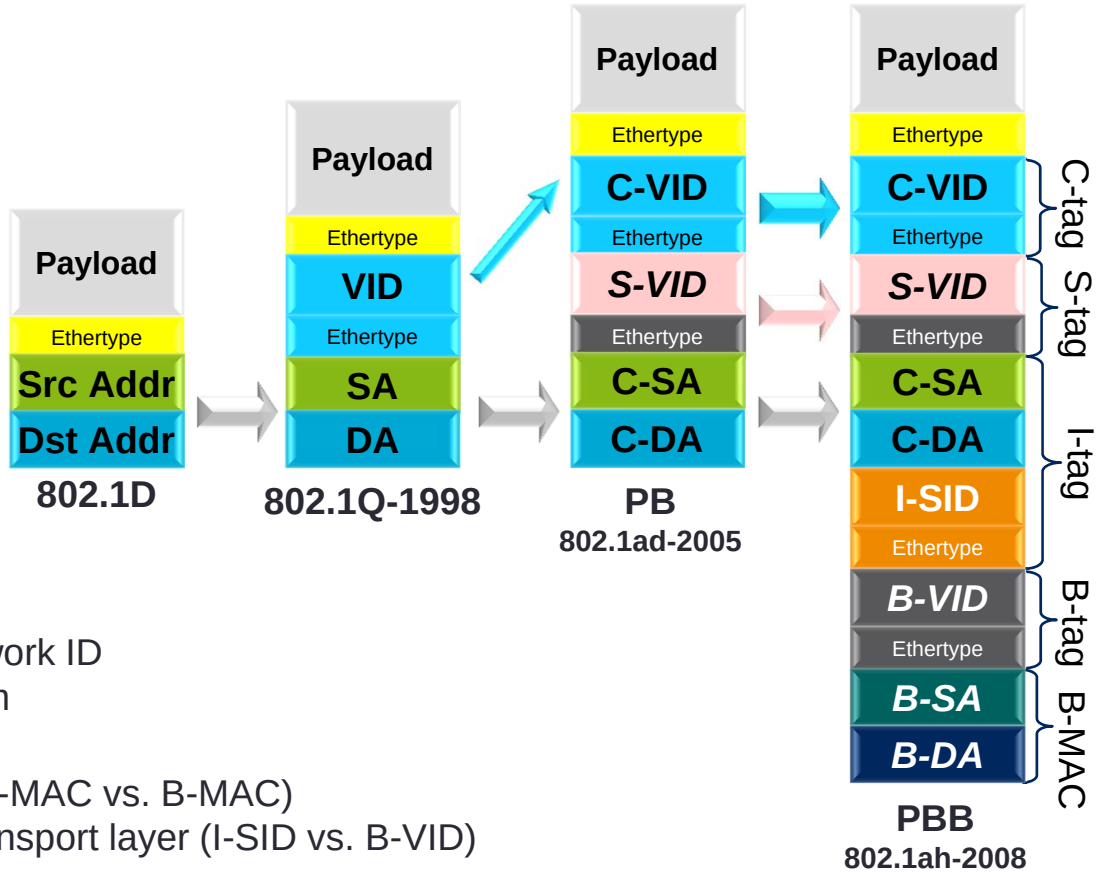
Network Overlays Example



Very rough analogy of IETF concept to 802.1 concept: P device ~ BCB; PE device ~ BEB; CE device ~ C-MAC bridge

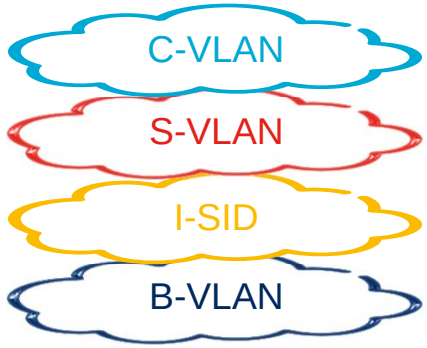
Network Virtualization Is Based on the Data Plane

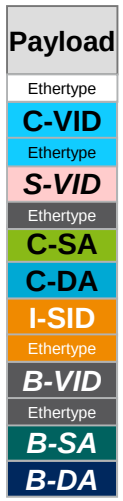
- Data plane evolution
  [up to 802.1Q-2011]
  - it is not complicated
  - ~ may think of tag stacking
- Provider Bridges
  (PB, Q-in-Q)
  - Scalability
    - Overlaying virtual networks
    - 4K VLAN problem solved
- Provider Backbone Bridges
  (PBB, MAC-in-MAC)
  - Scalability
    - 24-bit I-SID as a single virtual network ID
    - Forget about the 4K VLAN problem
  - Separation
    - MAC address space separation (C-MAC vs. B-MAC)
    - Service layer is separated from transport layer (I-SID vs. B-VID)
- Overall
  - Uniform forwarding kept: based on Destination MAC (DA) and VID
  - L2 data plane provides powerful virtualization
  - There may be several levels of tagging or encapsulation



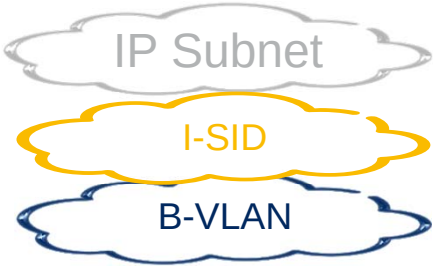
Virtual Networks and Overlays

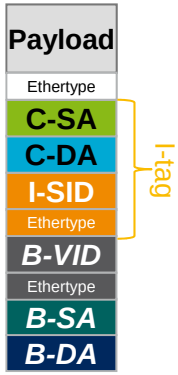
- Virtual network names do not bound their application!
- A lot of flexibility is provided, two examples shown here
- Using all L2 virtual network overlays





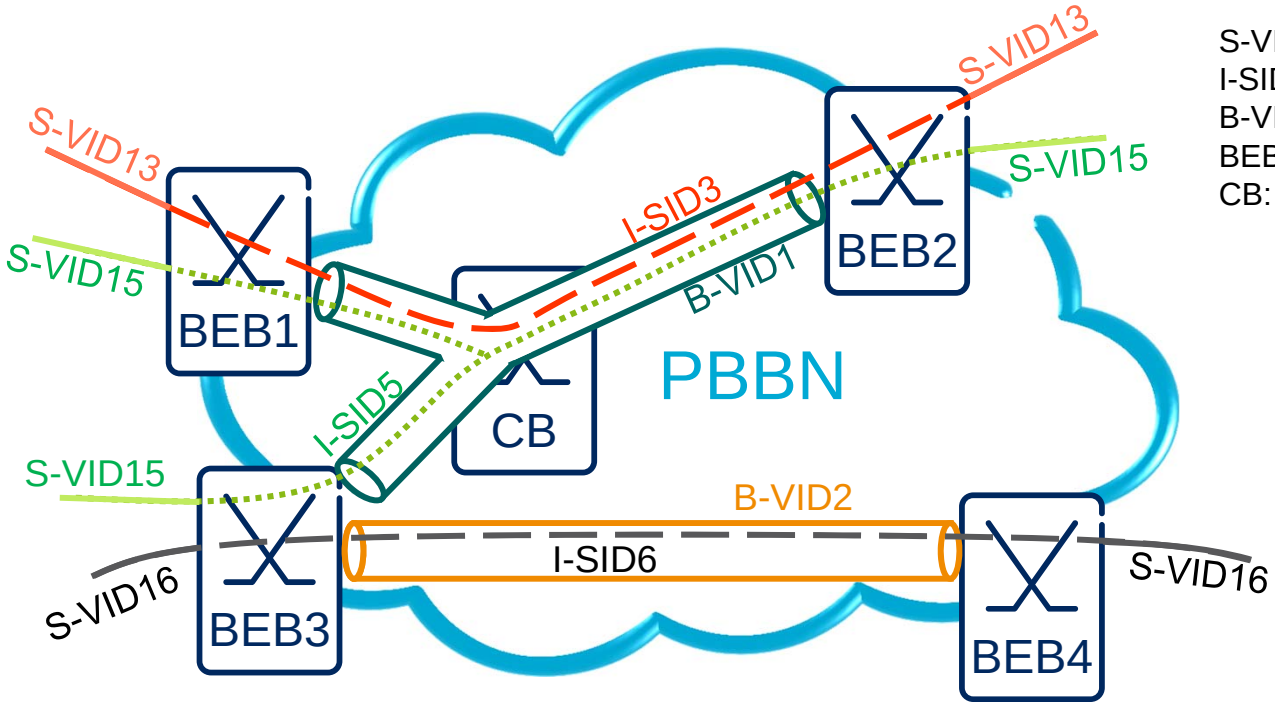
  - Can be used in data center and campus networks too, not only in provider environment
- IP is a native overlay on Ethernet
  - IP payload can be e.g. right after I-tag
  - Host can be a Virtual Machine
  - PBB can be the core of a data center



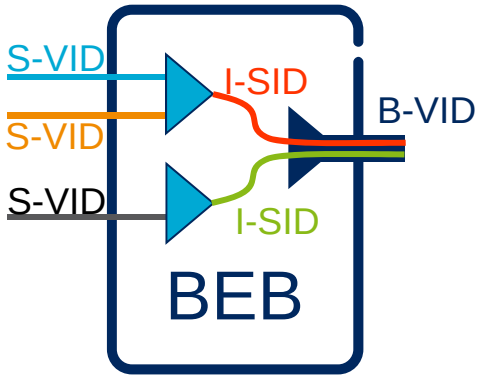


It Is All About Mapping of Virtual Networks to Each Other at Edges

- An External Entity needs to perform the mapping on the edges
- All the rest can be done automatically by the distributed control plane, unless the External Entity maintains full control, see next section
- 'Intelligence' is at the edges, Core Bridges are relatively 'dumb'



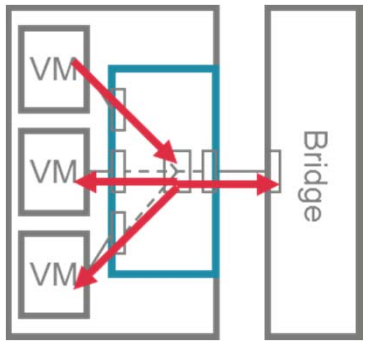
S-VID: Service VLAN ID
I-SID: Backbone Service Instance Identifier
B-VID: Backbone VLAN ID
BEB: Backbone Edge Bridge
CB: Core Bridge



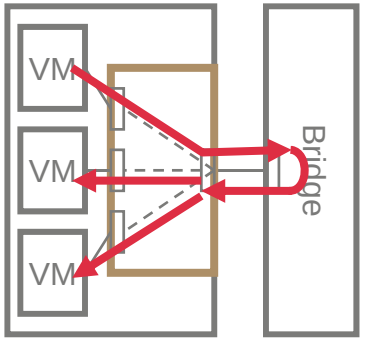
S-VID → I-SID → B-VID
many-to-one mappings

Edge Virtual Bridging [802.1Qbg]

- Edge Relay - a bridge incorporated into an end node (often in the network interface hardware, hypervisor or both).
  - Virtual Edge Bridge (VEB), or
    - Relays traffic between VMs like an external Bridge
    - Not required to support learning since VM addresses may be configured
    - Not required to support any spanning tree protocol as it is always at the bridged network edge
  - Virtual Edge Port Aggregator (VEPA)
    - Sends all traffic from VMs to the adjacent bridge
    - Reflective relay in external Bridge returns any frames destined to local VMs
    - Makes VM to VM traffic visible to adjacent bridge
    - Policies do not have to be distributed to the VEPA
- And the adjacent Edge Virtual Bridges that connect to them.



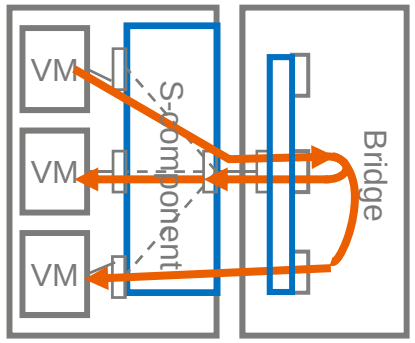
VEB



VEPA

S-Channels [also 802.1Qbg]

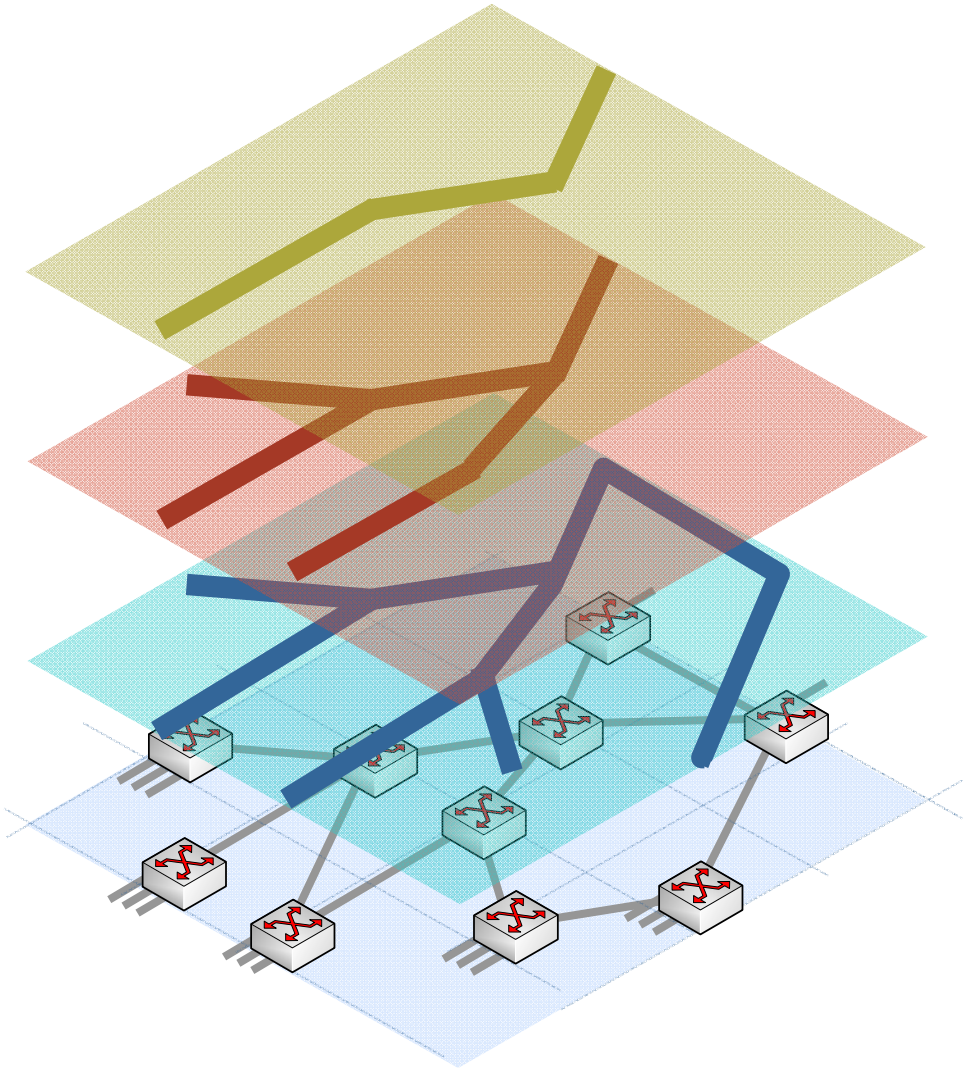
- S-Channels are virtual links between the end system and the adjacent Bridge
  - Traffic carries an SVLAN-Tag (from Provider Bridging) to identify it with an S-Channel
  - Each S-Channel can have a single VM, a VEB or VEPA attached
    - Normally, even with a single VM there will be a 2-port VEB to handle VLAN Tag insertion, removal and tagging

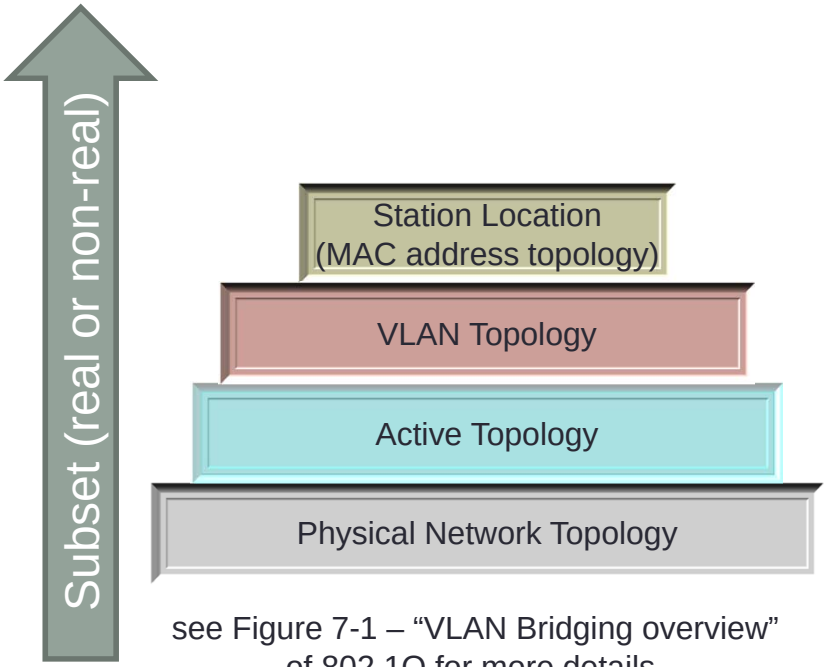


S-Channels

CONTROL PLANE

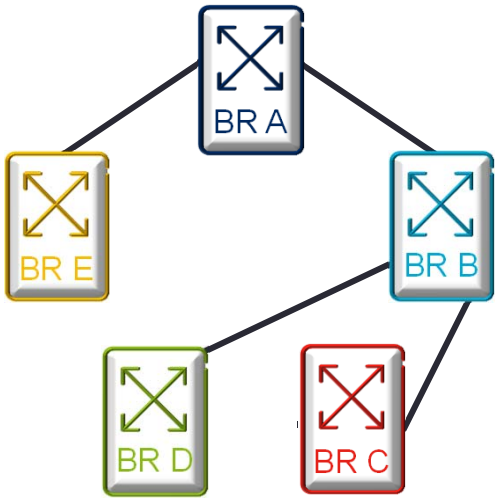
Topology Layers (Contexts)





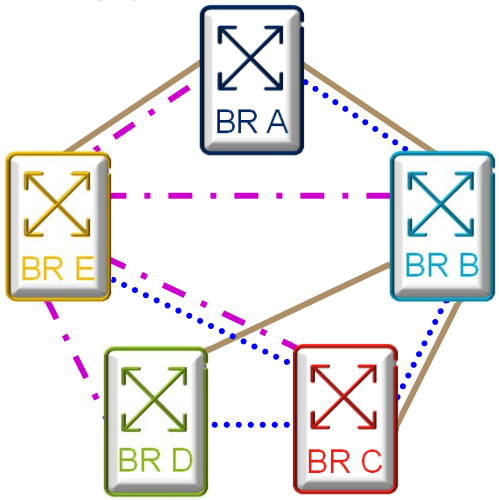
see Figure 7-1 – “VLAN Bridging overview” of 802.1Q for more details

The Distributed Protocols for Control of the Active Topology



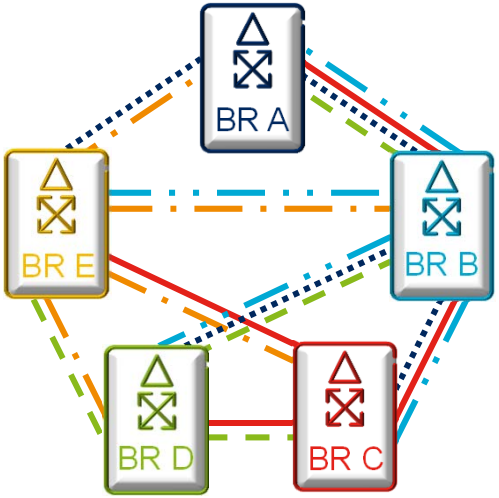
RSTP

Rapid Spanning Tree Protocol



MSTP

Multiple Spanning Tree Protocol



SPB

Shortest Path Bridging

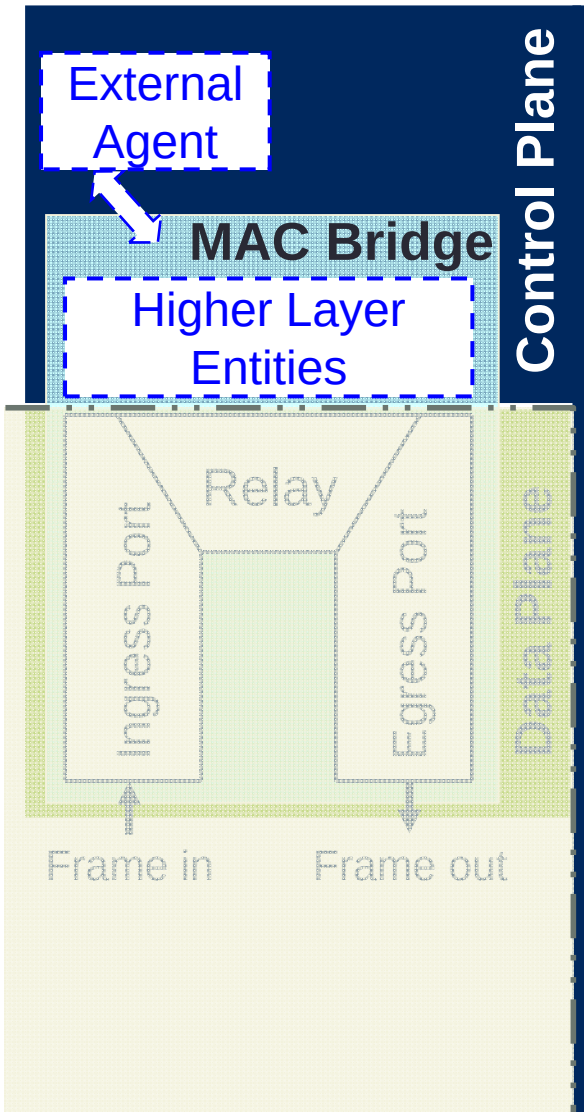
- RSTP: a single spanning tree shared by all traffic
- MSTP: different VLANs may share different spanning trees
- SPB: each node has its own **Shortest Path Tree (SPT)**
- ***We are not limited to shared spanning trees any more***

Note: the Spanning Tree Protocol (STP) is historical, it has been replaced by RSTP

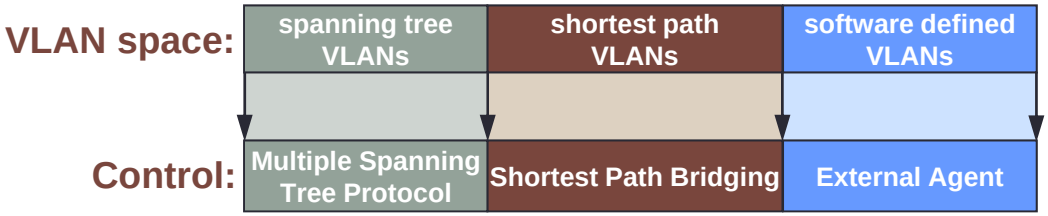
Multiple Registration Protocol (MRP)

- Flooding protocol (not unlike IS-IS or OSPF) that registers, on every bridge port, one's neighbors' ability to transmit and/or need to receive various kinds of data:
  - Multiple VLAN Registration Protocol (MVRP): Frames flooded to particular VLANs, e.g. broadcasts or unknown unicasts.
  - Multiple MAC Registration Protocol (MMRP): Multicast MAC addresses or {VLAN, MAC} pairs. *Not necessarily IP multicast.*
  - Multiple Stream Reservation Protocol (MSRP or SRP): Talkers wanting to send or Listeners wanting to receive data flows with bandwidth, latency, and congestion loss requirements.
- In some cases MRP is being supplanted by IS-IS.

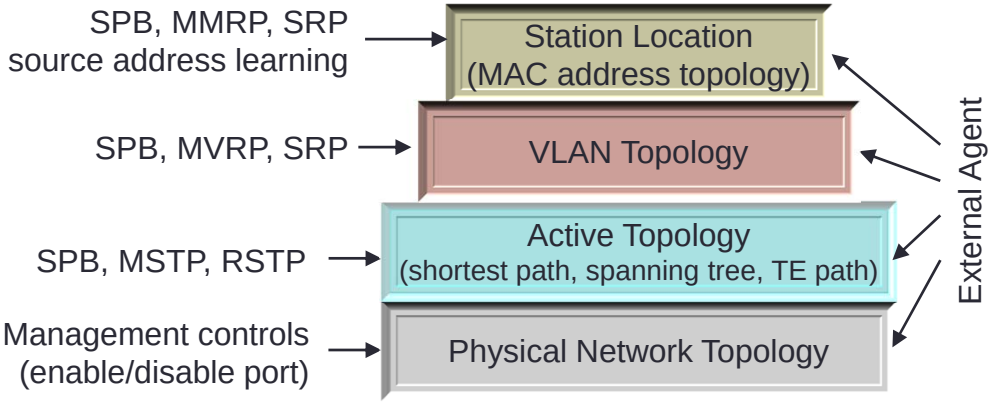
Control Plane Overview



- A VLAN is assigned to a control mode
  - Multiple control modes may co-exist in the same network
  - Hybrid control by distributed protocols and an External Agent, e.g. and SDN controller for TE paths
  - External control can be a non-802.1 protocol: PCE, GMPLS



- Summary of control options



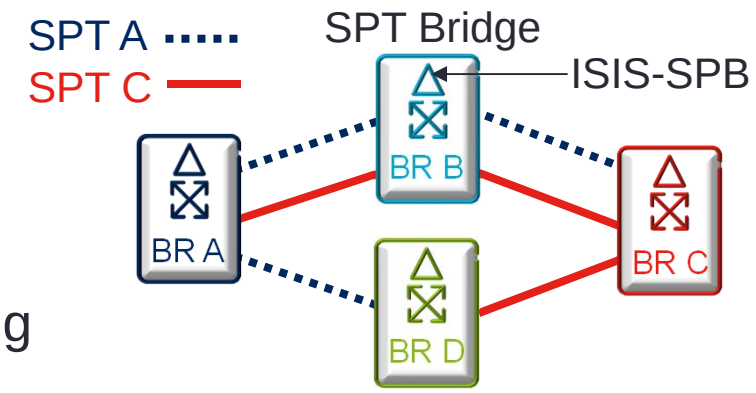
Software Defined Networking Aspects

- Software Defined Networking (SDN) principles are supported by 802.1Q
- Separation of the control plane from the data plane
  - The bridge architecture separates the control plane from the data plane (see page 13)
  - The External Agent is geographically separated
- Separate topologies per VLAN
  - Any given VLAN can be assigned to MSTP, SPB, External Agent, or any other standard- or user-defined control methodology
- Centralized controller having a view of the network
  - The External Agent can be a centralized SDN Controller
  - The bridges may run the Link Layer Discovery Protocol (LLDP) [802.1AB] for retrieval by controller
  - The bridges can run IS-IS to distribute topology, whether any VLANs are assigned to control by SPB or not
- Programmability of the network
  - Well defined objects and functionality for programming the bridges

Shortest Path Bridging (SPB)

- SPB applies a link state control protocol to MAC Bridging
  - Based on the ISO **Intermediate System to Intermediate System (IS-IS)** intra-domain routing information exchange protocol → **ISIS-SPB**
  - Leverages the automation features of link state, e.g. auto-discovery
  - Preserves the MAC Service model, e.g. delivery in-order
- ISIS-SPB operation
  - Link state data base → Identical replica at each bridge
    - Topology information
    - Properties of the bridges
    - Service information
  - Computation instead of signaling or registration protocols
    - Leverage Moore's law and technology trends
- ISIS-SPB specifications
  - IEEE 802.1aq specifies operation and backwards compatibility provisions
  - ISIS extensions for SPB (new TLVs) also documented in IETF RFC 6329

SPB Operation Modes



- A bridge only uses its own SPT for frame forwarding
  - Destination MAC + VID based forwarding allows two options to realize the SPTs

SPB has two operation modes

The implementation of the same principles to forwarding is different

- **SPBM**: SPB MAC
  - Backbone MAC identified SPTs
  - Designed to leverage the scalability provided by PBB /"MAC-in-MAC"/
  - No B-MAC flooding/learning
  - **Managed environments**

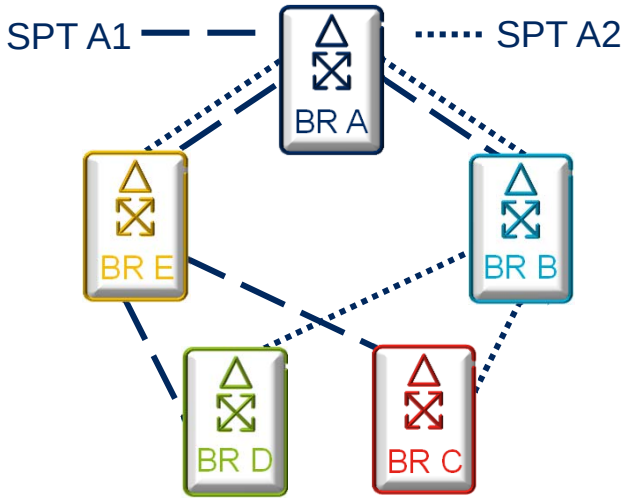
- **SPBV**: SPB VID
  - VID identified SPTs
  - Applicable to all types of VLANs
  - Flooding and learning
  - **Plug&play**

Load Spreading

- Using the shortest path automatically spreads traffic load to some extent

- Further load-spreading by exploiting equal cost paths to create multiple SPT Sets
  - Up to 16 standard tie-breaking variations to produce diverse SPTs

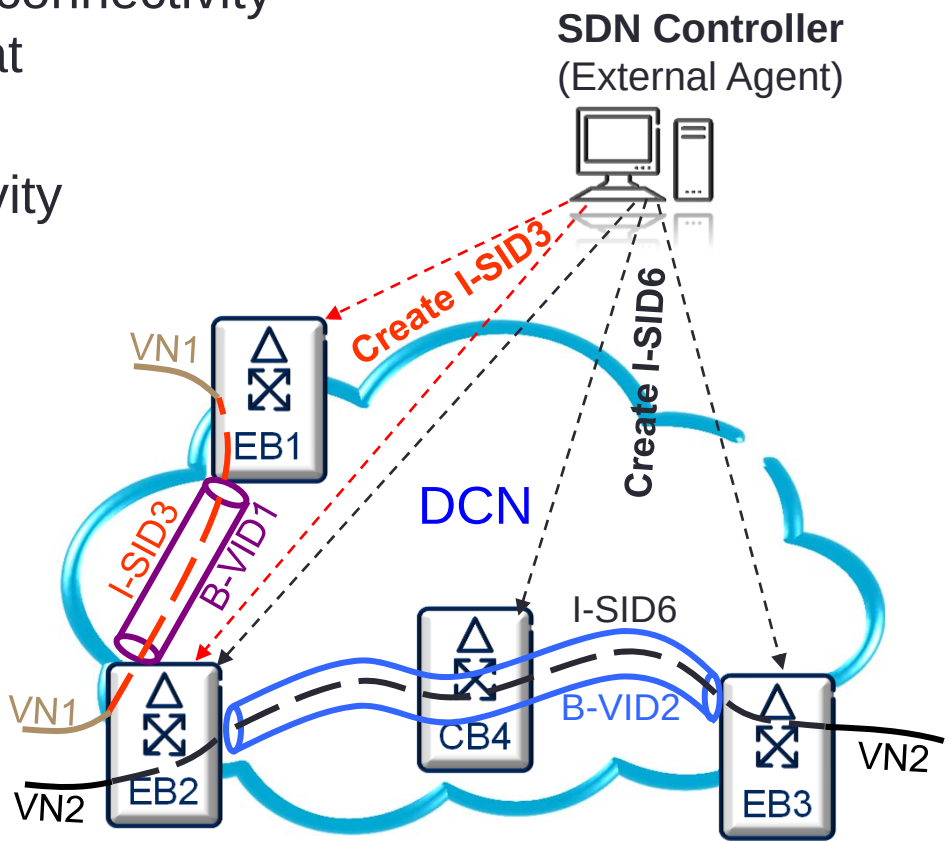
- Provisioned load spreading
  - A VLAN is assigned to an SPT Set



SPT options for Bridge A

A Use Case: A Data Center with SPB and SDN Control

- SPB and SDN fit together and complement each other
- Virtual Network (VN) 1 is supported by SPBM
  - SDN Controller instantiates the connectivity service to be provided for VN1 at the Edge Bridges (EB)
  - SPBM establishes the connectivity service thorough the Data Center Network (DCN)
- VN2 is supported by SDN
  - SDN Controller establishes the connectivity service to be provided for VN2 thorough the entire DCN



SPB Features

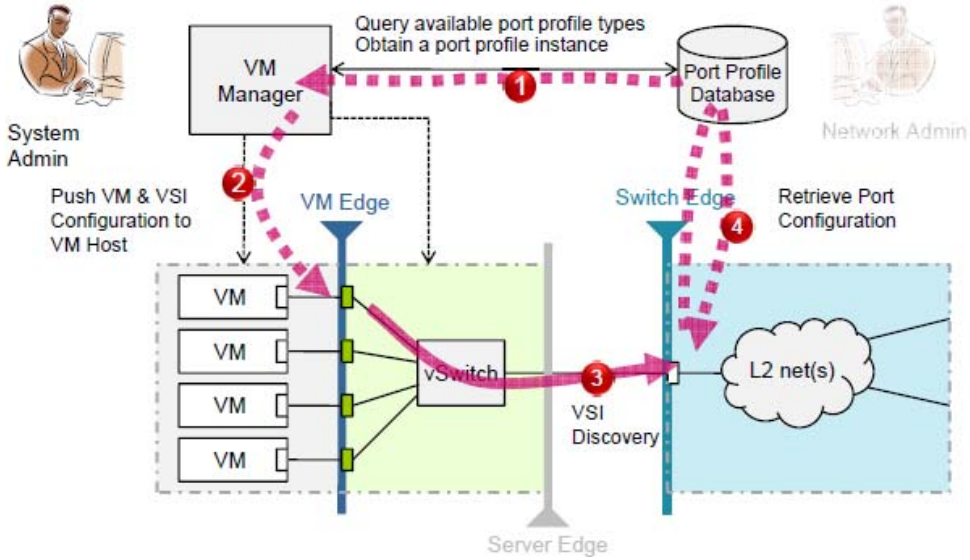
- Single link state control for large networks
- High degree of automation
- Scalability (scales as IS-IS)
- Deterministic multi-path routing for unicast and multicast
- Address learning confined to the network edge
- Fast convergence (within the range of 100 msec)
- All 802.1 standards supported, e.g.
  - Connectivity Fault Management (802.1ag CFM)
  - Edge Virtual Bridging (802.1Qbg EVB)
- Metro Ethernet Forum (MEF) services natively provided
  - E-LINE, E-TREE, E-LAN

Ongoing SPB Related Activities

- Deployments
  - Multiple vendors shipping product
  - Three interops so far: Alcatel-Lucent, Avaya, Huawei, Solana, Spirent
- Equal Cost Multiple Paths (ECMP) [802.1Qbp]
  - Per hop load balancing for unicast
  - Shared trees for multicast
  - Standardized Flow Hash → OAM enabler
  - New tag to carry Flow Hash and TTL
- Path Control and Reservation (PCR) [802.1Qca]
  - Beyond shortest path → Explicit path control
  - Leveraging link state for
    - Bandwidth and stream reservation
    - Redundancy (protection or restoration) for data flows
    - Distribution of control parameters for time synchronization and scheduling

Edge Virtual Bridging Control [802.1Qbg]

- Edge Virtual Bridge discovery and S-channel configuration
  - Link Layer Discovery Protocol (LLDP) [802.1AB]
- Virtual Machine (VM) migration
  - Virtual Station Interfaces (VSI): the network interface of a VM
  - VSI Discovery and Configuration Protocol (VDP) is used to notify an adjacent bridge of VSIs



Enhancements to Bridging of 802.11 [802.1Qbz , 802.11ak]

- Adapting an 802.11 medium to behave like a wired medium for connecting bridges.
- Each wireless point-to-point connection can be made visible to IS-IS as a point-to-point link.
- Broadcasts to multiple stations are handled as an optimization of multicasts/broadcasts of the same frame to individual point-to-point links.
- Heuristics and costs cause bridges to avoid wireless links except where required for connectivity, and to prevent network flapping.
- An Access Point is not *attached* to a bridge, it **is** a bridge.
- A non-AP station can be a bridge, as well.

Operation, Administration, and Maintenance (OAM)

Connectivity Fault Management (CFM)

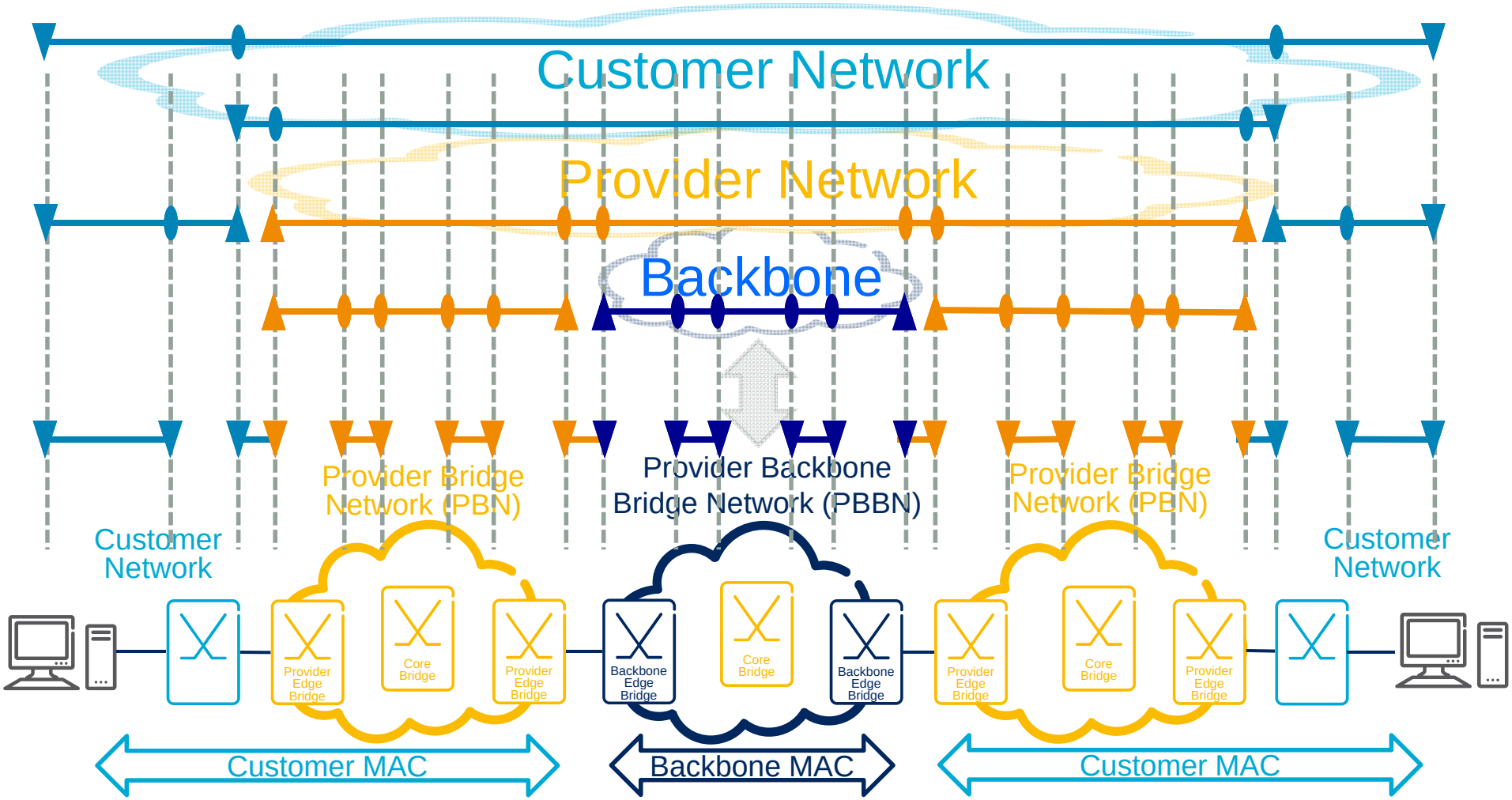
- CFM/OAM was created in parallel with ITU-T Y.1731.
- Its value lies in its architecture, which supports:
  - Protocol interactions among separate administrations with a minimum of common configuration.
  - Multiple levels of operation, with the ability both to propagate errors to higher levels, and drill down to lower levels when performing fault isolation.
  - Completely different technologies can be supported at different levels, e.g. Ethernet over pseudowires over routing over frame relay over Ethernet over optical.
  - Information hiding, to make lower levels' topology, equipment, or control protocols invisible to higher layers.

CFM Supports Drill-down

End points

Intermediate points

A pair of endpoints at a given level see only the intermediate points at that level



Continuity Check Message (CCM)

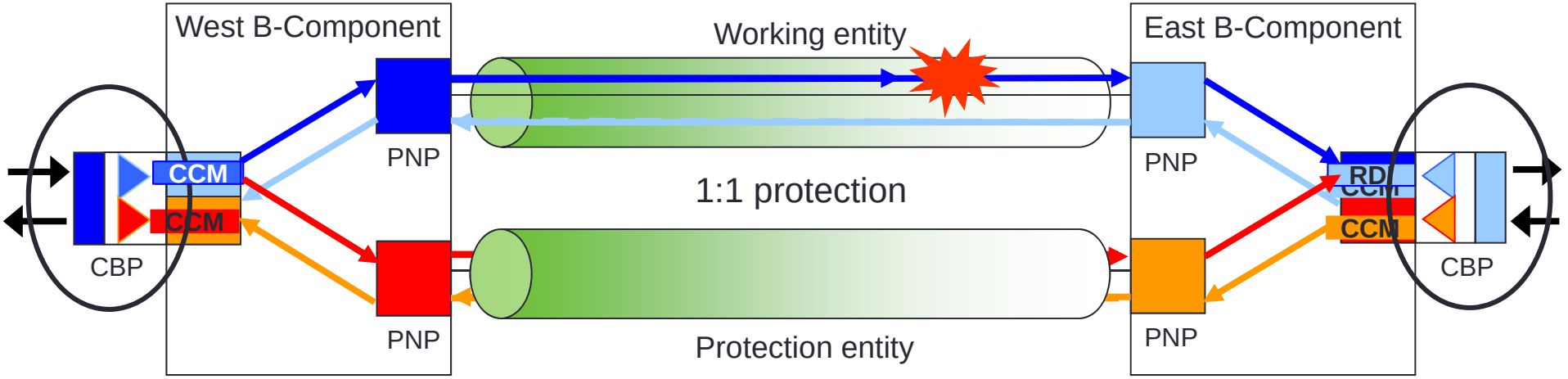
- CFM/OAM is designed from the start as a tool for multipoint services – not just point-to-point.
- Each end point:
  - Transmits regular multicast CCMs on its own level.
  - Has a list of other end points on its level from which it expects to receive CCMs.
  - Sets a ”Remote Defect Indication” (RDI) bit if it’s missing any CCMs, so that every end point is either in the ”everyone is happy” state or the ”someone is unhappy” state.
- The global circuit identifier in every CCM detects merged (cross-connected) services. Point-to-point continuity checks cannot detect merged services. Multicast messages can detect them.

Other CFM/OAM Messages

- End points / intermediate points tied to ports, not boxes
- Loopback Message and Reply (LBM, LBR)
  - Transmitted by end point, reflected by intermediate point or end point
  - Cannot be seen by higher or lower levels, confined by end points to a level
  - For debugging, not for monitoring
- Linktrace Message and Reply (LTM, LTR)
  - Within a level, finds intermediate points (if any) on the way to the end point
- ITU-T Y.1731 defines other TLVs and message types
  - For error reporting, frame loss measurement, latency measurement, and other maintenance actions

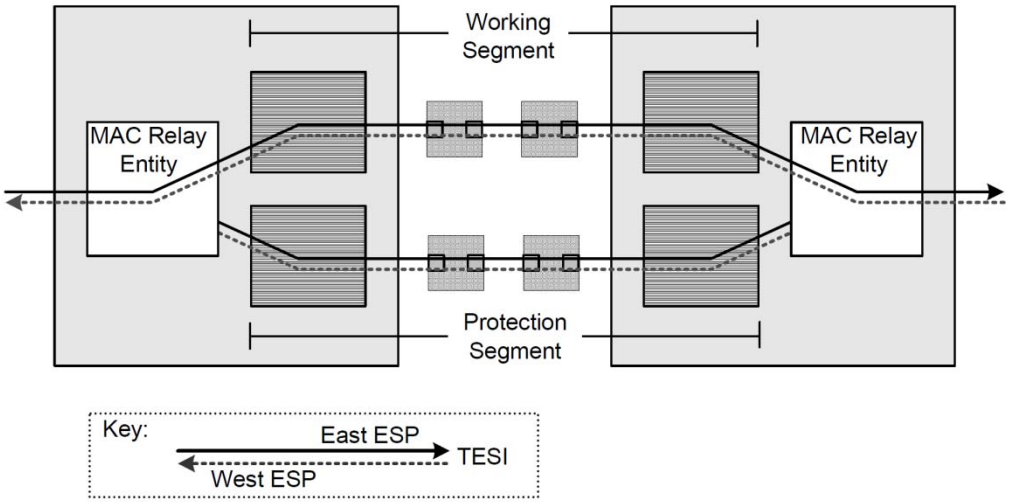
PROTECTION SWITCHING

TE Service Instance Protection Switching



- Externally controlled Bridges support end-to-end linear protection for point-to-point Traffic Engineered Service Instances (TESI), where a dedicated protection point-to-point TESI is established for one particular working point-to-point TESI, and the traffic is automatically switched from the working TESI to the protection TESI when a failure occurs on the working entity.
- The protection switching may be triggered by manual operation or by CFM information arising from, periodic monitoring of the working and protection paths, or from physical layer monitoring, such as loss of signal or other defects detected through CFM.
- The PBB-TE protection switching mechanism aims to offer the capability to switch completely (both ends) in less than 50 ms.
- Switching is achieved by changing the Backbone Service Instance table B-VID entries on the Customer Backbone Ports associated with the TESI Maintenance End Points (MEP).

Infrastructure Segment Protection [8021.Qbf]



- Externally controlled Provider Bridges can support localized protection of selected traffic engineered services traversing a common sequence of Provider Bridges, which is called Infrastructure Segment.
- The 1:1 Infrastructure Protection Switching (IPS) is based on the TESI protection switching state machines
- In addition, M:1 IPS provided
- IPS may be triggered automatically by a change in the operational state of an Infrastructure Segment or manually by administrative command.

MANAGEMENT

802.1Q Management

- Clause 12 Managed Objects (Information Model)
  - Structured text description, evolving to structured tabular summary
- Clause 17 SMIv2 MIBs (Data Model)
  - IETF style preamble (structure, security, relationships)
  - 10+ MIB modules – per technology
  - Traps (Notifications) only specified for CFM & PBB-TE
  - Limited counters
  - Based on original IETF BRIDGEMIB work
    - RFC 4663, “Transferring MIB Work from IETF Bridge MIB WG to IEEE 802.1 WG”
  - Use of ifMIB

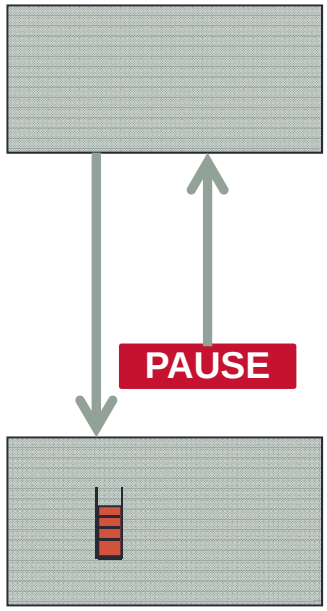
QUALITY OF SERVICE

Enhanced Transmission Selection (ETS) [802.1Qaz]

- Provides for allocation of link bandwidth to traffic classes
  - Proprietary weighted round robin features were already common
  - ETS provides a uniform way to manage the distribution.
- Coexists with strict priority and credit-based shaper traffic classes
  - Strict priority and credit-based shaper traffic goes first
  - ETS distributes remaining bandwidth
- Data Center Bridging eXchange Protocol (DCBX - also in 802.1Qaz) uses LLDP to share ETS and PFC configuration with link partner
  - An end system may use that information to adapt configuration to match the network

Priority-based Flow Control (PFC) [802.1Qbb]

- Prevents congestion drop for protocols designed for flow controlled networks (e.g. Fiber Channel over Ethernet)
  - Priorities are individually configured with PFC
  - Traffic in other priorities not affected
- Operates across a single hop
- PFC Pause Frame is sent to pause transmission for a time duration when receive buffer reaches high water mark. Sending with zero time value releases the pause.

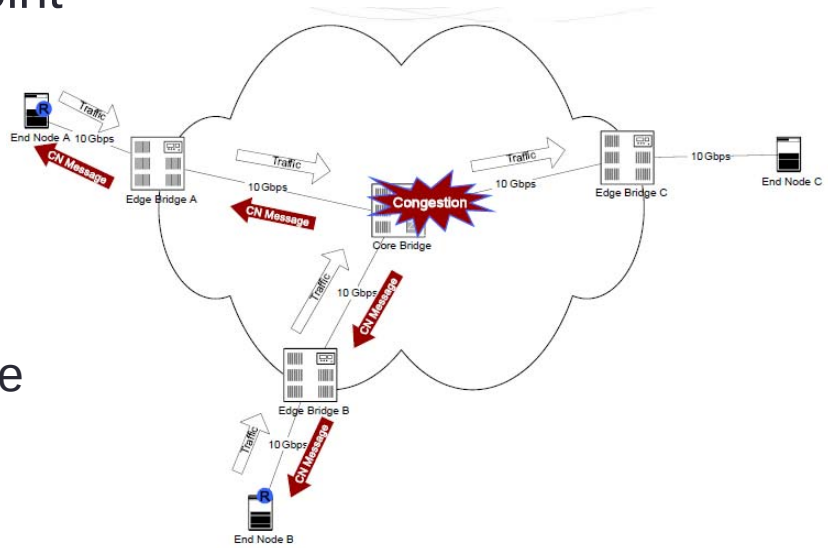


Buffer reaches high water mark

Pause is sent

Congestion Notification (CN)

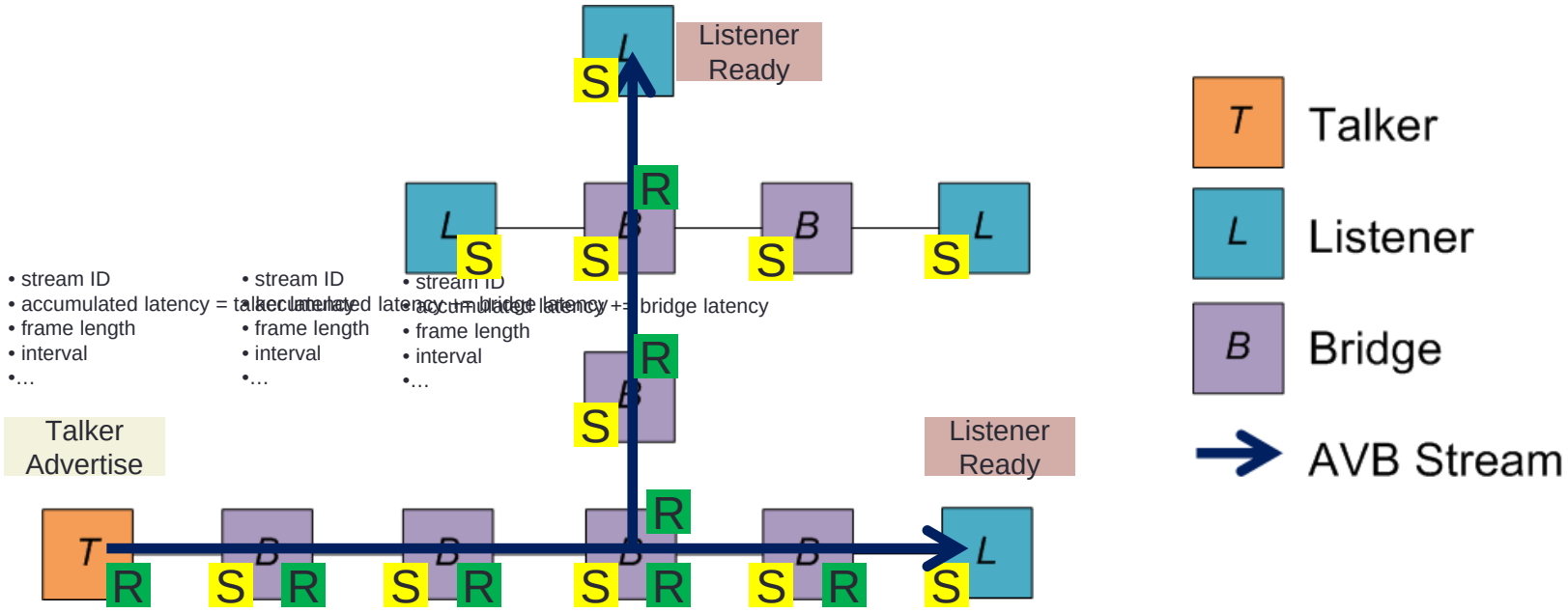
- CN is applied to traffic in a CN priority
- Works in a CN cloud where all devices support CN
- Can be used in conjunction with PFC
  - PFC provides fast reaction
  - CN slows sources on a longer time scale (~ 10 ms for bandwidth delay product of 5 Mbit)
- CN message sent from congestion point to source MAC address of sampled frame
  - Quantized feedback 1 to 31 indicates severity of congestion
  - Up to 64 bytes of the beginning of the sampled frame included in CN message



Stream Reservation

- The Stream Reservation Protocol (SRP):
  - Advertises streams in the whole network
  - Registers the path of streams
  - Calculates the “worst case latency”
  - Specifies the forwarding rules for AVB streams
  - Establishes an AVB domain
  - Reserves the bandwidth for AVB streams
  - An MRP Application
- Especially the bandwidth reservation is important in order to:
  - Protect the best effort traffic, as only 75% of the bandwidth can be reserved for SR class traffic
  - Protect the SR class traffic as it is not possible to use more bandwidth for SR class traffic than 75% (this is an important factor in order to guarantee a certain latency)

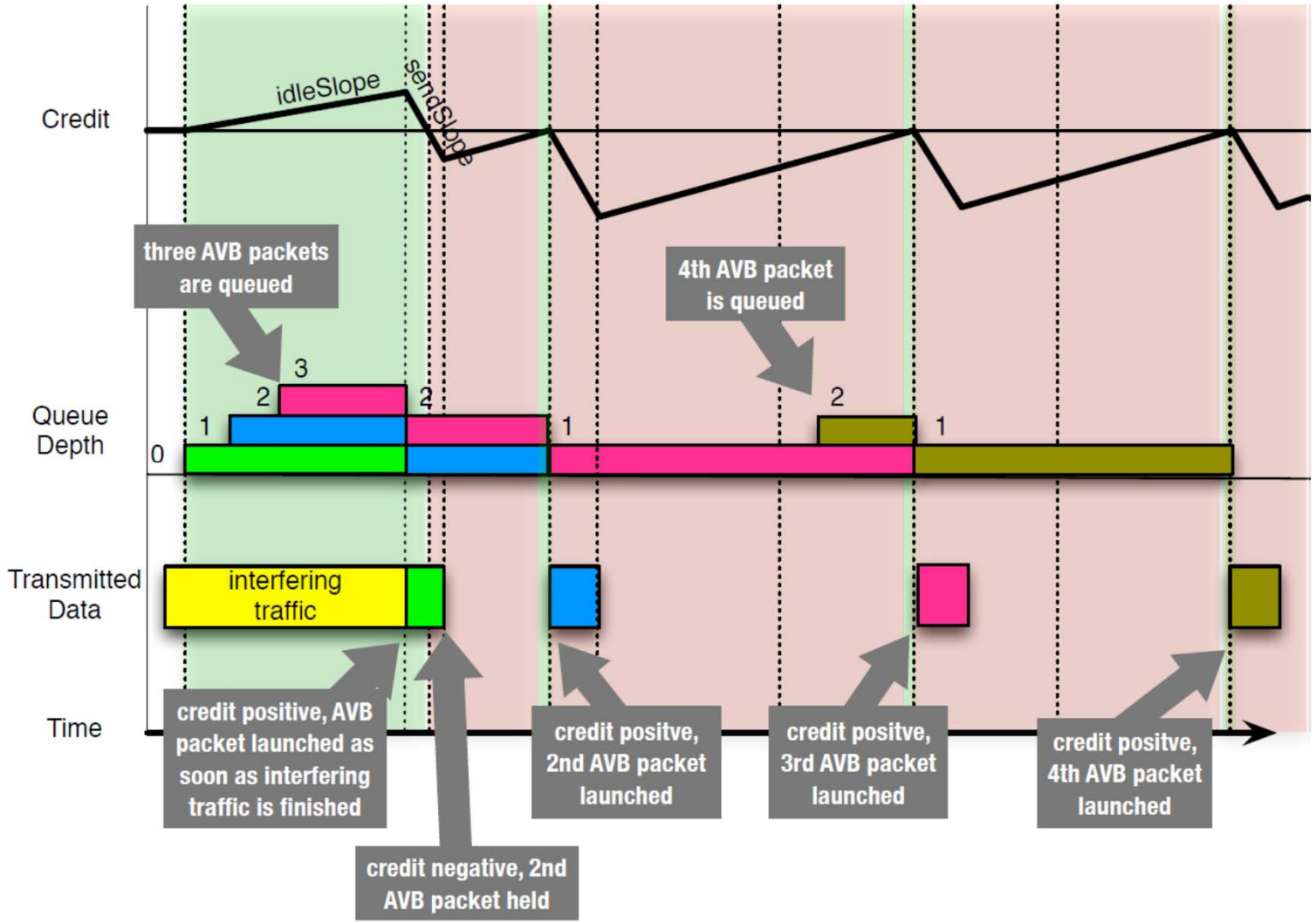
Stream Reservation Example



Traffic Shaping

- As audio/video streams require a high bandwidth utilization, it was necessary to set the maximum available bandwidth for this new traffic class quite high (75%)
- The Credit Based Shaper (CBS) spaces out the frames as much as possible in order to reduce bursting and bunching, thus
  - Protects the best effort traffic as the maximum interference (AVB stream burst) for the highest non-AVB priority is limited and known
  - Protects the AVB streams, as it limits the back to back AVB stream bursts which can interfere in a bridge
- The Credit Based Shaper in combination with the Stream Reservation Protocol is intended to provide delays under 250 us per bridge.

Credit Based Shaper Example



Preemption and Time Scheduled Queuing

- The credit based shaper works well for audio/video applications, but is not suitable for control applications where worst case delays must be reduced to a minimum.
- Time-aware (scheduled) queuing combined with preemption reduces delays to near the best theoretical levels, with the minimum impact on non-scheduled traffic.
  - SRP or a management agent is required to provide an admission control scheme to limit low-latency traffic to the amount that can be supported by the links in the path between a talker and corresponding listener(s)

Policing

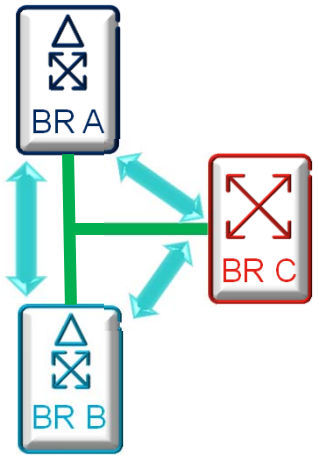
- Every frame can be marked “green” or “yellow” using the Drop Eligible bit available for S-tags and B-tags, or a priority code point in C-tags.
- Policing is done per input port, but only after it is determined that a frame can be delivered to some port. Frames that are dropped by the forwarding mechanism are not policed.
- Policing is two-color in (green or yellow) and three-color out (green, yellow, or red). Red are dropped. Yellow frames have a higher probability of being discarded than green frames.
- Policing algorithm is from Metro Ether Forum spec 10.2.

Other 802.1 Standards not Covered by This Tutorial

Link Aggregation [802.1AX-REV]

- Revision in progress
- Includes Distributed Resilient Network Interconnect (DRNI)
- No longer tied to 802.3 – works over any real or virtual medium
- Supports one, two or three systems at each end of the aggregation
- Connects two networks so that neither network is aware of the details of the interconnect
- Failures do not propagate from network to network
- Systems can be bridges, routers, end stations, or anything else
- Backwards compatible with existing Link Aggregation
- Allows systems to negotiate which data streams take which path, so that bi-directionally congruent flows are possible, and so that extensive state synchronization (e.g., of forwarding tables) is not necessary among systems
- Supports any means of identifying streams: VLANs, 5-tuples, etc.

Link Layer Discovery Protocol (LLDP) [802.1AB]



- LLDP is a link layer protocol used by network devices for advertising their identity, capabilities, and neighbors on an IEEE 802 local area network, principally wired Ethernet.
- Information Exchanged is in the form of TLVs and includes mandatory and *optional* information such as:
  - System name and description
  - Port name and description
  - IP management address
  - *VLAN name*
  - *System capabilities (switching, routing, etc.)*
  - *MAC/PHY information*
  - *MDI power*
  - *Link aggregation*
- LLDP is extensible and has been extended for DCB networks (e.g. VDP and DCBX).
- LLDP MIB is a continuation of the IETF work on Physical Topology MIB [RFC 2922]

Time Synchronization [802.1AS]

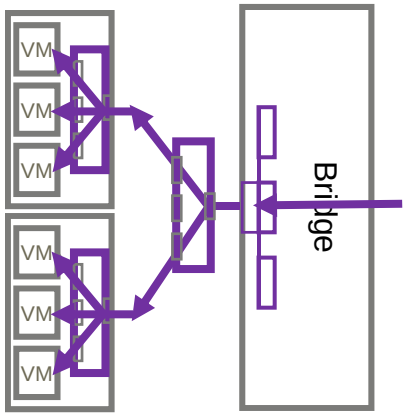
- Specifies distribution of precise timing
- Includes an IEEE 1588 Precision Time Protocol (PTP) profile that specifies timing transport over full-duplex IEEE 802.3 links
  - The interfaces are either a simplified, tightly controlled boundary clocks or ordinary clocks
- Also specifies transport over other media not covered in IETF 1588
  - IEEE 802.11 WiFi
  - IEEE 802.3 Ethernet Passive Optical Network (EPON)
  - Coordinated Shared Network (CSN) – e.g. MoCA, ITU-T G.9960/G.9961

Audio Video Bridging Systems [802.1BA]

- Provides profiles building networks to transport time-sensitive audio and/or video data streams
- Profiles cover features, options and configurations needed to meet latency targets

Bridge Port Extension [802.1BR]

- Extended Bridge is formed by a Controlling Bridge plus attached Port Extenders
  - Each port of a Port Extender is a virtual port of the Controlling Bridge
  - All traffic is relayed by the Controlling Bridge
  - Externally (including to network management, the Extended Bridge is a Bridge
  - A Port Extender may be in an end system
  - Port Extenders may be cascaded
  - Multicast replication allows a frame to be replicated to selected ports by the Port Extenders



Security

- Port-based Network Access Control [802.1X]
  - Defines encapsulation of Extensible Authentication Protocol (EAP) over IEEE 802 (EAP over LAN, or EAPOL).
  - Widely deployed on both wired and Wi-Fi networks
- MAC Security (MACsec) [802.1AE]
  - MACsec secures a link not a conversation
  - MACsec counters 802.1X man-in-the-middle attacks
- Secure Device Identity [802.1AR]
  - Supports trail of trust from manufacturer to user
  - Defines how a Secure Device Identifier may be cryptographically bound to a device to support device identity authentication.

SUMMARY

Summary

- MAC bridging is both a long standing and an evolving technology
- Continuing coordination is necessary between IETF and 802.1
  - MAC bridging and IP technology are intertwined
  - The organizations now have leadership meetings
  - Can only be based on an up-to-date understanding on what is going on in both groups
  - For example QoS
    - QoS is about picking the next packet to be sent out of the box whether the box is a L2 or L3 device
- 802.1 has always been open for collaboration
  - 802.1 is an open SDO
  - Regular meetings: http://www.ieee802.org/1/meetings
  - Get IEEE standards: https://standards.ieee.org/about/get/index.html
  - IEEE standards store: http://www.techstreet.com/ieeegate.html
  - Access to “802.1 private area“ is free. Access control is for ongoing work and prepublication standards. Ask 802.1 people!

Acknowledgements

- The authors would like to thank David Allan, Christian Boiger, Nigel Bragg, and Dan Romascanu for their review and contribution.

REFERENCES

IEEE 802.1 Standards – Interworking

- **IEEE 802.1AB-2009**, “IEEE standard for local and metropolitan area networks: Station and media access control connectivity discovery,” September 2009. http://standards.ieee.org/getieee802/download/802.1AB-2009.pdf
- **IEEE 802.1AX-2008**, “IEEE standard for local and metropolitan area networks: Link aggregation,” November 2008. http://standards.ieee.org/getieee802/download/802.1AX-2008.pdf
- **IEEE 802.1D-2004**, ”IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges,” June 2004. http://standards.ieee.org/getieee802/download/802.1D-2004.pdf
- **IEEE 802.1H-1997**, “IEEE technical report and guidelines - Part 5: Media access control (MAC) bridging of Ethernet V2.0 in local area networks,” May 2002, http://standards.ieee.org/getieee802/download/802.1H-1997.pdf
- **IEEE 802.1Q-2011**, ”IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks,” August 2011. http://standards.ieee.org/getieee802/download/802.1Q-2011.pdf
- **IEEE 802.1aq-2012**, “IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 20: Shortest path bridging,” June 2012. http://standards.ieee.org/getieee802/download/802.1aq-2012.pdf
- **IEEE 802.1Qbc-2011**, “IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 16: Provider bridging: Remote customer service interfaces,” September 2011. http://standards.ieee.org/getieee802/download/802.1Qbc-2011.pdf
- **IEEE 802.1Qbe-2011**, “IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 15: Multiple I-SID registration protocol,” September 2011. http://standards.ieee.org/getieee802/download/802.1Qbe-2011.pdf
- **IEEE 802.1Qbf-2011**, “IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 19: PBB-TE infrastructure segment protection,” December 2011. http://standards.ieee.org/getieee802/download/802.1Qbf-2011.pdf

- Note that 802.1Q-2011 incorporates amendments 802.1ad-2005, 802.1ak-2007, 802.1ag-2007, 802.1ah-2008, 802-1Q-2005/Cor-1-2008, 802.1ap-2008, 802.1Qaw-2009, 802.1Qay-2009, 802.1aj-2009, 802.1Qav-2009, 802.1Qau-2010, and 802.1Qat-2010.

IEEE 802.1 Standards – Time-Sensitive Networking

- **IEEE 802.1AS-2011**, "IEEE standard for local and metropolitan area networks: Timing and synchronization for time-sensitive applications in bridged local area networks," March 2011. http://standards.ieee.org/getieee802/download/802.1AS-2011.pdf
- **IEEE 802.1BA-2011**, "IEEE standard for local and metropolitan area networks: Audio video bridging systems," 2011. http://standards.ieee.org/findstds/standard/802.1BA-2011.html
- Note that 802.1Q-2011 incorporates TSN amendments
  - 802.1Qat-2010, "IEEE standard for local and metropolitan area networks: Virtual bridged local area networks – Amendment 14: Stream reservation protocol (SRP)"
  - 802.1Qav-2009, "IEEE standard for local and metropolitan area networks: Virtual bridged local area networks – Amendment 12: Forwarding and queuing enhancements for time-sensitive streams"

IEEE 802.1 Standards – Data Center Bridging

- **IEEE 802.1BR-2012**, "IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks: Bridge port extension," 2012. http://standards.ieee.org/getieee802/download/802.1BR-2012.pdf
- **IEEE 802.1Qaz-2011**, "IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 18: Enhanced transmission selection for bandwidth sharing between traffic classes," September 2001. http://standards.ieee.org/getieee802/download/802.1Qaz-2011.pdf
- **IEEE 802.1Qbb-2011**, "IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 17: Priority-based flow control," September 2011. http://standards.ieee.org/getieee802/download/802.1Qbb-2011.pdf
- **IEEE 802.1Qbg-2012**, "IEEE standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment 21: Edge virtual bridging," 2012. http://standards.ieee.org/getieee802/download/802.1Qbg-2012.pdf
- Note that 802.1Q-2011 incorporates 802.1Qau-2010, "IEEE standard for local and metropolitan area networks: Virtual bridged local area networks – Amendment 13: Congestion notification,"

IEEE 802.1 Standards – Security

- **IEEE 802.1AE-2006**, “IEEE standard for local and metropolitan area networks: Media access control (MAC) security,” August 2006. http://standards.ieee.org/getieee802/download/802.1AE-2006.pdf
- **IEEE 802.1AEbn-2011**, “IEEE standard for local and metropolitan area networks: Media access control (MAC) security amendment 1: Galois counter code - Advanced encryption standard - 256 (GCM-AES-256) cipher suite,” October 2011. http://standards.ieee.org/getieee802/download/802.1AEbn-2011.pdf
- **IEEE 802.1AR-2009**, “IEEE standard for local and metropolitan area networks: Secure device identity,” December 2009. http://standards.ieee.org/getieee802/download/802.1AR.-2009.pdf
- **IEEE 802.1X-2010**, “IEEE standard for local and metropolitan area networks: Port-based network access control,” February 2010. http://standards.ieee.org/getieee802/download/802.1X-2010.pdf

Ongoing IEEE 802.1 Projects

- Interworking
  - **P802-REV**, “Draft standard for local and metropolitan area networks: **Overview & architecture**,” Revision, http://www.ieee802.org/1/pages/802-rev.html
  - **P802.1AX-REV**, “Draft standard for local and metropolitan area networks: **Link aggregation**,” Revision incorporating **Distributed Resilient Network Interconnect (DRNI)**, http://www.ieee802.org/1/pages/802.1AX-rev.html
  - **P802.1Qbp**, “Draft standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment: **Equal cost multiple paths (ECMP)**,” http://www.ieee802.org/1/pages/802.1bp.html
  - **P802.1Qbz**, “Draft standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment: **Enhancements to Bridging of 802.11**,” http://www.ieee802.org/1/pages/802.1bz.html
  - **P802.1Qca**, “Draft standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment: **Path control and reservation**,” http://www.ieee802.org/1/pages/802.1ca.html
  - **P802.1Q-REV**, “Draft standard for local and metropolitan area networks: **Media access control (MAC) bridges and virtual bridged local area networks**,” Revision, http://www.ieee802.org/1/pages/802.1Q-2013.html
- Time-Sensitive Networking
  - **P802.1ASbt**, “Draft standard for local and metropolitan area networks: Timing and synchronization: **Enhancements and performance improvements**,” http://www.ieee802.org/1/pages/802.1asbt.html
  - **P802.1Qbv**, “Draft standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment: **Enhancements for scheduled traffic**,” http://www.ieee802.org/1/pages/802.1bv.html
  - **P802.1Qbu**, “Draft standard for local and metropolitan area networks: Media access control (MAC) bridges and virtual bridged local area networks – Amendment: **Frame preemption**,” http://www.ieee802.org/1/pages/802.1bu.html
- Security
  - **P802.1AEbw**, “Draft standard for local and metropolitan area networks: Media access control (MAC) security – Amendment 2: **Extended packet numbering**,” http://www.ieee802.org/1/pages/802.1aebw.html
  - **P802.1Xbx**, “Draft standard for local and metropolitan area networks: Port-based network access control – Amendment 1: **MAC security key agreement protocol (MKA) extensions**,” http://www.ieee802.org/1/pages/802.1xbx.html

- Note that access to “802.1 private area“ is free. Access control is for ongoing work and prepublication standards. Ask 802.1 people!

Further Reading

- Book
  - D. Allan and N. Bragg, “802.1aq shortest path bridging design and evolution: The architect's perspective,” *John Wiley & Sons*, January 2012. http://onlinelibrary.wiley.com/book/10.1002/9781118164327
- Papers
  - M. D. Johas Teener, P. Klein, A. N. Fredette, C. Gunther, D. Olsen, C. Boiger, and K. Stanton, “Heterogeneous networks for audio and video – Using IEEE 802.1 audio video bridging,” Proceedings of the IEEE – Special issue on smart home, May 2013. http://ieeexplore.ieee.org/servlet/opac?punumber=5, http://ieee802.org/1/files/public/docs2013/avb-mjt-et-all-AVB-for-IEEE-Smart-Home-0213.pdf
  - D. Allan, J. Farkas, and S. Mansfield, “Intelligent load balancing for shortest path bridging,” *IEEE Communications Magazine*, July 2012. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6231293
  - D. Allan, P. Ashwood-Smith, N. Bragg, J. Farkas, D. Fedyk, M. Ouellete, M. Seaman, and P. Unbehagen, ”Shortest path bridging: Efficient control of larger Ethernet networks,” *IEEE Communications Magazine*, October 2010. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=5594687
  - D. Allan, P. Ashwood-Smith, N. Bragg, and D. Fedyk, “Provider link state bridging,” *IEEE Communications Magazine*, September 2008. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4623715
  - M. Alizadeh, A. Kabbani, B. Atikoglu, and B. Prabhakar, "Stability Analysis of QCN: The Averaging Principle," *Proceedings of the ACM Special Interest Group on Computer Systems Performance, SIGMETRICS 2011,* 2011. http://www.stanford.edu/~balaji/papers/11stabilityanalysis.pdf
  - M. Alizadeh, B. Atikoglu, A. Kabbani, A. Laksmikantha, R. Pan, B. Prabhakar, and M. Seaman, “Data center transport mechanisms: congestion control theory and IEEE standardization,” *Proceedings of the 46th Annual Allerton Conference on Communications, Control and Computing*, September 2008. http://www.stanford.edu/~balaji/papers/QCN.pdf
- Tutorial
  - Deterministic Ethernet – IEEE 802.1 standards for real-time process control, industrial automation, and vehicular networks, http://www.ieee802.org/802_tutorials/2012-11/8021-tutorial-final-v4.pdf
- Wikipedia
  - Time-Sensitive Networking: http://en.wikipedia.org/wiki/Audio_Video_Bridging
  - Shortest Path Bridging: http://en.wikipedia.org/wiki/IEEE_802.1aq

ABBREVIATIONS

ACM	Association for Computing Machinery
AVB	Audio Video Bridging
AP	Access Point
BCB	Backbone Core Bridge
BEB	Backbone Edge Bridge
B-MAC	Backbone MAC
BMCA	Best Master Clock Algorithm
B-VID	Backbone VLAN ID
B-VLAN	Backbone VLAN
CCM	Continuity Check Message
CBS	Credit Based Shaper
CM	Clock Master
CS	Clock Slave
C-MAC	Customer MAC
C-TAG	Customer TAG
C-VID	Customer VLAN ID
C-VLAN	Customer VLAN
CFM	Connectivity Fault Management
DA	Destination Address
DCB	Data Center Bridging
DCBX	Data Center Bridging eXchange
DCN	Data Center Network
DRNI	Distributed Resilient Network Interconnect
EB	Edge Bridge
ECMP	Equal Cost Multiple Paths
E-LINE	Ethernet Line (point-to-point) service
E-LAN	Ethernet LAN (multipoint) service
E-TREE	Ethernet Tree (rooted multipoint) service
EVB	Edge Virtual Bridging
FDDI	Fiber Distributed Data Interface
GM	Grand Master
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IPS	Infrastructure Protection Switching
IP	Internet Protocol
I-SID	Backbone Service Instance Identifier
IS-IS	Intermediate System to Intermediate System
ISIS-SPB	IS-IS for SPBV and SPBM
ISO	International Organization for Standardization
I-tag	Backbone Service Instance TAG
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
IWK	Interworking
LAN	Local Area Network
MAC	Media Access Control
LBM	Loopback Message
LBR	Loopback Reply
LLDP	Link Layer Discovery Protocol
LTM	Linktrace Message
LTR	Linktrace Reply
MAC-in-MAC	used for PBB
MAN	Metro Area Network
MEF	Metro Ethernet Forum

MEP	Maintenance association End Point
MIB	Management Information Base
MIP	Maintenance domain Intermediate Point
MoCA	Multimedia over Coax Alliance
MKA	MAC Security Key Agreement Protocol
MMRP	Multiple MAC registration Protocol
MRP	Multiple Registration Protocol
MSRP	Multiple Stream registration Protocol
MSTP	Multiple Spanning Tree Protocol
MVRP	Multiple VLAN Registration Protocol
OAM	Operations, Administration and Maintenance
PAR	Project Authorization Request
PB	Provider Bridge
PBB	Provider Backbone Bridge
PBB-TE	Provider Backbone Bridging - Traffic Engineering
PCR	Path Control and Reservation
PE	Provider Edge
PFC	Priority Flow Control
PTP	Precision Time Protocol
Q-in-Q	used for PB
QCN	Quantized Congestion Notification
QoS	Quality of Service
SDH	Synchronous Digital Hierarchy
S-VID	Service VLAN ID
S-VLAN	Service VLAN
SPB	Shortest Path Bridging
SPBM	Shortest Path Bridging MAC
RDI	Remote Defect Indication
RFC	Request For Comments
RSTP	Rapid Spanning Tree Protocol
SDN	Software Defined Network
SONET	Synchronous Optical Networking
SPBV	Shortest Path Bridging VID
SPT	Shortest Path Tree
SR	Stream Reservation
SRP	Stream Reservation Protocol
S-tag	Service TAG
S-VLAN	Service VLAN
STP	Spanning Tree Protocol
TESI	Traffic Engineering Service Instance
TSN	Time-Sensitive Networking
TTL	Time to Live
TLV	Type, Length, Value
VDP	VSI Discovery and Configuration Protocol
VID	VLAN Identifier
VLAN	Virtual LAN
VM	Virtual Machine
VN	Virtual Network
VoIP	Voice over IP
VSI	Virtual Service Instance