Advanced Computer Networks

Interconnection Layer 2: bridges and VLANs

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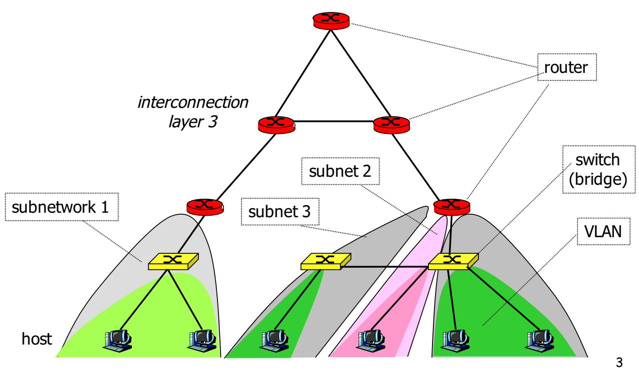
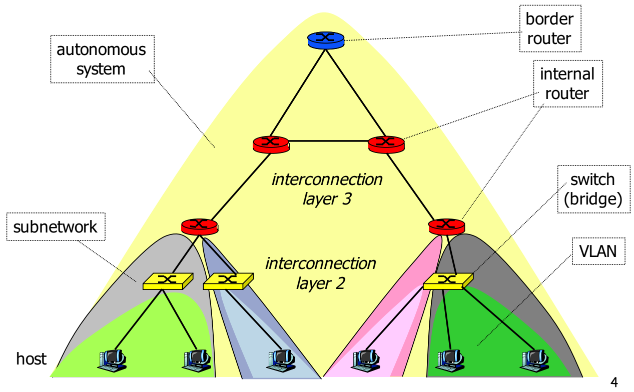
Contents

- Transparent bridges
- Spanning Tree Protocol (STP)
- Rapid Spanning Tree Protocol (RSTP)
- VLANs

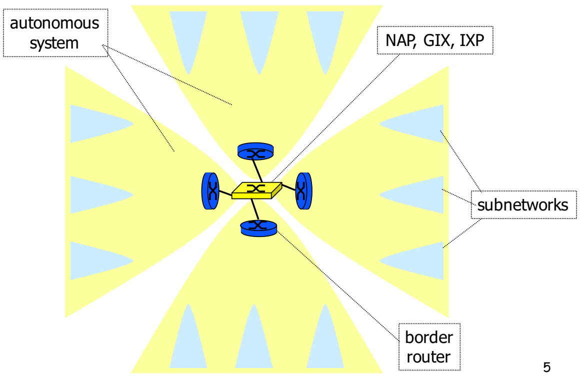
Interconnection structure



Autonomous systems



Internet



Interconnection of AS

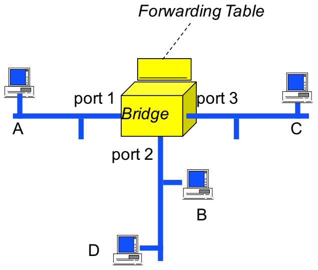
- Border routers
  - interconnect AS
- NAP or GIX, or IXP
  - exchange of traffic - peering
- Route construction
  - based on the path through a series of AS
  - based on administrative policies
  - routing tables: aggregation of entries
  - works if no loops and at least one route - routing protocols (EGP - External Routing Protocols)

Transparent Bridging (TB)

- Bridges are intermediate systems that forward MAC frames to destinations based on MAC addresses
- Interconnect systems beyond one LAN segment, keeping main characteristics of LAN
  - without additional addresses
    - MAC addresses used to identify end systems
- End systems ignore that there are transparent bridges
  - bridge is transparent
  - MAC frames not changed by bridges
  - frames not sent *to* bridge, but rather: bridge is promiscuous
    - listens to all frames and retransmits if needed

Transparent Bridging (TB)

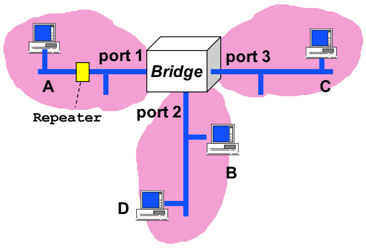
- Administrator creates the forwarding table
- TB operation
  - connectionless forwarding, unstructured addresses



Forwarding Table

Dest MAC addr	Port Nb
A	1
B	2
C	3
D	2

LB: Learning Bridge



Forwarding Table

Dest MAC addr	Port Nb

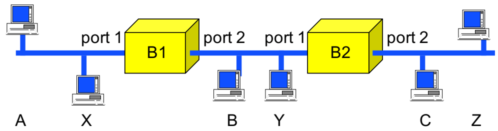
Forwarding Table

Dest MAC addr	Port Nb
A	1
B	2
C	3
D	2

- Bridge builds forwarding table by reading all traffic
  - bridges are plug and play: no address configuration (no IP address needed)
  - table built by **learning** from SA field in MAC frame
  - a table entry has limited life (`MaxLife`, 5 minutes)
- Flooding if destination address unknown or group address

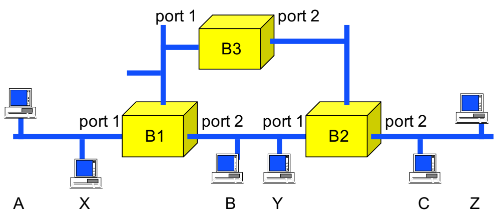
Several Learning Bridges

- Can the learning bridge be extended to a network of bridges?
- How does B2 see the network?



Loops

- What happens when A sends a frame to B?
  - assume empty forwarding table



Loop-Free topology

- Learning bridge works well on Loop-Free topology only
  - Bidirectional graph: node = bridge, edge = connection through LAN
  - Loop free - bidirectional graph = bidirectional tree
    - examples: line, star
  - On a tree, there is only one path from A to B

Spanning Tree Bridges

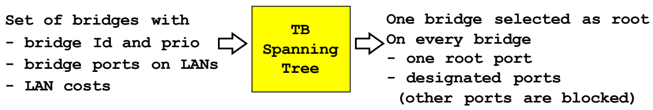
- Based on learning bridge:
  - table driven forwarding, flooding if unknown DA or multicast, learning
- Forces topology to a tree
  - Spanning Tree algorithm run by all bridges
  - Some ports blocked to prevent loops
    - ports that are allowed to forward frames (in either way) are said to be "in the forwarding state" or called "forwarding ports"
- Interconnection of bridges
  - several parallel paths for reliability
  - Spanning Tree algorithm chooses one path at a given instant

Forwarding Method

Individual PDU forwarding	`Copy all frames on all forwarding ports`
	`Frame received on port i ->`
	`/* port i is forwarding */`
	`If DA is unicast, is in forwarding table with port j and j is a forwarding port then copy to port j else flood all forwarding ports i`
	`Update forwarding table with (i, SA)`

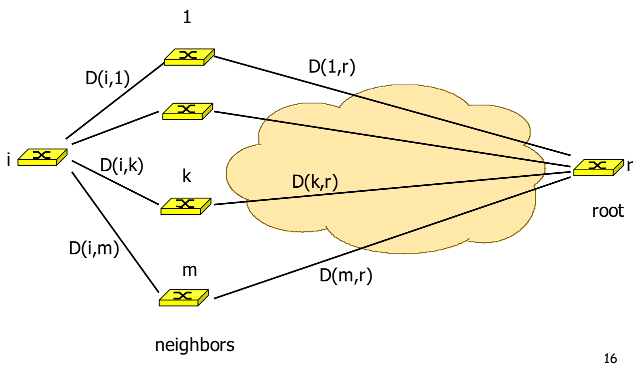
Control method	`Maintain spanning tree and port states` `Learn addresses on reading traffic`

TB Spanning Tree Specification



- Bridges viewed as a bidirectional graph (nodes = bridges)
- Selection of the root bridge
  - lowest priority with lowest identifier
- Spanning Tree = shortest path tree from root to all bridges
  - edge costs set by management, high cost = less traffic
  - based on distributed Bellman-Ford (distance vector)
    - cost_to_root = best_announced_cost + local_cost

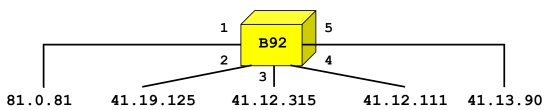
Bellman-Ford algorithm



Spanning Tree Specification

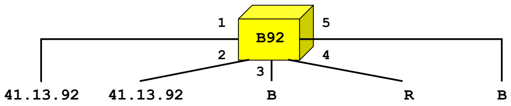
- **Root** port on one bridge = port towards root, shortest path
  - in case of equal costs, lowest id chosen
- Designated bridge
  - one per LAN
  - it has the shortest path to root via root port
- **Designated** ports
  - all ports for which the bridge is designated
  - connect LANs to the spanning tree
- Ports other than root or designated are **blocked**
- Configuration messages
  - `rootId.cost_to_root.senderId.port (41.13.92.3)`
  - `simplified: rootId.cost_to_root.senderId`

Spanning Tree example



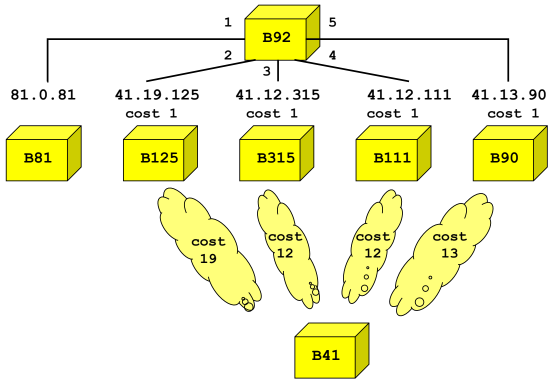
- Best root: `41`
- Best cost: `12 + 1 = 13`, on port 3 or `4 (cost=1)`
- **Root port**: `4`, because `111<315`
- New message: `41.13.92`
- Ports `1` and `2` are **designated**: `41.13.92` is better than `81.0.81` and `41.19.125`
- Port `3` and `5` are **blocked**: `41.13.92` is not better than `41.12.315` nor `41.13.90`

Spanning Tree example

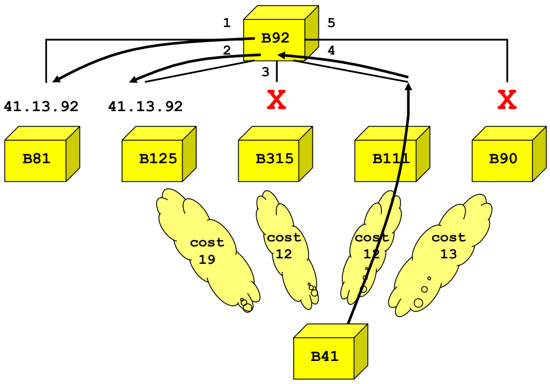


- Message **41.13.92** sent periodically on ports **1** and **2**
- Ports **1, 2, 4** participate in forwarding (they are in the Spanning Tree)

Spanning Tree example



Spanning Tree example



STP - Spanning Tree protocol

- IEEE 802.1D
- Distributed in all bridges
- Bridges exchange messages with neighbours in order to both
  - elect a root
  - determine shortest path tree to root
    - root port = port towards root on shortest path tree
    - designated ports = connect LANs to the spanning tree
    - designated bridge = one per LAN, has shortest path to root via root port

STP (IEEE 802.1d)

- Each bridge has a Bridge Identifier number, based on MAC address + configurable offset
- Bridge with smallest Bridge Identifier is the "root"
- Each link has a cost

Link Bit Rate	Cost
4 Mb/s	250
10 Mb/s	100
16 Mb/s	62
45 Mb/s	39
100 Mb/s	19
155 Mb/s	14
622 Mb/s	6
1 Gb/s	4
10 Gb/s	2

Bridge PDUs

- Control method uses control frames called Bridge PDUs (BPDUs)
  - 802.3 encapsulation, LLC frame with SAP = x42
  - MAC DA = all bridges (multicast) 01 80 C2 00 00 00
- BPDUs are not forwarded by bridges
  - unlike all other frames BPDUs are sent by one bridge to all bridges on the same LAN segment
  - reminder: a data frame is never sent to bridge by end system
- Configuration BPDU contains
  - root Id
  - cost to root (from sender of config BPDU)
  - id of sender
  - port number (omitted in the examples)

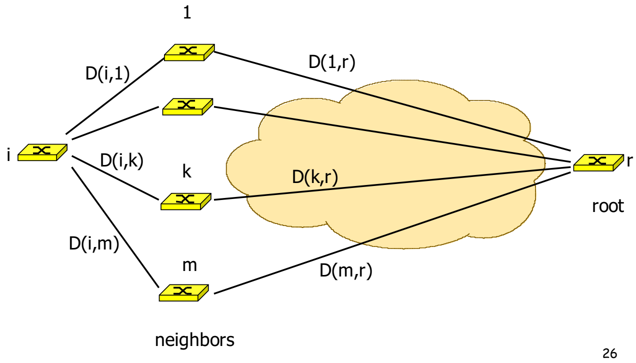
Initialization of Spanning Tree

- Bridge initially assumes self as a root
- Bridge computes own new config BPDU based on received information
  - determine best root so far
  - distance to root with Bellman-Ford

```
distance D from me to root =
     min [D(me, neighbor) + D(neighbor, root)]
```

- On every port, Bridge transmits config BPDU until it receives a better config BPDU on that port
  - better = closer to root (lower cost or lower Id)
- On every port, bridge maintains copy of best config BPDU sent or received

Bellman-Ford algorithm



Basic ST Procedure

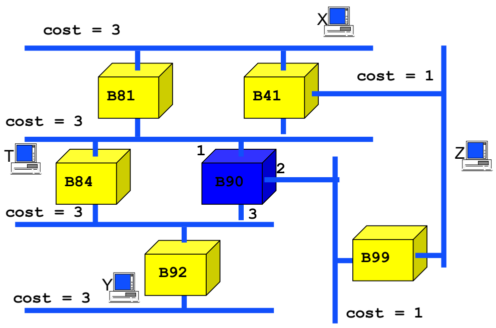
```
config BPDU received on any port or port enabled ->

compute new root;
compute new cost to root;  /* Bellman Ford */
build new_config_BPDU;
for all ports i do
      if new_config_BPDU better than stored_config[i]
            then store and send on port i;
end

compute root port /* smaller distance to root */
designated ports = ports where config BPDU was sent
blocked ports = other ports
```

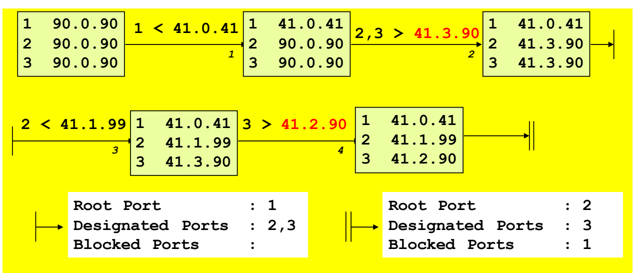
```
r.c.s better than r'.c'.s' iff
    (r<r') or (r=r' and c<c') or (r=r' and c=c' and s<s')
```

Complex example



Initialization of Spanning Tree

- Bridge B90 prepares config BPDU `90.0.90` and sends on all ports; B90 configuration tables:

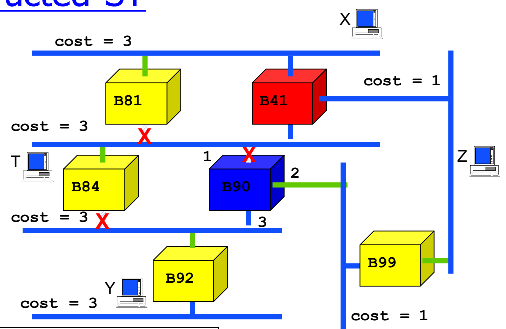


message received on port 1: `1 < 41.0.41` message format: `rootId.cost_to_root.senderId`

Comments

- When receiving a message we compare the cost (with the local cost included), but we store the message received (without the cost)
- On receiving `41.0.41` on port 1:
  - `41.3.41 < 90.0.90? yes -> 1 becomes root`
  - `new config msg = 41.3.90`
    `41.3.90 < 90.0.90? yes -> 2 becomes designated`
    `41.3.90 < 90.0.90? yes -> 3 becomes designated`
- On receiving `41.1.99` on port 2:
  - `41.2.99 < 41.3.41? yes -> 2 becomes root`
  - `new config msg = 41.2.90`
    `41.2.90 < 41.3.90? yes -> 3 becomes designated`
    `41.2.90 < 41.0.41? no  -> 1 becomes blocked`

Constructed ST



Forwarding Tables:	
B41 1:X 2:YZ 3:T	B81 1:XYZT
B84 1:XYZT	B90 2:XZT 3:Y
B92 2:XZT 3:Y	B99 1:Y 2:XZT

root port | designated port

X blocked port

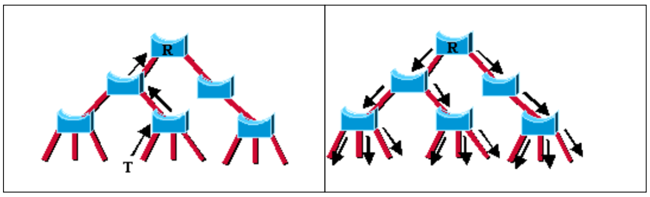
STP Topology Management

- Topology change can be
  - **local** - a configuration msg changes the state of a port (one port changes into the Forwarding or Blocking state)
  - **global** - topology update mechanism via root
- Detection
  - configuration message is too old (the path to the root is no longer available)
  - receive a new better configuration
- When topology change detected
  - inform root
  - restart spanning tree computation
  - force bridges to use a shorter timeout interval (purge the forwarding table)

Topology change

- When one bridge detects a topology change
  - bridge sends topology update BPDU towards root and enters Listening state (upstream bridges repeat BPDU up to root)
  - root forwards new config BPDU with "topology change flag" set during `ForwardDelay` (15 s) + `MaxAge` (20 s)
    - causes all bridges to use the short timeout value for the forwarding table (see later)
    - until BDPU from root received with "topology change" flag cleared

Example



New link added to bridge

Topology update sent to root

Topology update sent by root on ST for `MaxAge + ForwardDelay`

All bridges recompute ST + set forwarding tables in learning state

Source: CISCO RSTP White Paper

Configuration monitoring

- root sends a configuration message every `HelloTime` (2 s)
- message received with `Age`, retransmitted with `Age += 1`
- if `Age` = `MaxAge` (20 s), delete the stored configuration and restarts basic ST procedure

```
Root sends config BPDUs every HelloTime;
```

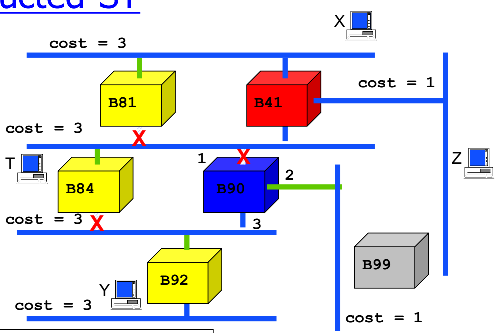
```
Bridge B receives config BPDU on root port i ->
    Reset timer Age on stored_config[i]
    for all designated ports j
        B sends own config BPDU
        B resets timer Age on stored_config[j]

Bridge B timeouts (MaxAge) stored_config[j]->
    delete stored_config[j];
    B performs basic ST procedure;
```


Timers

- Timers used in topology management
  - `HelloTime` (2 s): time interval between Config BPDUs sent by the Root Bridge.
  - `ForwardDelay` (15 s): time interval that a bridge port spends in both the Listening and Learning states
  - `MaxAge` (20 s): time interval that a bridge stores a BPDU before discarding it
  - recommended values for a spanning tree of diameter 7
- Time to update
  - detect and rebuild: 35 s = 20 s + 15 s
- Time to change from blocking to forwarding state
  - detect, rebuild, and learn addresses: 50 s = 20 s + 15 s + 15 s

Constructed ST

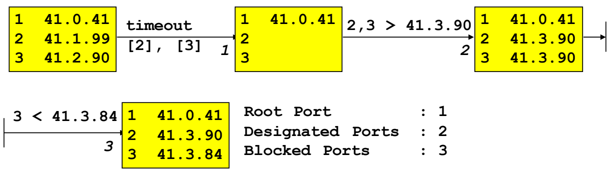


Forwarding Tables:
B41 1:X 2:YZ 3:T   B81 1:XYZT
B84 1:XYZT   B90 2:XZT 3:Y
B92 1:XZT 2:Y   B99 1:Y 2:XZT

root port | designated port
X blocked port

Example

- B99 powered off; stored config at B90:

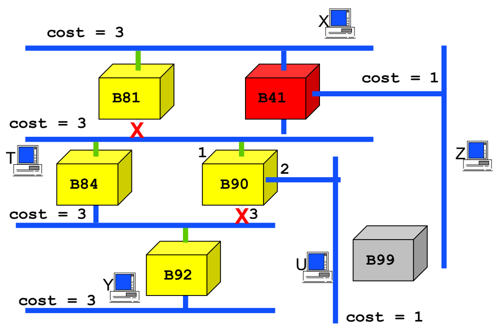


- Spanning Tree after failure?

Comments

- After timeout:
  - `41.3.41 is the best configuration -> 1 becomes root`
  - `new config msg = 41.3.90`
  - `2 and 3 becomes designated`
- On receiving **41.3.84** on port 3:
  - `41.6.84 < 41.3.41? no -> 1 stays root`
  - `new config msg = 41.3.90`
    `2 stays designated`
    `41.3.90 < 41.3.84? no -> 3 becomes blocked`

ST after failure



Synchronization with Forwarding

- Topology changes cause loops or loss of connectivity
  - during reconfiguration, topology is not yet (in general) loop free
  - even transient loops should be avoided
- Solution: Forwarding state is not immediately operational
  - pre-forwarding states:
    - Listening (accept config msgs, no forwarding): wait for stabilization of ST (**ForwardDelay**, 15 sec)
    - Learning (learn MAC addresses, no forwarding): wait for addresses to be learnt (**ForwardDelay**, 15 sec)

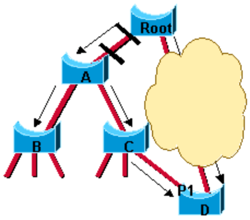
State	*Actions* Forward	ST	Learn
Blocking			x
Listening			x
Learning		x	x
Forwarding	x	x	x

Forwarding Table entry timers

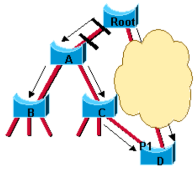
- **MaxLife** = duration of an entry in the forwarding table
- Two timer values are used
  - long timer (5mn): normal case
  - short timer = **ForwardDelay** (15 s): after spanning tree updates
- Timer switching mechanism
  - Bridge B detects change in ST -> **MaxLife = ForwardDelay**

Example

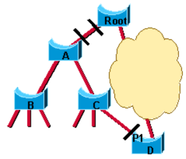
- Bridge A newly connected to root. What happens ?



Source: CISCO RSTP White Paper



1. A and root run ST procedure on new ports.
2. This triggers new BPDUs sent to B and C
3. D computes port p1 as new root



1. p1 at D is set to listening state for 15 s
2. p1 at D is set to learning state for 15 s

topology change is fast (in this case), but forwarding is not enabled immediately

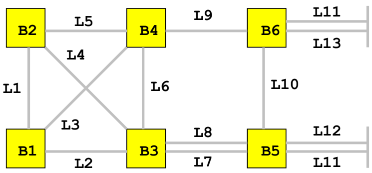
RSTP - Rapid ST protocol

- IEEE 802.1W
- Evolution of STP
- Goal: fast reconfiguration
- Improvement of handling topology changes and synchronization with packet forwarding
  - avoids use of timers as much as possible
- Main improvements are
  - fast reconfiguration: use of alternate paths to root or backup path to a LAN
  - fast transition to forwarding state with negotiation protocol instead of relying on timers
  - fast flushing of forwarding tables after topology changes

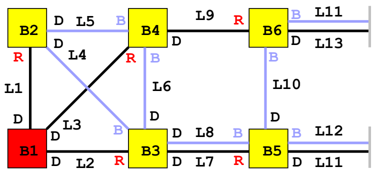
Port Roles in RSTP

- A port **role** is one of: root, designated, alternate, backup, blocked
- ***root*** port = port towards root (same as STP)
- ***designated*** port = connects LAN to the spanning tree (same as STP)
- Port that is not root nor designated
  - is ***alternate***: connects the bridge to root after topology update (alternate path to root)
  - is ***backup***: connects LAN to the spanning tree after topology update (alternate path to root for the LAN)
  - is ***blocked***: not in the spanning tree

Another example of STP

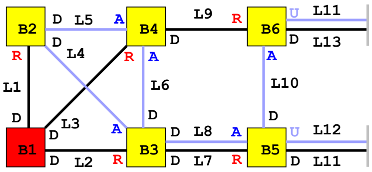


Constructed ST



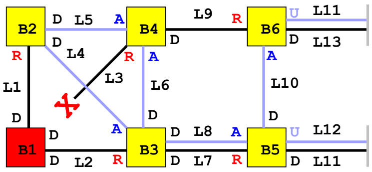
- B1 - root
- R - root ports, D - designated ports, B - blocked ports

ST constructed by RSTP



- B1 - root
- R - root ports, D - designated ports, B - blocked ports
- A - alternative ports, U - backup ports

L3 fails



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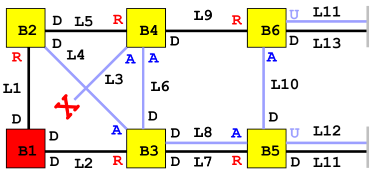
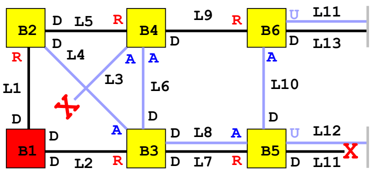
L3 fails



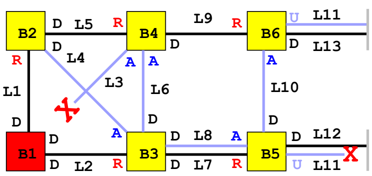
- On B4
  - port on L3 becomes A and state Discarding
  - port on L5 becomes R and state Forwarding

L11 fails



- B1 - root
- R - root ports, D - designated ports, B - blocked ports
- A - alternative ports, U - backup ports

L11 fails

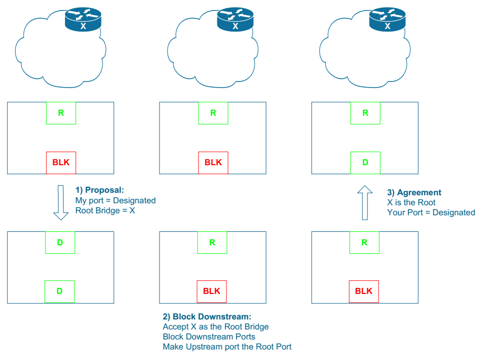


- On B5
  - port on L11 becomes U and state Discarding
  - port on L12 becomes D and state Forwarding

RSTP - Rapid ST protocol

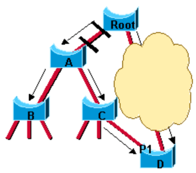
- If topology change
  - same reconstruction protocol as STP
  - topology change notification flooded accross ST
- Rapid recovery
  - Proposal/Agreement sequence between bridges that change state of a port: immediate transition to Forwarding state
  - link failure detection by MAC layer
    - change R to A and D to U (order of 10 ms)
    - but similar delay to STP, if topology update

RSTP - Rapid ST protocol



RSTP - Rapid ST protocol

- Better root information received:
  - block all designated ports
  - send Proposal BPDU on all potential designated ports
- Downstream bridges:
  - compare Proposal with the current root information
  - if Proposal is better
    - elect root port
    - block all downstream ports
    - send Agreement BPDU upstream
    - send Proposal BPDU on all potential designated ports
  - Otherwise
    - bridge that rejects Proposal – it has better root information
    - blocks the port on which it received Proposal
    - end of sync



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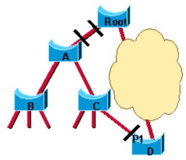
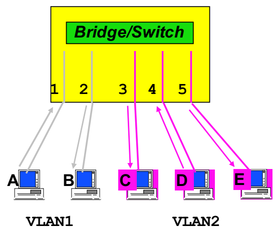


1. p1 at D is set to listening state for 15 s
2. p1 at D is set to learning state for 15 s

topology change is fast (in this case), but forwarding is not enabled immediately

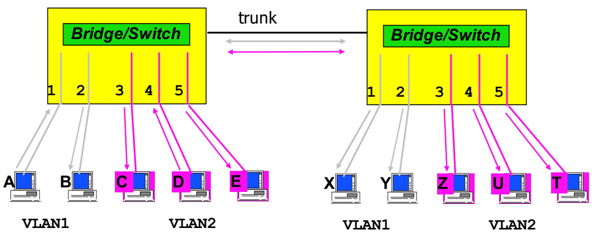
VLAN - Virtual LAN

- Keep the advantages of Layer 2 interconnection
  - auto-configuration (addresses, topology - Spanning Tree)
  - performance of switching
- Enhance with functionalities of Layer 3
  - extensibility
  - spanning large distances
  - traffic filtering
- Limit broadcast domains
- Security
  - separate subnetworks



Virtual LANs

- No traffic between different VLANs
- VLANs build on bridges or switches



VLANs

- How to define which port belongs to a VLAN?
  - per port
    - simple, secure, not flexible for moving hosts (one host per port)
  - per MAC address
    - several hosts per port, flexible for moving hosts, not secure, difficult to manage, problems with protocols Layer 3 (should be coupled with dynamic address negotiation - DHCP)
  - per Layer 3 protocol
    - allows to limit frame broadcast (VLAN1: IP, VLAN2: IPX)
  - per Layer 3 address
    - one VLAN per IP subnetwork
    - flexible for moving hosts
    - less efficient (requires inspecting packets)
  - per IP Multicast group
    - hosts that join an IP multicast group can be seen as members of the same virtual LAN

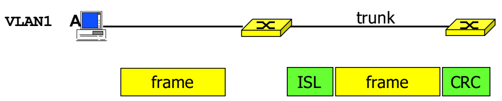
VLANs

- How to extend VLAN to several bridges/switches?
  - needs frame identification - *tagging*
- Frame tagging
  - explicit tagging
    - add VLAN identifier to MAC frames
  - implicit tagging
    - VLAN Id deduced from port number, MAC address, layer 3 protocol, layer 3 address, IP Multicast group
  - implicit tagging makes use of filtering database
    - mapping between VLAN Id and the appropriate field (e.g. layer 3 address)

Frame tagging

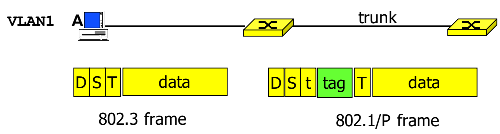
- VLAN identifier in frames
  - usually done by the first switch/bridge
- Standards
  - CISCO: ISL (Inter-Switch Link)
  - IEEE 802.1Q/802.1P

ISL (Inter-Switch Link)



- CISCO: ISL (Inter-Switch Link)
  - proprietary solution: encapsulates a frame in an ISL frame (26 bytes header, 4 bytes CRC)
  - incompatible with other vendors - increased maximal length of 802.3 frame

802.1Q



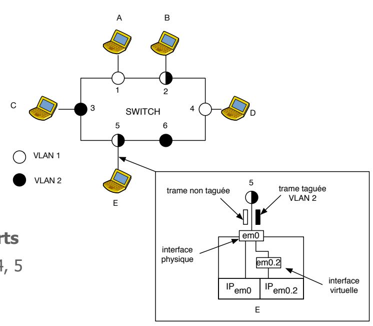
- Frame encapsulation
  - extension for assigning frame priority and VLAN tag
  - t - 2 bytes of TPI (Tag Protocol Identifier): 0x8100
  - tag - 2 bytes of TCI (Tag Control Information): priority (3 bits), VLAN Id (12 bits) (VID 0x001 often reserved for management)
  - max length = 1522 bytes

802.1Q

- Bridge/switch keeps track of VLAN members based on dynamic filtering entries
  - Dynamic Registration: specify ports registered for a specific VLAN
    - added and deleted using GARP VLAN Registration Protocol (GVRP), GARP is the Generic Attribute Registration Protocol
  - Group Registration: indicate frames to a group MAC address
    - added and deleted using Group Multicast Registration Protocol (GMRP)
    - multicasts sent on a single VLAN without affecting other VLANs

Tagged VLANs

- VLAN table

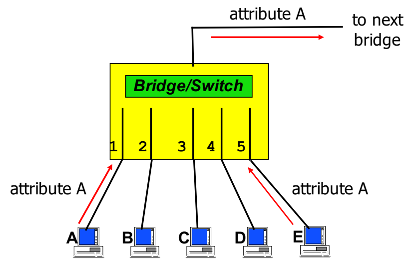


VLAN	tag	ports
1	untagged	1, 4, 5
1	tagged	2
2	untagged	2,3
2	tagged	5

GARP

- Defines
  - method to declare attributes to other GARP participants
  - frame type to use (GPDU)
  - rules for registering/deleting attributes
- How does it work?
  - bridge wants to declare an attribute
  - send a declaration
  - other bridges propagate the declaration

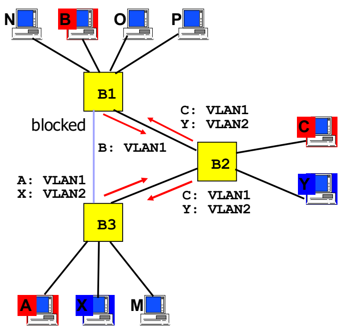
GARP



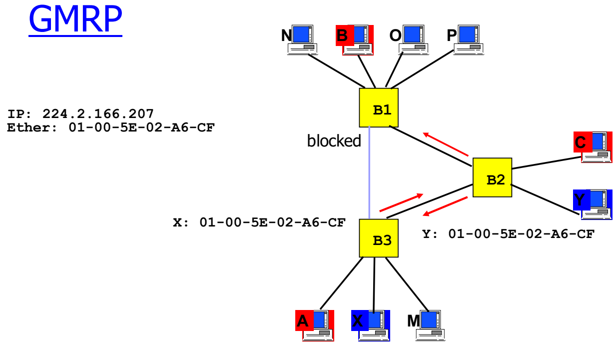
- Attribute propagation
  - stored at bridge
  - multiple attributes are filtered out - only one declaration is propagated
  - propagation follows the spanning tree of bridges

GARP

- Attributes on VLAN memebership are sent over the spanning tree
- Frames are forwarded according to this information



GMRP



- Register to a group address - it uses GARP
- Multicast frames are forwarded according to this information

Conclusion

- Ethernet switches/bridges dominate
- 1Gb/s switches for hosts, 10-40-100 Gb/s in the backbone
- Complex interconnection
  - parallel paths may exist for reliability
  - SPT or RSTP guarantees loop-free interconnection
  - VLANs help to structure the interconnection
    - separate broadcast domains
  - limited scalability
- Products
  - Switch/Router - integrated ports: Layer 2 and Layer 3
  - administrator chooses the right level for each port