Course Booklet

Scaling Networks

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Scaling Networks Course Booklet

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Contents at a Glance

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Command Syntax Conventions

The conventions used to present command syntax in this book are the same conventions used in the IOS Command Reference. The Command Reference describes these conventions as follows:

- **Boldface** indicates commands and keywords that are entered literally as shown. In actual configuration examples and output (not general command syntax), boldface indicates commands that are manually input by the user (such as a **show** command).
- *Italic* indicates arguments for which you supply actual values.
- Vertical bars (|) separate alternative, mutually exclusive elements.
- Square brackets ([ ]) indicate an optional element.
- Braces ({ }) indicate a required choice.
- Braces within brackets ([{ }]) indicate a required choice within an optional element.

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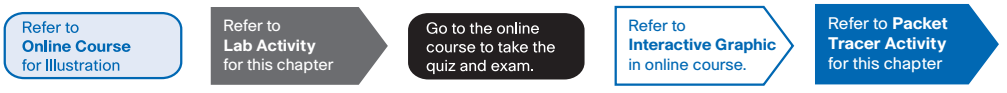

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CHAPTER 1

Introduction to Scaling Networks

1.0 Introduction to Scaling Networks

1.0.1.1 Introduction

As a business grows, so does its networking requirements. Businesses rely on the network infrastructure to provide mission-critical services. Network outages can result in lost revenue and lost customers. Network designers must design and build an enterprise network that is scalable and highly available.

This chapter introduces strategies that can be used to systematically design a highly functional network, such as the hierarchical network design model, the Cisco Enterprise Architecture, and appropriate device selections. The goals of network design are to limit the number of devices impacted by the failure of a single network device, provide a plan and path for growth, and create a reliable network.

Refer to **Lab Activity** for this chapter

1.0.1.2 Class Activity - Network by Design

Network by Design

Your employer is opening a new, branch office.

You have been reassigned to the site as the network administrator where your job will be to design and maintain the new branch network.

The network administrators at the other branches used the Cisco three-layer hierarchical model when designing their networks. You decide to use the same approach.

To get an idea of what using the hierarchical model can do to enhance the design process, you research the topic.

Refer to **Interactive Graphic** in online course.

1.1 Implementing a Network Design

1.1.1 Hierarchical Network Design

1.1.1.1 The Need to Scale the Network

Businesses increasingly rely on their network infrastructure to provide mission-critical services. As businesses grow and evolve, they hire more employees, open branch offices, and expand into global markets. These changes directly affect the requirements of a network. A large business environment with many users, locations, and systems is referred to as an enterprise. The network that is used to support the business enterprise is called an enterprise network.

Click the Play button in the figure to view an animation of a small network expanding into an enterprise network.

An enterprise network must support the exchange of various types of network traffic, including data files, email, IP telephony, and video applications for multiple business units. All enterprise networks must:

- Support critical applications
- Support converged network traffic
- Support diverse business needs
- Provide centralized administrative control

Refer to **Online Course** for Illustration

1.1.1.2 Enterprise Business Devices

Users expect enterprise networks, such as the example shown in the figure, to be up 99.999 percent of the time. Outages in the enterprise network prevent the business from performing normal activities, which can result in a loss of revenue, customers, data, and opportunities.

To obtain this level of reliability, high-end, enterprise class equipment is commonly installed in the enterprise network. Designed and manufactured to more stringent standards than lower-end devices, enterprise equipment moves large volumes of network traffic.

Enterprise class equipment is designed for reliability, with features such as redundant power supplies and failover capabilities. Failover capability refers to the ability of a device to switch from a non-functioning module, service or device, to a functioning one with little or no break in service.

Purchasing and installing enterprise class equipment does not eliminate the need for proper network design.

Refer to **Online Course** for Illustration

1.1.1.3 Hierarchical Network Design

To optimize bandwidth on an enterprise network, the network must be organized so that traffic stays local and is not propagated unnecessarily onto other portions of the network. Using the three-layer hierarchical design model helps organize the network.

This model divides the network functionality into three distinct layers, as shown in Figure 1:

- Access layer
- Distribution layer
- Core layer

Each layer is designed to meet specific functions.

The access layer provides connectivity for the users. The distribution layer is used to forward traffic from one local network to another. Finally, the core layer represents a high-speed backbone layer between dispersed networks. User traffic is initiated at the access layer and passes through the other layers if the functionality of those layers is required.

Even though the hierarchical model has three layers, some smaller enterprise networks may implement a two-tier hierarchical design. In a two-tier hierarchical design, the core and distribution layers are collapsed into one layer, reducing cost and complexity, as shown in Figure 2.

Refer to **Online Course** for Illustration

1.1.1.4 Cisco Enterprise Architecture

The Cisco Enterprise Architecture divides the network into functional components while still maintaining the core, distribution, and access layers. As the figure shows, the primary Cisco Enterprise Architecture modules include:

- Enterprise Campus
- Enterprise Edge
- Service Provider Edge
- Remote

Enterprise Campus

The Enterprise Campus consists of the entire campus infrastructure, to include the access, distribution, and core layers. The access layer module contains Layer 2 or Layer 3 switches to provide the required port density. Implementation of VLANs and trunk links to the building distribution layer occurs here. Redundancy to the building distribution switches is important. The distribution layer module aggregates building access using Layer 3 devices. Routing, access control, and QoS are performed at this distribution layer module. The core layer module provides high-speed interconnectivity between the distribution layer modules, data center server farms, and the enterprise edge. Redundancy, fast convergence, and fault tolerance are the focus of the design in this module.

In addition to these modules, the Enterprise Campus can include other submodules such as:

- **Server Farm and Data Center Module**- This area provides high-speed connectivity and protection for servers. It is critical to provide security, redundancy, and fault tolerance. The network management systems monitor performance by monitoring device and network availability.
- **Services Module**- This area provides access to all services, such as IP Telephony services, wireless controller services, and unified services.

Enterprise Edge

The Enterprise Edge consists of the Internet, VPN, and WAN modules connecting the enterprise with the service provider's network. This module extends the enterprise services to remote sites and enables the enterprise to use Internet and partner resources. It provides QoS, policy reinforcement, service levels, and security.

Service Provider Edge

The Service Provider Edge provides Internet, Public Switched Telephone Network (PSTN), and WAN services.

All data that enters or exits the Enterprise Composite Network Model (ECNM) passes through an edge device. This is the point that all packets can be examined and a decision made whether the packet should be allowed on the enterprise network. Intrusion detection systems (IDS) and intrusion prevention systems (IPS) can also be configured at the enterprise edge to protect against malicious activity.

Refer to **Online Course** for Illustration

1.1.1.5 Failure Domains

A well-designed network not only controls traffic, but also limits the size of failure domains. A failure domain is the area of a network that is impacted when a critical device or network service experiences problems.

The function of the device that initially fails determines the impact of a failure domain. For example, a malfunctioning switch on a network segment normally affects only the hosts on that segment. However, if the router that connects this segment to others fails, the impact is much greater.

The use of redundant links and reliable enterprise-class equipment minimize the chance of disruption in a network. Smaller failure domains reduce the impact of a failure on company productivity. They also simplify the troubleshooting process, thereby, shortening the downtime for all users.

In the figure, click each network device to view the associated failure domain.

Limiting the Size of Failure Domains

Because a failure at the core layer of a network can have a potentially large impact, the network designer often concentrates on efforts to prevent failures. These efforts can greatly increase the cost of implementing the network. In the hierarchical design model, it is easiest and usually least expensive to control the size of a failure domain in the distribution layer. In the distribution layer, network errors can be contained to a smaller area; thus, affecting fewer users. When using Layer 3 devices at the distribution layer, every router functions as a gateway for a limited number of access layer users.

Switch Block Deployment

Routers, or multilayer switches, are usually deployed in pairs, with access layer switches evenly divided between them. This configuration is referred to as a building, or departmental, switch block. Each switch block acts independently of the others. As a result, the failure of a single device does not cause the network to go down. Even the failure of an entire switch block does not affect a significant number of end users.

Refer to **Interactive Graphic** in online course.

1.1.1.6 Activity – Identify Cisco Enterprise Architecture Modules

Refer to **Online Course** for Illustration

1.1.2 Expanding the Network

1.1.2.1 Design for Scalability

To support an enterprise network, the network designer must develop a strategy to enable the network to be available and to scale effectively and easily. Included in a basic network design strategy are the following recommendations:

- Use expandable, modular equipment or clustered devices that can be easily upgraded to increase capabilities. Device modules can be added to the existing equipment to support new features and devices without requiring major equipment upgrades. Some

devices can be integrated in a cluster to act as one device to simplify management and configuration.

- Design a hierarchical network to include modules that can be added, upgraded, and modified, as necessary, without affecting the design of the other functional areas of the network. For example, creating a separate access layer that can be expanded without affecting the distribution and core layers of the campus network.
- Create an IPv4 or IPv6 address strategy that is hierarchical. Careful IPv4 address planning eliminates the need to re-address the network to support additional users and services.
- Choose routers or multilayer switches to limit broadcasts and filter other undesirable traffic from the network. Use Layer 3 devices to filter and reduce traffic to the network core.

As shown in the figure, more advanced network design requirements include:

- Implementing redundant links in the network between critical devices and between access layer and core layer devices.
- Implementing multiple links between equipment, with either link aggregation (EtherChannel) or equal cost load balancing, to increase bandwidth. Combining multiple Ethernet links into a single, load-balanced EtherChannel configuration increases available bandwidth. EtherChannel implementations can be used when budget restrictions prohibit purchasing high-speed interfaces and fiber runs.
- Implementing wireless connectivity to allow for mobility and expansion.
- Using a scalable routing protocol and implementing features within that routing protocol to isolate routing updates and minimize the size of the routing table.

Refer to **Online Course** for Illustration

1.1.2.2 Planning for Redundancy

Implementing Redundancy

For many organizations, the availability of the network is essential to supporting business needs. Redundancy is an important part of network design for preventing disruption of network services by minimizing the possibility of a single point of failure. One method of implementing redundancy is by installing duplicate equipment and providing failover services for critical devices.

Another method of implementing redundancy is redundant paths, as shown in the figure. Redundant paths offer alternate physical paths for data to traverse the network. Redundant paths in a switched network support high availability. However, due to the operation of switches, redundant paths in a switched Ethernet network may cause logical Layer 2 loops. For this reason, Spanning Tree Protocol (STP) is required.

STP allows for the redundancy required for reliability, but eliminates the switching loops. It does this by providing a mechanism for disabling redundant paths in a switched network until the path is necessary, such as when failures occur. STP is an open standard protocol, used in a switched environment to create a loop-free logical topology.

More details about LAN redundancy and the operation of STP are covered in the chapter titled “LAN Redundancy”.

Refer to **Online Course** for Illustration

1.1.2.3 Increasing Bandwidth

Implementing EtherChannel

In hierarchical network design, some links between access and distribution switches may need to process a greater amount of traffic than other links. As traffic from multiple links converges onto a single, outgoing link, it is possible for that link to become a bottleneck. Link aggregation allows an administrator to increase the amount of bandwidth between devices by creating one logical link made up of several physical links. EtherChannel is a form of link aggregation used in switched networks, as shown in the figure.

EtherChannel uses the existing switch ports; therefore, additional costs to upgrade the link to a faster and more expensive connection are not necessary. The EtherChannel is seen as one logical link using an EtherChannel interface. Most configuration tasks are done on the EtherChannel interface, instead of on each individual port, ensuring configuration consistency throughout the links. Finally, the EtherChannel configuration takes advantage of load balancing between links that are part of the same EtherChannel, and depending on the hardware platform, one or more load-balancing methods can be implemented.

EtherChannel operation and configuration will be covered in more detail in the chapter titled "Link Aggregation".

Refer to **Online Course** for Illustration

1.1.2.4 Expanding the Access Layer

Implementing Wireless Connectivity

The network must be designed to be able to expand network access to individuals and devices, as needed. An increasingly important aspect of extending access layer connectivity is through wireless connectivity. Providing wireless connectivity offers many advantages, such as increased flexibility, reduced costs, and the ability to grow and adapt to changing network and business requirements.

To communicate wirelessly, end devices require a wireless NIC that incorporates a radio transmitter/receiver and the required software driver to make it operational. Additionally, a wireless router or a wireless access point (AP) is required for users to connect, as shown in the figure.

There are many considerations when implementing a wireless network, such as the types of wireless devices to use, wireless coverage requirements, interference considerations, and security considerations.

Wireless operation and implementation will be covered in more detail in the chapter titled "Wireless LANs".

Refer to **Online Course** for Illustration

1.1.2.5 Fine-tuning Routing Protocols

Managing the Routed Network

Enterprise networks and ISPs often use more advanced protocols, such as link-state protocols, because of their hierarchical design and ability to scale for large networks.

Link-state routing protocols such as Open Shortest Path First (OSPF), as shown in Figure 1, works well for larger hierarchical networks where fast convergence is important. OSPF routers establish and maintain neighbor adjacency or adjacencies, with other connected OSPF routers. When routers initiate an adjacency with neighbors, an exchange of link-state updates begins. Routers reach a FULL state of adjacency when they have synchronized

views on their link-state database. With OSPF, link state updates are sent when network changes occur.

OSPF is a popular link-state routing protocol that can be fine-tuned in many ways. The chapter titled "Adjust and Troubleshoot Single-Area OSPF" will cover some of the more advanced features of OSPF configuration and troubleshooting.

Additionally, OSPF supports a two-layer hierarchical design, or multiarea OSPF, as shown in Figure 2. All OSPF networks begin with Area 0, also called the backbone area. As the network is expanded, other, non-backbone areas can be created. All non-backbone areas must directly connect to area 0. The chapter titled "Multiarea OSPF" introduces the benefits, operation, and configuration of Multiarea OSPF.

Another popular routing protocol for larger networks is Enhanced Interior Gateway Routing Protocol (EIGRP). Cisco developed EIGRP as a proprietary distance vector routing protocol with enhanced capabilities. Although configuring EIGRP is relatively simple, the underlying features and options of EIGRP are extensive and robust. For example, EIGRP uses multiple tables to manage the routing process, as shown in Figure 3. EIGRP contains many features that are not found in any other routing protocols. It is an excellent choice for large, multi-protocol networks that employ primarily Cisco devices.

The chapter titled "EIGRP" introduces the operation and configuration of the EIGRP routing protocol, while the chapter titled "EIGRP Advanced Configurations and Troubleshooting" covers some of the more advanced configuration options of EIGRP.

Refer to **Interactive Graphic** in online course.

1.1.2.6 Activity: Identify Scalability Terminology

Refer to **Online Course** for Illustration

1.2 Selecting Network Devices

1.2.1 Switch Hardware

1.2.1.1 Switch Platforms

When designing a network, it is important to select the proper hardware to meet current network requirements, as well as allow for network growth. Within an enterprise network, both switches and routers play a critical role in network communication.

There are five categories of switches for enterprise networks, as shown in Figure 1:

- **Campus LAN Switches**- To scale network performance in an enterprise LAN, there are core, distribution, access, and compact switches. These switch platforms vary from fanless switches with eight fixed ports to 13-blade switches supporting hundreds of ports. Campus LAN switch platforms include the Cisco 2960, 3560, 3750, 3850, 4500, 6500, and 6800 Series.
- **Cloud-Managed Switches**- The Cisco Meraki cloud-managed access switches enable virtual stacking of switches. They monitor and configure thousands of switch ports over the web, without the intervention of onsite IT staff.
- **Data Center Switches**- A data center should be built based on switches that promote infrastructure scalability, operational continuity, and transport flexibility. The data center switch platforms include the Cisco Nexus Series switches and the Cisco Catalyst 6500 Series switches.

- **Service Provider Switches**- Service provider switches fall under two categories: aggregation switches and Ethernet access switches. Aggregation switches are carrier-grade Ethernet switches that aggregate traffic at the edge of a network. Service provider Ethernet access switches feature application intelligence, unified services, virtualization, integrated security, and simplified management.
- **Virtual Networking**- Networks are becoming increasingly virtualized. Cisco Nexus virtual networking switch platforms provide secure multi-tenant services by adding virtualization intelligence technology to the data center network.

When selecting switches, network administrators must determine the switch form factors. This includes fixed configuration (Figure 2), modular configuration (Figure 3), stackable (Figure 4), or non-stackable. The thickness of the switch, which is expressed in the number of rack units, is also important for switches that are mounted in a rack. For example, the fixed configuration switches shown in Figure 2 are all one rack units (1U).

In addition to these considerations, Figure 5 highlights other common business considerations when selecting switch equipment.

Refer to **Online Course** for Illustration

1.2.1.2 Port Density

The port density of a switch refers to the number of ports available on a single switch. The figure shows the port density of three different switches.

Fixed configuration switches typically support up to 48 ports on a single device. They have options for up to four additional ports for small form-factor pluggable (SFP) devices. High-port densities allow for better use of limited space and power. If there are two switches that each contain 24 ports, they would be able to support up to 46 devices, because at least one port per switch is lost with the connection of each switch to the rest of the network. In addition, two power outlets are required. Alternatively, if there is a single 48-port switch, 47 devices can be supported, with only one port used to connect the switch to the rest of the network, and only one power outlet needed to accommodate the single switch.

Modular switches can support very high-port densities through the addition of multiple switch port line cards. For example, some Catalyst 6500 switches can support in excess of 1,000 switch ports.

Large enterprise networks that support many thousands of network devices require high density, modular switches to make the best use of space and power. Without using a high-density modular switch, the network would need many fixed configuration switches to accommodate the number of devices that need network access. This approach can consume many power outlets and a lot of closet space.

The network designer must also consider the issue of uplink bottlenecks: A series of fixed configuration switches may consume many additional ports for bandwidth aggregation between switches, for the purpose of achieving target performance. With a single modular switch, bandwidth aggregation is less of an issue, because the backplane of the chassis can provide the necessary bandwidth to accommodate the devices connected to the switch port line cards.

Refer to **Online Course** for Illustration

1.2.1.3 Forwarding Rates

Forwarding rates define the processing capabilities of a switch by rating how much data the switch can process per second. Switch product lines are classified by forwarding rates, as shown in the figure. Entry-level switches have lower forwarding rates than enterprise-level switches. Forwarding rates are important to consider when selecting a switch. If the switch forwarding rate is too low, it cannot accommodate full wire-speed communication across all of its switch ports. Wire speed is the data rate that each Ethernet port on the switch is capable of attaining. Data rates can be 100 Mb/s, 1 Gb/s, 10 Gb/s, or 100 Gb/s.

For example, a typical 48-port gigabit switch operating at full wire speed generates 48 Gb/s of traffic. If the switch only supports a forwarding rate of 32 Gb/s, it cannot run at full wire speed across all ports simultaneously. Fortunately, access layer switches typically do not need to operate at full wire speed, because they are physically limited by their uplinks to the distribution layer. This means that less expensive, lower performing switches can be used at the access layer, and more expensive, higher performing switches can be used at the distribution and core layers, where the forwarding rate has a greater impact on network performance.

Refer to **Online Course** for Illustration

1.2.1.4 Power over Ethernet

PoE allows the switch to deliver power to a device over the existing Ethernet cabling. This feature can be used by IP phones and some wireless access points. Click the highlighted icons in Figure 1 to view PoE ports on each device.

PoE allows more flexibility when installing wireless access points and IP phones, allowing them to be installed anywhere that there is an Ethernet cable. A network administrator should ensure that the PoE features are required, because switches that support PoE are expensive.

The relatively new Cisco Catalyst 2960-C and 3560-C Series compact switches support PoE pass-through. PoE pass-through allows a network administrator to power PoE devices connected to the switch, as well as the switch itself, by drawing power from certain upstream switches. Click the highlighted icon in Figure 2 to view a Cisco Catalyst 2960-C.

Refer to **Online Course** for Illustration

1.2.1.5 Multilayer Switching

Multilayer switches are typically deployed in the core and distribution layers of an organization's switched network. Multilayer switches are characterized by their ability to build a routing table, support a few routing protocols, and forward IP packets at a rate close to that of Layer 2 forwarding. Multilayer switches often support specialized hardware, such as application-specific integrated circuits (ASICs). ASICs along with dedicated software data structures can streamline the forwarding of IP packets independent of the CPU.

There is a trend in networking toward a pure Layer 3 switched environment. When switches were first used in networks, none of them supported routing; now, almost all switches support routing. It is likely that soon all switches will incorporate a route processor because the cost of doing so is decreasing relative to other constraints. Eventually the term multilayer switch will be redundant.

As shown in the figure, the Catalyst 2960 switches illustrate the migration to a pure Layer 3 environment. With IOS versions prior to 15.x, these switches supported only one active switched virtual interface (SVI). With IOS 15.x, these switches now support multiple active

SVIs. This means that the switch can be remotely accessed via multiple IP addresses on distinct networks.

Refer to **Interactive Graphic** in online course.

1.2.1.6 Activity - Selecting Switch Hardware

Refer to **Packet Tracer Activity** for this chapter

1.2.1.7 Packet Tracer - Comparing 2960 and 3560 Switches

Background/Scenario

In this activity, you will use various commands to examine three different switching topologies and compare the similarities and differences between the 2960 and 3560 switches. You will also compare the routing table of a 1941 router with a 3560 switch.

Refer to **Lab Activity** for this chapter

1.2.1.8 Lab - Selecting Switching Hardware

In this lab, you will complete the following objectives:

- Part 1: Explore Cisco Switch Products
- Part 2: Select an Access Layer Switch
- Part 3: Select a Distribution/Core Layer Switch

Refer to **Online Course** for Illustration

1.2.2 Router Hardware

1.2.2.1 Router Requirements

In the distribution layer of an enterprise network, routing is required. Without the routing process, packets cannot leave the local network.

Routers play a critical role in networking by interconnecting multiple sites within an enterprise network, providing redundant paths, and connecting ISPs on the Internet. Routers can also act as a translator between different media types and protocols. For example, a router can accept packets from an Ethernet network and re-encapsulate them for transport over a Serial network.

Routers use the network portion of the destination IP address to route packets to the proper destination. They select an alternate path if a link goes down or traffic is congested. All hosts on a local network specify the IP address of the local router interface in their IP configuration. This router interface is the default gateway.

Routers also serve other beneficial functions:

- Provide broadcast containment
- Connect remote locations
- Group users logically by application or department
- Provide enhanced security

Click each highlighted area in the figure for more information on the functions of routers.

With the enterprise and the ISP, the ability to route efficiently and recover from network link failures is critical to delivering packets to their destination.

Refer to **Online Course** for Illustration

1.2.2.2 Cisco Routers

As the network grows, it is important to select the proper routers to meet its requirements. As shown in the figure, there are three categories of routers:

- **Branch Routers**- Branch routers optimize branch services on a single platform while delivering an optimal application experience across branch and WAN infrastructures. Maximizing service availability at the branch requires networks designed for 24x7x365 uptime. Highly available branch networks must ensure fast recovery from typical faults, while minimizing or eliminating the impact on service, and provide simple network configuration and management.
- **Network Edge Routers**- Network edge routers enable the network edge to deliver high-performance, highly secure, and reliable services that unite campus, data center, and branch networks. Customers expect a high-quality media experience and more types of content than ever before. Customers want interactivity, personalization, mobility, and control for all content. Customers also want to access content anytime and anyplace they choose, over any device, whether at home, at work, or on the go. Network edge routers must deliver enhance quality of service and nonstop video and mobile capabilities.
- **Service Provider Routers**- Service provider routers differentiate the service portfolio and increase revenues by delivering end-to-end scalable solutions and subscriber-aware services. Operators must optimize operations, reduce expenses, and improve scalability and flexibility, to deliver next-generation Internet experiences across all devices and locations. These systems are designed to simplify and enhance the operation and deployment of service-delivery networks.

Refer to **Online Course** for Illustration

1.2.2.3 Router Hardware

Routers also come in many form factors, as shown in the figure. Network administrators in an enterprise environment should be able to support a variety of routers, from a small desktop router to a rack-mounted or blade model.

Routers can also be categorized as fixed configuration or modular. With the fixed configuration, the desired router interfaces are built-in. Modular routers come with multiple slots that allow a network administrator to change the interfaces on the router. As an example, a Cisco 1841 router comes with two Fast Ethernet RJ-45 interfaces built-in, and two slots that can accommodate many different network interface modules. Routers come with a variety of different interfaces, such as Fast Ethernet, Gigabit Ethernet, Serial, and Fiber-Optic.

Refer to **Interactive Graphic** in online course.

1.2.2.4 Activity – Identify the Router Category

Refer to **Online Course** for Illustration

1.2.3 Managing Devices

1.2.3.1 Managing IOS Files and Licensing

With such a wide selection of network devices to choose from in the Cisco product line, an organization can carefully determine the ideal combination to meet the needs of the employees and the customers.

When selecting or upgrading a Cisco IOS device, it is important to choose the proper IOS image with the correct feature set and version. IOS refers to the package of routing, switching, security, and other internetworking technologies integrated into a single multitasking operating system. When a new device is shipped, it comes preinstalled with the software image and the corresponding permanent licenses for the customer-specified packages and features.

For routers, beginning with Cisco IOS Software release 15.0, Cisco modified the process to enable new technologies within the IOS feature sets, as shown in the figure.

The chapter title "IOS Images and Licensing" covers more information on managing and maintaining the Cisco IOS licenses.

Refer to **Online Course** for Illustration

1.2.3.2 In-Band versus Out-of-Band Management

Regardless of the Cisco IOS network device being implemented, there are two methods for connecting a PC to that network device for configuration and monitoring tasks. These methods include out-of-band and in-band management, as shown in the figure.

Out-of-band management is used for initial configuration or when a network connection is unavailable. Configuration using out-of-band management requires:

- Direct connection to console or AUX port
- Terminal emulation client

In-band management is used to monitor and make configuration changes to a network device over a network connection. Configuration using in-band management requires:

- At least one network interface on the device to be connected and operational
- Telnet, SSH, or HTTP to access a Cisco device

Refer to **Online Course** for Illustration

1.2.3.3 Basic Router CLI Commands

A basic router configuration includes the hostname for identification, passwords for security, assignment of IP addresses to interfaces for connectivity, and basic routing. Figure 1 shows the commands entered to enable a router with OSPF. Verify and save configuration changes using the **`copy running-config startup-config`** command. Figure 2 shows the results of the configuration commands that were entered in Figure 1. To clear the router configuration, use the **`erase startup-config`** command and then the **`reload`** command.

On Figure 3, use the Syntax Checker to verify router configurations using these **`show`** commands.

Refer to **Online Course** for Illustration

1.2.3.4 Basic Router Show Commands

Here are some of the most commonly used IOS commands to display and verify the operational status of the router and related network functionality. These commands are divided into several categories.

Routing Related:

- **show ip protocols**- Displays information about the routing protocols configured. If OSPF is configured, this includes the OSPF process ID, the router ID, networks the router is advertising, the neighbors the router is receiving updates from, and the default administrative distance, which is 110 for OSPF. (Figure 1)
- **show ip route**- Displays routing table information, including: routing codes, known networks, administrative distance and metrics, how routes were learned, next hop, static routes, and default routes. (Figure 2)
- **show ip ospf neighbor**- Displays information about OSPF neighbors that have been learned, including the Router ID of the neighbor, priority, the state (Full = adjacency has been formed), the IP address, and the local interface that learned of the neighbor. (Figure 3)

Interface Related:

- **show interfaces**- Displays interfaces with line (protocol) status, bandwidth, delay, reliability, encapsulation, duplex, and I/O statistics. If specified without a specific interface designation, all interfaces will be displayed. If a specific interface is specified after the command, information about that interface only will be displayed. (Figure 4)
- **show ip interfaces**- Displays interface information, including: protocol status, the IP address, if a helper address is configured, and whether an ACL is enabled on the interface. If specified without a specific interface designation, all interfaces will be displayed. If a specific interface is specified after the command, information about that interface only will be displayed. (Figure 5)
- **show ip interface brief**- Displays all interfaces with IP addressing information and interface and line protocols status. (Figure 6)
- **show protocols**- Displays information about the routed protocol that is enabled, and the protocol status of interfaces. (Figure 7)

Other connectivity related commands include the **show cdp neighbors** command (Figure 8). This command displays information on directly connected devices including Device ID, the local interface the device is connected to, capability (R = router, S = switch), the platform, and Port ID of the remote device. The details option includes IP addressing information and the IOS version.

Use the Syntax Checker in Figure 9 to verify router configurations using these **show** commands.

Refer to **Online Course** for Illustration

1.2.3.5 Basic Switch CLI commands

Basic switch configuration includes the hostname for identification, passwords for security, and assignment of IP addresses for connectivity. In-band access requires the switch to have an IP address. Figure 1 shows the commands entered to enable a switch.

Figure 2 shows the results of the configuration commands that were entered in Figure 1. Verify and save the switch configuration using the **copy running-config startup-config** command. To clear the switch configuration, use the **erase startup-config**

command and then the reload command. It may also be necessary to erase any VLAN information using the command **delete flash:vlan.dat**. When switch configurations are in place, view the configurations using the **show running-config** command.

Refer to **Online Course** for Illustration

1.2.3.6 Basic Switch Show Commands

Switches make use of common IOS commands for configuration, to check for connectivity and to display current switch status. Click buttons 1 to 4 for sample outputs of the commands and the important pieces of information that an administrator can gather from it.

Interface / Port Related:

- **show port-security**- Displays any ports with security activated. To examine a specific interface, include the interface ID. Information included in the output: the maximum addresses allowed, current count, security violation count, and action to be taken. (Figure 1)
- **show port-security address**- Displays all secure MAC addresses configured on all switch interfaces. (Figure 2)
- **show interfaces**- Displays one or all interfaces with line (protocol) status, bandwidth, delay, reliability, encapsulation, duplex, and I/O statistics. (Figure 3)
- **show mac-address-table**- Displays all MAC addresses that the switch has learned, how those addresses were learned (dynamic/static), the port number, and the VLAN assigned to the port. (Figure 4)

Like the router, the switch also supports the **show cdp neighbors** command.

The same in-band and out-of-band management techniques that apply to routers also applies to switch configuration.

Refer to **Online Course** for Illustration

1.3 Summary

Refer to **Lab Activity** for this chapter

1.3.1.1 Class Activity - Layered Network Design Simulation

Layered Network Design Simulation

As the network administrator for a very small network, you want to prepare a simulated-network presentation for your branch manager to explain how the network currently operates.

The small network includes the following equipment:

- One 2911 series router
- One 3560 switch
- One 2960 switch
- Four user workstations (PCs or laptops)
- One printer

Refer to **Online Course** for Illustration

1.3.1.2 Basic Switch Configurations

Refer to **Packet Tracer Activity** for this chapter

1.3.1.3 Packet Tracer - Skills Integration Challenge

Background/Scenario

As a recently hired LAN technician, your network manager has asked you to demonstrate your ability to configure a small LAN. Your tasks include configuring initial settings on two switches using the Cisco IOS and configuring IP address parameters on host devices to provide end-to-end connectivity. You are to use two switches and two hosts/PCs on a cabled and powered network.

Refer to **Online Course** for Illustration

1.3.1.4 Summary

The hierarchical network design model divides network functionality into the access layer, the distribution layer, and the core layer. The Cisco Enterprise Architecture further divides the network into functional components.

A well-designed network controls traffic and limits the size of failure domains. Routers and multilayer switches can be deployed in pairs so that the failure of a single device does not cause service disruptions.

A network design should include an IP addressing strategy, scalable, and fast-converging routing protocols, appropriate Layer 2 protocols, and modular or clustered devices that can be easily upgraded to increase capacity.

A mission-critical server should have a connection to two different access layer switches. It should have redundant modules when possible, and a power backup source. It may be appropriate to provide multiple connections to one or more ISPs.

Security monitoring systems and IP telephony systems must have high availability and often have special design considerations.

The network designer should specify a router from the appropriate category: branch router, network edge router, or service provider router. It is important to also deploy the appropriate type of switches for a given set of requirements, switch features and specifications, and expected traffic flow.

Go to the online course to take the quiz and exam.

Chapter 1 Quiz

This quiz is designed to provide an additional opportunity to practice the skills and knowledge presented in the chapter and to prepare for the chapter exam. You will be allowed multiple attempts and the grade does not appear in the gradebook.

Chapter 1 Exam

The chapter exam assesses your knowledge of the chapter content.

Your Chapter Notes

CHAPTER 2

LAN Redundancy

2.0 LAN Redundancy

2.0.1.1 Introduction

Network redundancy is a key to maintaining network reliability. Multiple physical links between devices provide redundant paths. The network can then continue to operate when a single link or port has failed. Redundant links can also share the traffic load and increase capacity.

Multiple paths need to be managed so that Layer 2 loops are not created. The best paths are chosen, and an alternate path is immediately available should a primary path fail. The Spanning Tree Protocols are used to manage Layer 2 redundancy.

Redundant devices, such as multilayer switches or routers, provide the capability for a client to use an alternate default gateway should the primary default gateway fail. A client may now have multiple paths to more than one possible default gateway. First Hop Redundancy Protocols are used to manage how a client is assigned a default gateway, and to be able to use an alternate default gateway should the primary default gateway fail.

This chapter focuses on the protocols used to manage these forms of redundancy. It also covers some of the potential redundancy problems and their symptoms.

Refer to
Lab Activity
for this chapter

2.0.1.2 Class Activity - Stormy Traffic

Stormy Traffic

It is your first day on the job as a network administrator for a small- to medium-sized business. The previous network administrator left suddenly after a network upgrade took place for the business.

During the upgrade, a new switch was added. Since the upgrade, many employees complain that they are having trouble accessing the Internet and servers on your network. In fact, most of them cannot access the network at all. Your corporate manager asks you to immediately research what could be causing these connectivity problems and delays.

So you take a look at the equipment operating on your network at your main distribution facility in the building. You notice that the network topology seems to be visually correct and that cables have been connected correctly, routers and switches are powered on and operational, and switches are connected together to provide backup or redundancy.

However, one thing you do notice is that all of your switches' status lights are constantly blinking at a very fast pace to the point that they almost appear solid. You think you have found the problem with the connectivity issues your employees are experiencing.

Use the Internet to research STP. As you research, take notes and describe:

- Broadcast storm
- Switching loops
- The purpose of STP
- Variations of STP

Complete the reflection questions that accompany the PDF file for this activity. Save your work and be prepared to share your answers with the class.

Refer to **Interactive Graphic** in online course.

2.1 Spanning Tree Concepts

2.1.1 Purpose of Spanning Tree

2.1.1.1 Redundancy at OSI Layers 1 and 2

The three-tier hierarchical network design that uses core, distribution, and access layers with redundancy, attempts to eliminate a single point of failure on the network. Multiple cabled paths between switches provide physical redundancy in a switched network. This improves the reliability and availability of the network. Having alternate physical paths for data to traverse the network makes it possible for users to access network resources, despite path disruption.

Click the Play button in Figure 1 to view an animation on redundancy.

1. PC1 is communicating with PC4 over a redundant network topology.
2. When the network link between S1 and S2 is disrupted, the path between PC1 and PC4 is automatically adjusted to compensate for the disruption.
3. When the network connection between S1 and S2 is restored, the path is then readjusted to route traffic directly from S2 to S1 to get to PC4.

For many organizations, the availability of the network is essential to supporting business needs; therefore, the network infrastructure design is a critical business element. Path redundancy is a solution for providing the necessary availability of multiple network services by eliminating the possibility of a single point of failure.

Note The OSI Layer 1 redundancy is illustrated using multiple links and devices, but more than just physical planning is required to complete the network setup. For the redundancy to work in a systematic way, the use of OSI Layer 2 protocols, such as STP is also required.

Redundancy is an important part of hierarchical design for preventing disruption of network services to users. Redundant networks require adding physical paths; but, logical redundancy must also be part of the design. However, redundant paths in a switched Ethernet network may cause both physical and logical Layer 2 loops.

Logical Layer 2 loops may occur due to the natural operation of switches, specifically, the learning and forwarding process. When multiple paths exist between two devices on a network, and there is no spanning tree implementation on the switches, a Layer 2 loop occurs. A Layer 2 loop can result in three primary issues, as listed in Figure 2.

Refer to **Online Course** for Illustration

2.1.1.2 Issues with Layer 1 Redundancy: MAC Database Instability

MAC Database Instability

Ethernet frames do not have a time to live (TTL) attribute, like IP packets. As a result, if there is no mechanism enabled to block continued propagation of these frames on a switched network, they continue to propagate between switches endlessly, or until a link is disrupted and breaks the loop. This continued propagation between switches can result in MAC database instability. This can occur due to broadcast frames forwarding.

Broadcast frames are forwarded out all switch ports, except the original ingress port. This ensures that all devices in a broadcast domain are able to receive the frame. If there is more than one path for the frame to be forwarded out, an endless loop can result. When a loop occurs, it is possible for the MAC address table on a switch to constantly change with the updates from the broadcast frames, resulting in MAC database instability.

Click the Play button in the figure to view the animation. When the animation pauses, read the text to the left of the topology. The animation will continue after the short pause.

In the animation:

1. PC1 sends out a broadcast frame to S2. S2 receives the broadcast frame on F0/11. When S2 receives the broadcast frame, it updates its MAC address table to record that PC1 is available on port F0/11.
2. Because it is a broadcast frame, S2 forwards the frame out all ports, including Trunk1 and Trunk2. When the broadcast frame arrives at S3 and S1, they update their MAC address tables to indicate that PC1 is available out port F0/1 on S1 and out port F0/2 on S3.
3. Because it is a broadcast frame, S3 and S1 forward the frame out all ports, except the ingress port. S3 sends the broadcast frame from PC1 to S1. S1 sends the broadcast frame from PC1 to S3. Each switch updates its MAC address table with the incorrect port for PC1.
4. Each switch again forwards the broadcast frame out all of its ports, except the ingress port, resulting in both switches forwarding the frame to S2.
5. When S2 receives the broadcast frames from S3 and S1, the MAC address table is updated again, this time with the last entry received from the other two switches.

This process repeats over and over again until the loop is broken by physically disconnecting the connections causing the loop or powering down one of the switches in the loop. This creates a high CPU load on all switches caught in the loop. Because the same frames are constantly being forwarded back and forth between all switches in the loop, the CPU of the switch must process a lot of data. This slows down performance on the switch when legitimate traffic arrives.

A host caught in a network loop is not accessible to other hosts on the network. Additionally, due to the constant changes in the MAC address table, the switch does not know out of which port to forward unicast frames. In the example above, the switches will

have the incorrect ports listed for PC1. Any unicast frame destined for PC1 loops around the network, just as the broadcast frames do. More and more frames looping around the network eventually create a broadcast storm.

Refer to **Online Course** for Illustration

2.1.1.3 Issues with Layer 1 Redundancy: Broadcast Storms

Broadcast Storm

A broadcast storm occurs when there are so many broadcast frames caught in a Layer 2 loop that all available bandwidth is consumed. Consequently, no bandwidth is available for legitimate traffic and the network becomes unavailable for data communication. This is an effective denial of service.

A broadcast storm is inevitable on a looped network. As more devices send broadcasts over the network, more traffic is caught within the loop, consuming resources. This eventually creates a broadcast storm that causes the network to fail.

There are other consequences of broadcast storms. Because broadcast traffic is forwarded out every port on a switch, all connected devices have to process all broadcast traffic that is being flooded endlessly around the looped network. This can cause the end device to malfunction because of the high processing requirements for sustaining such a high traffic load on the NIC.

Click the Play button in the figure to view an animation of a broadcast storm. When the animation pauses, read the text to the right of the topology. The animation will continue after the short pause.

In the animation:

1. PC1 sends a broadcast frame out onto the looped network.
2. The broadcast frame loops between all the interconnected switches on the network.
3. PC4 also sends a broadcast frame out on to the looped network.
4. The PC4 broadcast frame also gets caught in the loop between all the interconnected switches, just like the PC1 broadcast frame.
5. As more devices send broadcasts over the network, more traffic is caught within the loop, consuming resources. This eventually creates a broadcast storm that causes the network to fail.
6. When the network is fully saturated with broadcast traffic that is looping between the switches, new traffic is discarded by the switch because it is unable to process it.

Because devices connected to a network are regularly sending out broadcast frames, such as ARP requests, a broadcast storm can develop in seconds. As a result, when a loop is created, the switched network is quickly brought down.

Refer to **Online Course** for Illustration

2.1.1.4 Issues with Layer 1 Redundancy: Duplicate Unicast Frames

Multiple Frame Transmissions

Broadcast frames are not the only type of frames that are affected by loops. Unicast frames sent onto a looped network can result in duplicate frames arriving at the destination device.

Click the Play button in the figure to view an animation of this issue. When the animation pauses, read the text to the right of the topology. The animation will continue after the short pause.

In the animation:

1. PC1 sends a unicast frame destined for PC4.
2. S2 does not have an entry for PC4 in its MAC table, so it floods the unicast frame out all switch ports in an attempt to find PC4.
3. The frame arrives at switches S1 and S3.
4. S1 does have a MAC address entry for PC4, so it forwards the frame out to PC4.
5. S3 also has an entry in its MAC address table for PC4, so it forwards the unicast frame out Trunk3 to S1.
6. S1 receives the duplicate frame and forwards the frame out to PC4.
7. PC4 has now received the same frame twice.

Most upper layer protocols are not designed to recognize, or cope with, duplicate transmissions. In general, protocols that make use of a sequence-numbering mechanism assume that the transmission has failed and that the sequence number has recycled for another communication session. Other protocols attempt to hand the duplicate transmission to the appropriate upper layer protocol to be processed and possibly discarded.

Layer 2 LAN protocols, such as Ethernet, lack a mechanism to recognize and eliminate endlessly looping frames. Some Layer 3 protocols implement a TTL mechanism that limits the number of times a Layer 3 networking device can retransmit a packet. Lacking such a mechanism, Layer 2 devices continue to retransmit looping traffic indefinitely. A Layer 2 loop-avoidance mechanism, STP, was developed to address these problems.

To prevent these issues from occurring in a redundant network, some type of spanning tree must be enabled on the switches. Spanning tree is enabled, by default, on Cisco switches to prevent Layer 2 loops from occurring.

Refer to **Packet Tracer Activity** for this chapter

2.1.1.5 Packet Tracer - Examining a Redundant Design

Background/Scenario

In this activity, you will observe how STP operates, by default, and how it reacts when faults occur. Switches have been added to the network "out of the box". Cisco switches can be connected to a network without any additional action required by the network administrator. For the purpose of this activity, the bridge priority was modified.

Refer to **Online Course** for Illustration

2.1.2 STP Operation

2.1.2.1 Spanning Tree Algorithm: Introduction

Redundancy increases the availability of the network topology by protecting the network from a single point of failure, such as a failed network cable or switch. When physical redundancy is introduced into a design, loops and duplicate frames occur. Loops and duplicate frames have severe consequences for a switched network. The Spanning Tree Protocol (STP) was developed to address these issues.

STP ensures that there is only one logical path between all destinations on the network by intentionally blocking redundant paths that could cause a loop. A port is considered blocked when user data is prevented from entering or leaving that port. This does not include bridge protocol data unit (BPDU) frames that are used by STP to prevent loops. Blocking the redundant paths is critical to preventing loops on the network. The physical paths still exist to provide redundancy, but these paths are disabled to prevent the loops from occurring. If the path is ever needed to compensate for a network cable or switch failure, STP recalculates the paths and unblocks the necessary ports to allow the redundant path to become active.

Click the Play button in Figure 1 to view STP in action.

In the example, all switches have STP enabled:

1. PC1 sends a broadcast out onto the network.
2. S2 is configured with STP and has set the port for Trunk2 to a blocking state. The blocking state prevents ports from being used to forward user data, thus preventing a loop from occurring. S2 forwards a broadcast frame out all switch ports, except the originating port from PC1 and the port for Trunk2.
3. S1 receives the broadcast frame and forwards it out all of its switch ports, where it reaches PC4 and S3. S3 forwards the frame out the port for Trunk2 and S2 drops the frame. The Layer 2 loop is prevented.

Click the Play in Figure 2 to view STP recalculation when a failure occurs.

In this example:

1. PC1 sends a broadcast out onto the network.
2. The broadcast is then forwarded around the network, just as in the previous animation.
3. The trunk link between S2 and S1 fails, resulting in the previous path being disrupted.
4. S2 unblocks the previously blocked port for Trunk2 and allows the broadcast traffic to traverse the alternate path around the network, permitting communication to continue. If this link comes back up, STP reconverges and the port on S2 is again blocked.

STP prevents loops from occurring by configuring a loop-free path through the network using strategically placed “blocking-state” ports. The switches running STP are able to compensate for failures by dynamically unblocking the previously blocked ports and permitting traffic to traverse the alternate paths.

Up to now, we have used the term Spanning Tree Protocol and the acronym STP. The usage of the Spanning Tree Protocol term and the STP acronym can be misleading. Many professionals generically use these to refer to various implementations of spanning tree, such as Rapid Spanning Tree Protocol (RSTP) and Multiple Spanning Tree Protocol (MSTP). In order to communicate spanning tree concepts correctly, it is important to refer to the particular implementation or standard in context. The latest IEEE documentation on spanning tree, IEEE-802-1D-2004, says “STP has now been superseded by the Rapid Spanning Tree Protocol (RSTP)”; so one sees that the IEEE uses “STP” to refer to the original implementation of spanning tree and “RSTP” to describe the version of spanning tree specified in IEEE-802.1D-2004. In this curriculum, when the original Spanning Tree Protocol is the context of a discussion, the phrase “original 802.1D spanning tree” is used to avoid confusion.

Note STP is based on an algorithm invented by Radia Perlman while working for Digital Equipment Corporation, and published in the 1985 paper "An Algorithm for Distributed Computation of a Spanning Tree in an Extended LAN".

Refer to **Online Course** for Illustration

2.1.2.2 Spanning Tree Algorithm: Port Roles

IEEE 802.1D STP uses the Spanning Tree Algorithm (STA) to determine which switch ports on a network must be put in blocking state to prevent loops from occurring. The STA designates a single switch as the root bridge and uses it as the reference point for all path calculations. In the figure, the root bridge (switch S1) is chosen through an election process. All switches participating in STP exchange BPDU frames to determine which switch has the lowest bridge ID (BID) on the network. The switch with the lowest BID automatically becomes the root bridge for the STA calculations.

Note For simplicity, assume until otherwise indicated that all ports on all switches are assigned to VLAN 1. Each switch has a unique MAC address associated with VLAN 1.

A BPDU is a messaging frame exchanged by switches for STP. Each BPDU contains a BID that identifies the switch that sent the BPDU. The BID contains a priority value, the MAC address of the sending switch, and an optional extended system ID. The lowest BID value is determined by the combination of these three fields.

After the root bridge has been determined, the STA calculates the shortest path to it. Each switch uses the STA to determine which ports to block. While the STA determines the best paths to the root bridge for all switch ports in the broadcast domain, traffic is prevented from being forwarded through the network. The STA considers both path and port costs when determining which ports to block. The path costs are calculated using port cost values associated with port speeds for each switch port along a given path. The sum of the port cost values determines the overall path cost to the root bridge. If there is more than one path to choose from, STA chooses the path with the lowest path cost.

When the STA has determined which paths are most desirable relative to each switch, it assigns port roles to the participating switch ports. The port roles describe their relation in the network to the root bridge and whether they are allowed to forward traffic:

- **Root ports**- Switch ports closest to the root bridge. In the figure, the root port on S2 is F0/1 configured for the trunk link between S2 and S1. The root port on S3 is F0/1, configured for the trunk link between S3 and S1. Root ports are selected on a per-switch basis.
- **Designated ports**- All non-root ports that are still permitted to forward traffic on the network. In the figure, switch ports (F0/1 and F0/2) on S1 are designated ports. S2 also has its port F0/2 configured as a designated port. Designated ports are selected on a per-trunk basis. If one end of a trunk is a root port, then the other end is a designated port. All ports on the root bridge are designated ports.
- **Alternate and backup ports**- Alternate ports and backup ports are configured to be in a blocking state to prevent loops. In the figure, the STA configured port F0/2 on S3 in the alternate role. Port F0/2 on S3 is in the blocking state. Alternate ports are selected only on trunk links where neither end is a root port. Notice in the figure that only

one end of the trunk is blocked. This allows for faster transition to a forwarding state, when necessary. (Blocking ports only come into play when two ports on the same switch are connected to each other via a hub or single cable.)

- **Disabled ports**- A disabled port is a switch port that is shut down.

Refer to **Online Course** for Illustration

2.1.2.3 Spanning Tree Algorithm: Root Bridge

As shown in Figure 1, every spanning tree instance (switched LAN or broadcast domain) has a switch designated as the root bridge. The root bridge serves as a reference point for all spanning tree calculations to determine which redundant paths to block.

An election process determines which switch becomes the root bridge.

Figure 2 shows the BID fields. The BID is made up of a priority value, an extended system ID, and the MAC address of the switch.

All switches in the broadcast domain participate in the election process. After a switch boots, it begins to send out BPDU frames every two seconds. These BPDUs contain the switch BID and the root ID.

As the switches forward their BPDU frames, adjacent switches in the broadcast domain read the root ID information from the BPDU frames. If the root ID from a BPDU received is lower than the root ID on the receiving switch, then the receiving switch updates its root ID, identifying the adjacent switch as the root bridge. Actually, it may not be an adjacent switch, but could be any other switch in the broadcast domain. The switch then forwards new BPDU frames with the lower root ID to the other adjacent switches. Eventually, the switch with the lowest BID ends up being identified as the root bridge for the spanning tree instance.

There is a root bridge elected for each spanning tree instance. It is possible to have multiple distinct root bridges. If all ports on all switches are members of VLAN 1, then there is only one spanning tree instance. The extended system ID plays a role in how spanning tree instances are determined.

Refer to **Online Course** for Illustration

2.1.2.4 Spanning Tree Algorithm: Path Cost

When the root bridge has been elected for the spanning tree instance, the STA starts the process of determining the best paths to the root bridge from all destinations in the broadcast domain. The path information is determined by summing up the individual port costs along the path from the destination to the root bridge. Each “destination” is actually a switch port.

The default port costs are defined by the speed at which the port operates. As shown in Figure 1, 10 Gb/s Ethernet ports have a port cost of 2, 1 Gb/s Ethernet ports have a port cost of 4, 100 Mb/s Fast Ethernet ports have a port cost of 19, and 10 Mb/s Ethernet ports have a port cost of 100.

Note As newer, faster Ethernet technologies enter the marketplace, the path cost values may change to accommodate the different speeds available. The non-linear numbers in the table accommodate some improvements to the older Ethernet standard. The values have already been changed to accommodate the 10 Gb/s Ethernet standard. To illustrate the continued change associated with high-speed networking, Catalyst 4500 and 6500 switches support a longer path cost method; for example, 10 Gb/s has a 2000 path cost, 100 Gb/s has a 200 path cost, and 1 Tb/s has a 20 path cost.

Although switch ports have a default port cost associated with them, the port cost is configurable. The ability to configure individual port costs gives the administrator the flexibility to manually control the spanning tree paths to the root bridge.

To configure the port cost of an interface (Figure 2), enter the **`spanning-tree cost`** value command in interface configuration mode. The value can be between 1 and 200,000,000.

In the example, switch port F0/1 has been configured with a port cost of 25 using the **`spanning-tree cost 25`** interface configuration mode command on the F0/1 interface.

To restore the port cost back to the default value of 19, enter the **`no spanning-tree cost`** interface configuration mode command.

The path cost is equal to the sum of all the port costs along the path to the root bridge (Figure 3). Paths with the lowest cost become preferred, and all other redundant paths are blocked. In the example, the path cost from S2 to the root bridge S1, over path 1 is 19 (based on the IEEE-specified individual port cost), while the path cost over path 2 is 38. Because path 1 has a lower overall path cost to the root bridge, it is the preferred path. STP then configures the redundant path to be blocked, preventing a loop from occurring.

To verify the port and path cost to the root bridge, enter the **`show spanning-tree`** command (Figure 4). The Cost field near the top of the output is the total path cost to the root bridge. This value changes depending on how many switch ports must be traversed to get to the root bridge. In the output, each interface is also identified with an individual port cost of 19.

Refer to **Online Course** for Illustration

2.1.2.5 802.1D BPDU Frame Format

The spanning tree algorithm depends on the exchange of BPDUs to determine a root bridge. A BPDU frame contains 12 distinct fields that convey path and priority information used to determine the root bridge and paths to the root bridge.

Click the BPDU fields in Figure 1 to see more detail.

- The first four fields identify the protocol, version, message type, and status flags.
- The next four fields are used to identify the root bridge and the cost of the path to the root bridge.
- The last four fields are all timer fields that determine how frequently BPDU messages are sent and how long the information received through the BPDU process (next topic) is retained.

Figure 2 shows a BPDU frame that was captured using Wireshark. In the example, the BPDU frame contains more fields than previously described. The BPDU message is encapsulated in an Ethernet frame when it is transmitted across the network. The 802.3 header indicates the source and destination addresses of the BPDU frame. This frame has a destination MAC address of 01:80:C2:00:00:00, which is a multicast address for the spanning tree group. When a frame is addressed with this MAC address, each switch that is configured for spanning tree accepts and reads the information from the frame; all other devices on the network disregard the frame.

In the example, the root ID and the BID are the same in the captured BPDU frame. This indicates that the frame was captured from a root bridge. The timers are all set to the default values.

Refer to **Online Course** for Illustration

2.1.2.6 BPDU Propagation and Process

Each switch in the broadcast domain initially assumes that it is the root bridge for a spanning tree instance, so the BPDU frames sent contain the BID of the local switch as the root ID. By default, BPDU frames are sent every two seconds after a switch is booted; that is, the default value of the Hello timer specified in the BPDU frame is two seconds. Each switch maintains local information about its own BID, the root ID, and the path cost to the root.

When adjacent switches receive a BPDU frame, they compare the root ID from the BPDU frame with the local root ID. If the root ID in the BPDU is lower than the local root ID, the switch updates the local root ID and the ID in its BPDU messages. These messages indicate the new root bridge on the network. The distance to the root bridge is also indicated by the path cost update. For example, if the BPDU was received on a Fast Ethernet switch port, the path cost would increment by 19. If the local root ID is lower than the root ID received in the BPDU frame, the BPDU frame is discarded.

After a root ID has been updated to identify a new root bridge, all subsequent BPDU frames sent from that switch contain the new root ID and updated path cost. That way, all other adjacent switches are able to see the lowest root ID identified at all times. As the BPDU frames pass between other adjacent switches, the path cost is continually updated to indicate the total path cost to the root bridge. Each switch in the spanning tree uses its path costs to identify the best possible path to the root bridge.

The following summarizes the BPDU process:

Note Priority is the initial deciding factor when electing a root bridge. If the priorities of all the switches are the same, the device with the lowest MAC address becomes the root bridge.

1. Initially, each switch identifies itself as the root bridge. S2 forwards BPDU frames out all switch ports. (Figure 1)
2. When S3 receives a BPDU from switch S2, S3 compares its root ID with the BPDU frame it received. The priorities are equal, so the switch is forced to examine the MAC address portion to determine which MAC address has a lower value. Because S2 has a lower MAC address value, S3 updates its root ID with the S2 root ID. At that point, S3 considers S2 as the root bridge. (Figure 2)

3. When S1 compares its root ID with the one in the received BPDU frame, it identifies its local root ID as the lower value and discards the BPDU from S2. (Figure 3)
4. When S3 sends out its BPDU frames, the root ID contained in the BPDU frame is that of S2. (Figure 4)
5. When S2 receives the BPDU frame, it discards it after verifying that the root ID in the BPDU matched its local root ID. (Figure 5)
6. Because S1 has a lower priority value in its root ID, it discards the BPDU frame received from S3. (Figure 6)
7. S1 sends out its BPDU frames. (Figure 7)
8. S3 identifies the root ID in the BPDU frame as having a lower value and, therefore, updates its root ID values to indicate that S1 is now the root bridge. (Figure 8)
9. S2 identifies the root ID in the BPDU frame as having a lower value and, therefore, updates its root ID values to indicate that S1 is now the root bridge. (Figure 9)

Refer to **Online Course** for Illustration

2.1.2.7 Extended System ID

The bridge ID (BID) is used to determine the root bridge on a network. The BID field of a BPDU frame contains three separate fields:

- Bridge priority
- Extended system ID
- MAC address

Each field is used during the root bridge election.

Bridge Priority

The bridge priority is a customizable value that can be used to influence which switch becomes the root bridge. The switch with the lowest priority, which implies the lowest BID, becomes the root bridge because a lower priority value takes precedence. For example, to ensure that a specific switch is always the root bridge, set the priority to a lower value than the rest of the switches on the network. The default priority value for all Cisco switches is 32768. The range is 0 to 61440 in increments of 4096. Valid priority values are 0, 4096, 8192, 12288, 16384, 20480, 24576, 28672, 32768, 36864, 40960, 45056, 49152, 53248, 57344, and 61440. All other values are rejected. A bridge priority of 0 takes precedence over all other bridge priorities.

Extended System ID

Early implementations of IEEE 802.1D were designed for networks that did not use VLANs. There was a single common spanning tree across all switches. For this reason, in older Cisco switches, the extended system ID could be omitted in BPDU frames. As VLANs became common for network infrastructure segmentation, 802.1D was enhanced to include support for VLANs, requiring the VLAN ID to be included in the BPDU frame. VLAN information is included in the BPDU frame through the use of the extended system ID. All newer switches include the use of the extended system ID by default.

As shown in Figure 1, the bridge priority field is 2 bytes or 16-bits in length; 4-bits used for the bridge priority and 12-bits for the extended system ID, which identifies the VLAN participating in this particular STP process. Using these 12 bits for the extended system

ID reduces the bridge priority to 4 bits. This process reserves the rightmost 12 bits for the VLAN ID and the far left 4 bits for the bridge priority. This explains why the bridge priority value can only be configured in multiples of 4096, or 2^12. If the far left bits are 0001, then the bridge priority is 4096; if the far left bits are 1111, then the bridge priority is 61440 (= 15 x 4096). The Catalyst 2960 and 3560 Series switches do not allow the configuration of a bridge priority of 65536 (= 16 x 4096) because it assumes use of a 5th bit that is unavailable due to the use of the extended system ID.

The extended system ID value is added to the bridge priority value in the BID to identify the priority and VLAN of the BPDU frame.

When two switches are configured with the same priority and have the same extended system ID, the switch having the MAC address with the lowest hexadecimal value will have the lower BID. Initially, all switches are configured with the same default priority value. The MAC address is then the deciding factor on which switch is going to become the root bridge. To ensure that the root bridge decision best meets network requirements, it is recommended that the administrator configure the desired root bridge switch with a lower priority. This also ensures that the addition of new switches to the network does not trigger a new spanning tree election, which can disrupt network communication while a new root bridge is being selected.

In Figure 2, S1 has a lower priority than the other switches; therefore, it is preferred as the root bridge for that spanning tree instance.

When all switches are configured with the same priority, as is the case with all switches kept in the default configuration with a priority of 32768, the MAC address becomes the deciding factor for which switch becomes the root bridge (Figure 3).

Note In the example, the priority of all the switches is 32769. The value is based on the 32768 default priority and the VLAN 1 assignment associated with each switch (32768+1).

The MAC address with the lowest hexadecimal value is considered to be the preferred root bridge. In the example, S2 has the lowest value for its MAC address and is, therefore, designated as the root bridge for that spanning tree instance.

Refer to **Interactive Graphic** in online course.

2.1.2.8 Activity - Identify 802.1D Port Roles

Refer to **Interactive Graphic** in online course.

2.1.2.9 Video Demonstration - Observing Spanning Tree Protocol Operation

Refer to **Lab Activity** for this chapter

2.1.2.10 Lab – Building a Switched Network with Redundant Links

In this lab, you will complete the following objectives:

- Part 1: Build the Network and Configure Basic Device Settings
- Part 2: Determine the Root Bridge
- Part 3: Observe STP Port Selection Based on Port Cost
- Part 4: Observe STP Port Selection Based on Port Priority

Refer to **Online Course** for Illustration

2.2 Varieties of Spanning Tree Protocols

2.2.1 Overview

2.2.1.1 List of Spanning Tree Protocols

Several varieties of spanning tree protocols have emerged since the original IEEE 802.1D.

The varieties of spanning tree protocols include:

- **STP**- This is the original IEEE 802.1D version (802.1D-1998 and earlier) that provides a loop-free topology in a network with redundant links. Common Spanning Tree (CST) assumes one spanning tree instance for the entire bridged network, regardless of the number of VLANs.
- **PVST+**- This is a Cisco enhancement of STP that provides a separate 802.1D spanning tree instance for each VLAN configured in the network. The separate instance supports PortFast, UplinkFast, BackboneFast, BPDU guard, BPDU filter, root guard, and loop guard.
- **802.1D-2004**- This is an updated version of the STP standard, incorporating IEEE 802.1w.
- **Rapid Spanning Tree Protocol (RSTP) or IEEE 802.1w**- This is an evolution of STP that provides faster convergence than STP.
- **Rapid PVST+**- This is a Cisco enhancement of RSTP that uses PVST+. Rapid PVST+ provides a separate instance of 802.1w per VLAN. The separate instance supports PortFast, BPDU guard, BPDU filter, root guard, and loop guard.
- **Multiple Spanning Tree Protocol (MSTP)**- This is an IEEE standard inspired by the earlier Cisco proprietary Multiple Instance STP (MISTP) implementation. MSTP maps multiple VLANs into the same spanning tree instance. The Cisco implementation of MSTP is MST, which provides up to 16 instances of RSTP and combines many VLANs with the same physical and logical topology into a common RSTP instance. Each instance supports PortFast, BPDU guard, BPDU filter, root guard, and loop guard.

A network professional, whose duties include switch administration, may be required to decide which type of spanning tree protocol to implement.

Note The legacy Cisco-proprietary features UplinkFast and BackboneFast are not described in this course. These features are superseded by the implementation of Rapid PVST+, which incorporates these features as part of the implementation of the RSTP standard.

Refer to **Online Course** for Illustration

2.2.1.2 Characteristics of the Spanning Tree Protocols

These are characteristics of the various spanning tree protocols. The italicized words indicate whether the particular spanning tree protocol is Cisco-proprietary or an IEEE standard implementation:

- **STP**- Assumes one *IEEE 802.1D* spanning tree instance for the entire bridged network, regardless of the number of VLANs. Because there is only one instance, the CPU and

memory requirements for this version are lower than for the other protocols. However, because there is only one instance, there is only one root bridge and one tree. Traffic for all VLANs flows over the same path, which can lead to suboptimal traffic flows. Because of the limitations of 802.1D, this version is slow to converge.

- **PVST+**- A Cisco enhancement of STP that provides a separate instance of the Cisco implementation of 802.1D for each VLAN that is configured in the network. The separate instance supports PortFast, UplinkFast, BackboneFast, BPDU guard, BPDU filter, root guard, and loop guard. Creating an instance for each VLAN increases the CPU and memory requirements, but allows for per-VLAN root bridges. This design allows the spanning tree to be optimized for the traffic of each VLAN. Convergence of this version is similar to the convergence of 802.1D. However, convergence is per-VLAN.
- **RSTP** (or *IEEE 802.1w*) - An evolution of spanning tree that provides faster convergence than the original 802.1D implementation. This version addresses many convergence issues, but because it still provides a single instance of STP, it does not address the suboptimal traffic flow issues. To support that faster convergence, the CPU usage and memory requirements of this version are slightly higher than those of CST, but less than those of RSTP+.
- **Rapid PVST+**- A Cisco enhancement of RSTP that uses PVST+. It provides a separate instance of 802.1w per VLAN. The separate instance supports PortFast, BPDU guard, BPDU filter, root guard, and loop guard. This version addresses both the convergence issues and the suboptimal traffic flow issues. However, this version has the largest CPU and memory requirements.
- **MSTP**- The *IEEE 802.1s* standard, inspired by the earlier Cisco proprietary MISTP implementation. To reduce the number of required STP instances, MSTP maps multiple VLANs that have the same traffic flow requirements into the same spanning tree instance.
- **MST**- The Cisco implementation of MSTP, which provides up to 16 instances of RSTP (802.1w) and combines many VLANs with the same physical and logical topology into a common RSTP instance. Each instance supports PortFast, BPDU guard, BPDU filter, root guard, and loop guard. The CPU and memory requirements of this version are less than those of Rapid PVST+, but more than those of RSTP.

The default spanning tree mode for Cisco Catalyst switches is PVST+, which is enabled on all ports. PVST+ has much slower convergence after a topology change than Rapid PVST+.

Note It is important to distinguish between the legacy IEEE 802.1D-1998 (and earlier) standard and the IEEE 802.1D-2004 standard. IEEE 802.1D-2004 incorporates RSTP functionality, while IEEE 802.1D-1998 refers to the original implementation of the spanning tree algorithm. Newer Cisco switches running newer versions of the IOS, such as Catalyst 2960 switches with IOS 15.0, run PVST+ by default, but incorporate many of the specifications of IEEE 802.1D-1998 in this mode (such as alternate ports in place of the former non-designated ports); but to run rapid spanning tree on such a switch it still must be explicitly configured for rapid spanning tree mode.

Refer to **Interactive Graphic** in online course.

2.2.1.3 Activity - Identify Types of Spanning Tree Protocols

Refer to **Online Course** for Illustration

2.2.2 PVST+

2.2.2.1 Overview of PVST+

The original IEEE 802.1D standard defines a Common Spanning Tree (CST) that assumes only one spanning tree instance for the entire switched network, regardless of the number of VLAN. A network running CST has these characteristics:

- No load sharing is possible. One uplink must block for all VLANs.
- The CPU is spared. Only one instance of spanning tree must be computed.

Cisco developed PVST+ so that a network can run an independent instance of the Cisco implementation of IEEE 802.1D for each VLAN in the network. With PVST+, it is possible for one trunk port on a switch to be blocking for a VLAN while not blocking for other VLANs. PVST+ can be used to implement Layer 2 load balancing. Because each VLAN runs a separate instance of STP, the switches in a PVST+ environment require greater CPU process and BPDU bandwidth consumption than a traditional CST implementation of STP.

In a PVST+ environment, spanning tree parameters can be tuned so that half of the VLANs forward on each uplink trunk. In the figure, port F0/3 on S2 is the forwarding port for VLAN 20, and F0/2 on S2 is the forwarding port for VLAN 10. This is accomplished by configuring one switch to be elected the root bridge for half of the VLANs in the network, and a second switch to be elected the root bridge for the other half of the VLANs. In the figure, S3 is the root bridge for VLAN 20, and S1 is the root bridge for VLAN 10. Multiple STP root bridges per VLAN increases redundancy in the network.

Networks running PVST+ have these characteristics:

- Optimum load balancing can result.
- One spanning tree instance for each VLAN maintained can mean a considerable waste of CPU cycles for all the switches in the network (in addition to the bandwidth that is used for each instance to send its own BPDU). This would only be problematic if a large number of VLANs are configured.

Refer to **Online Course** for Illustration

2.2.2.2 Port States and PVST+ Operation

STP facilitates the logical loop-free path throughout the broadcast domain. The spanning tree is determined through the information learned by the exchange of the BPDU frames between the interconnected switches. To facilitate the learning of the logical spanning tree, each switch port transitions through five possible port states and three BPDU timers.

The spanning tree is determined immediately after a switch is finished booting up. If a switch port transitions directly from the blocking to the forwarding state without information about the full topology during the transition, the port can temporarily create a data

loop. For this reason, STP introduces the five port states. The figure describes the following port states that ensure no loops are created during the creation of the logical spanning tree:

- **Blocking**- The port is an alternate port and does not participate in frame forwarding. The port receives BPDU frames to determine the location and root ID of the root bridge switch and what port roles each switch port should assume in the final active STP topology.
- **Listening**- Listens for the path to the root. STP has determined that the port can participate in frame forwarding according to the BPDU frames that the switch has received thus far. At this point, the switch port not only receives BPDU frames, it also transmits its own BPDU frames and inform adjacent switches that the switch port is preparing to participate in the active topology.
- **Learning**- Learns the MAC addresses. The port prepares to participate in frame forwarding and begins to populate the MAC address table.
- **Forwarding**- The port is considered part of the active topology. It forwards data frames and sends and receives BPDU frames.
- **Disabled**- The Layer 2 port does not participate in spanning tree and does not forward frames. The disabled state is set when the switch port is administratively disabled.

Note that the number of ports in each of the various states (blocking, listening, learning, or forwarding) can be displayed with the **`show spanning-tree summary`** command.

For each VLAN in a switched network, PVST+ performs four steps to provide a loop-free logical network topology:

1. **Elects one root bridge**- Only one switch can act as the root bridge (for a given VLAN). The root bridge is the switch with the lowest bridge ID. On the root bridge, all ports are designated ports (in particular, no root ports).
2. **Selects the root port on each non-root bridge**- STP establishes one root port on each non-root bridge. The root port is the lowest-cost path from the non-root bridge to the root bridge, indicating the direction of the best path to the root bridge. Root ports are normally in the forwarding state.
3. **Selects the designated port on each segment**- On each link, STP establishes one designated port. The designated port is selected on the switch that has the lowest-cost path to the root bridge. Designated ports are normally in the forwarding state, forwarding traffic for the segment.
4. **The remaining ports in the switched network are alternate ports**- Alternate ports normally remain in the blocking state, to logically break the loop topology. When a port is in the blocking state, it does not forward traffic, but can still process received BPDU messages.

Refer to **Online Course** for Illustration

2.2.2.3 Extended System ID and PVST+ Operation

In a PVST+ environment, the extended switch ID ensures each switch has a unique BID for each VLAN.

For example, the VLAN 2 default BID would be 32770 (priority 32768, plus the extended system ID of 2). If no priority has been configured, every switch has the same default

priority and the election of the root for each VLAN is based on the MAC address. This method is a random means of selecting the root bridge.

There are situations where the administrator may want a specific switch selected as the root bridge. This may be for a variety of reasons, including the switch is more centrally located within the LAN design, the switch has higher processing power, or the switch is simply easier to access and manage remotely. To manipulate the root bridge election, simply assign a lower priority to the switch that should be selected as the root bridge.

Refer to **Interactive Graphic** in online course.

2.2.2.4 Activity - Identifying PVST+ Operation

Refer to **Online Course** for Illustration

2.2.3 Rapid PVST+

2.2.3.1 Overview of Rapid PVST+

RSTP (IEEE 802.1w) is an evolution of the original 802.1D standard and is incorporated into the IEEE 802.1D-2004 standard. The 802.1w STP terminology remains primarily the same as the original IEEE 802.1D STP terminology. Most parameters have been left unchanged, so users familiar with STP can easily configure the new protocol. Rapid PVST+ is simply the Cisco implementation of RSTP on a per-VLAN basis. With Rapid PVST+, an independent instance of RSTP runs for each VLAN.

The figure shows a network running RSTP. S1 is the root bridge with two designated ports in a forwarding state. RSTP supports a new port type: port F0/3 on S2 is an alternate port in discarding state. Notice that there are no blocking ports. RSTP does not have a blocking port state. RSTP defines port states as discarding, learning, or forwarding.

RSTP speeds the recalculation of the spanning tree when the Layer 2 network topology changes. RSTP can achieve much faster convergence in a properly configured network, sometimes in as little as a few hundred milliseconds. RSTP redefines the type of ports and their state. If a port is configured to be an alternate port or a backup port, it can immediately change to forwarding state without waiting for the network to converge. The following briefly describes RSTP characteristics:

- RSTP is the preferred protocol for preventing Layer 2 loops in a switched network environment. Many of the differences were established by Cisco-proprietary enhancements to the original 802.1D. These enhancements, such as BPDUs carrying and sending information about port roles only to neighboring switches, require no additional configuration and generally perform better than the earlier Cisco-proprietary versions. They are now transparent and integrated in the protocol's operation.
- Cisco-proprietary enhancements to the original 802.1D, such as UplinkFast and BackboneFast, are not compatible with RSTP.
- RSTP (802.1w) supersedes the original 802.1D while retaining backward compatibility. Much of the original 802.1D terminology remains and most parameters are unchanged. In addition, 802.1w is capable of reverting back to legacy 802.1D to interoperate with legacy switches on a per-port basis. For example, the RSTP spanning tree algorithm elects a root bridge in exactly the same way as the original 802.1D.
- RSTP keeps the same BPDU format as the original IEEE 802.1D, except that the version field is set to 2 to indicate RSTP, and the flags field uses all 8 bits.

- RSTP is able to actively confirm that a port can safely transition to the forwarding state without having to rely on any timer configuration.

Refer to **Online Course** for Illustration

2.2.3.2 RSTP BPDU

RSTP uses type 2, version 2 BPDUs. The original 802.1D STP uses type 0, version 0 BPDUs. However, a switch running RSTP can communicate directly with a switch running the original 802.1D STP. RSTP sends BPDUs and populates the flag byte in a slightly different manner than in the original 802.1D:

- Protocol information can be immediately aged on a port if Hello packets are not received for three consecutive Hello times, six seconds by default, or if the max age timer expires.
- Because BPDUs are used as a keepalive mechanism, three consecutively missed BPDUs indicate lost connectivity between a bridge and its neighboring root or designated bridge. The fast aging of the information allows failures to be detected quickly.

Note Like STP, an RSTP switch sends a BPDU with its current information every Hello time period (two seconds, by default), even if the RSTP bridge does not receive any BPDUs from the root bridge.

As shown in the figure, RSTP uses the flag byte of version 2 BPDU:

- Bits 0 and 7 are used for topology change and acknowledgment as they are in the original 802.1D.
- Bits 1 and 6 are used for the Proposal Agreement process (used for rapid convergence).
- Bits from 2 to 5 encode the role and state of the port.
- Bits 4 and 5 are used to encode the port role using a 2-bit code.

Refer to **Online Course** for Illustration

2.2.3.3 Edge Ports

An RSTP edge port is a switch port that is never intended to be connected to another switch device. It immediately transitions to the forwarding state when enabled.

The RSTP edge port concept corresponds to the PVST+ PortFast feature; an edge port is directly connected to an end station and assumes that no switch device is connected to it. RSTP edge ports should immediately transition to the forwarding state, thereby skipping the time-consuming original 802.1D listening and learning port states.

The Cisco RSTP implementation, Rapid PVST+, maintains the PortFast keyword, using the **`spanning-tree portfast`** command for edge port configuration. This makes the transition from STP to RSTP seamless.

Figure 1 shows examples of ports that can be configured as edge ports. Figure 2 shows examples of ports that are non-edge ports.

Note Configuring an edge port to be attached to another switch is not recommended. This can have negative implications for RSTP because a temporary loop may result, possibly delaying the convergence of RSTP.

Refer to **Online Course** for Illustration

2.2.3.4 Link Types

The link type provides a categorization for each port participating in RSTP by using the duplex mode on the port. Depending on what is attached to each port, two different link types can be identified:

- **Point-to-Point**- A port operating in full-duplex mode typically connects a switch to a switch and is a candidate for rapid transition to forwarding state.
- **Shared**- A port operating in half-duplex mode connects a switch to a hub that attaches multiple devices.

In the figure, click each link to learn about the link types.

The link type can determine whether the port can immediately transition to forwarding state, assuming certain conditions are met. These conditions are different for edge ports and non-edge ports. Non-edge ports are categorized into two link types, point-to-point and shared. The link type is automatically determined, but can be overridden with an explicit port configuration using the `spanning-tree link-type` parameter command.

Edge port connections and point-to-point connections are candidates for rapid transition to forwarding state. However, before the link-type parameter is considered, RSTP must determine the port role. Characteristics of port roles with regard to link types include the following:

- Root ports do not use the link-type parameter. Root ports are able to make a rapid transition to the forwarding state as soon as the port is in sync.
- Alternate and backup ports do not use the link-type parameter in most cases.
- Designated ports make the most use of the link-type parameter. Rapid transition to the forwarding state for the designated port occurs only if the link-type parameter is set to point-to-point.

Refer to **Interactive Graphic** in online course.

2.2.3.5 Activity - Identify Port Roles in Rapid PVST+

Refer to **Interactive Graphic** in online course.

2.2.3.6 Activity - Compare PVST+ and Rapid PVST+

Refer to **Online Course** for Illustration

2.3 Spanning Tree Configuration

2.3.1 PVST+ Configuration

2.3.1.1 Catalyst 2960 Default Configuration

The table shows the default spanning tree configuration for a Cisco Catalyst 2960 series switch. Notice that the default spanning tree mode is PVST+.

Refer to **Online Course** for Illustration

2.3.1.2 Configuring and Verifying the Bridge ID

When an administrator wants a specific switch to become a root bridge, the bridge priority value must be adjusted to ensure it is lower than the bridge priority values of all the other switches on the network. There are two different methods to configure the bridge priority value on a Cisco Catalyst switch.

Method 1

To ensure that the switch has the lowest bridge priority value, use the **spanning-tree vlan** vlan-id **root primary** command in global configuration mode. The priority for the switch is set to the predefined value of 24,576 or to the highest multiple of 4,096, less than the lowest bridge priority detected on the network.

If an alternate root bridge is desired, use the **spanning-tree vlan** vlan-id **root secondary** global configuration mode command. This command sets the priority for the switch to the predefined value of 28,672. This ensures that the alternate switch becomes the root bridge if the primary root bridge fails. This assumes that the rest of the switches in the network have the default 32,768 priority value defined.

In Figure 1, S1 has been assigned as the primary root bridge using the **spanning-tree vlan 1 root primary** command, and S2 has been configured as the secondary root bridge using the **spanning-tree vlan 1 root secondary** command.

Method 2

Another method for configuring the bridge priority value is using the **spanning-tree vlan** vlan-id **priority** value global configuration mode command. This command gives more granular control over the bridge priority value. The priority value is configured in increments of 4,096 between 0 and 61,440.

In the example, S3 has been assigned a bridge priority value of 24,576 using the **spanning-tree vlan 1 priority 24576** command.

To verify the bridge priority of a switch, use the **show spanning-tree** command. In Figure 2, the priority of the switch has been set to 24,576. Also notice that the switch is designated as the root bridge for the spanning tree instance.

Use the Syntax Checker in Figure 3 to configure switches S1, S2, and S3. Using Method 2 described above, configure S3 manually, setting the priority to 24,576 for VLAN 1. Using Method 1, configure S2 as the secondary root VLAN 1 and configure S1 as the primary root for VLAN 1. Verify the configuration with the **show spanning-tree** command on S1.

Refer to **Online Course** for Illustration

2.3.1.3 PortFast and BPDU Guard

PortFast is a Cisco feature for PVST+ environments. When a switch port is configured with PortFast that port transitions from blocking to forwarding state immediately, bypassing the usual 802.1D STP transition states (the listening and learning states). You can use PortFast on access ports to allow these devices to connect to the network immediately, rather than waiting for IEEE 802.1D STP to converge on each VLAN. Access ports are ports which are connected to a single workstation or to a server.

In a valid PortFast configuration, BPDUs should never be received, because that would indicate that another bridge or switch is connected to the port, potentially causing a spanning tree loop. Cisco switches support a feature called BPDU guard. When it is enabled,

BPDU guard puts the port in an *error-disabled* state on receipt of a BPDU. This will effectively shut down the port. The BPDU guard feature provides a secure response to invalid configurations because you must manually put the interface back into service.

Cisco PortFast technology is useful for DHCP. Without PortFast, a PC can send a DHCP request before the port is in forwarding state, denying the host from getting a usable IP address and other information. Because PortFast immediately changes the state to forwarding, the PC always gets a usable IP address.

Note Because the purpose of PortFast is to minimize the time that access ports must wait for spanning tree to converge, it should only be used on access ports. If you enable PortFast on a port connecting to another switch, you risk creating a spanning tree loop.

To configure PortFast on a switch port, enter the **spanning-tree portfast** interface configuration mode command on each interface that PortFast is to be enabled, as shown in Figure 2. The **spanning-tree portfast default** global configuration mode command enables PortFast on all nontrunking interfaces.

To configure BPDU guard on a Layer 2 access port, use the **spanning-tree bpduguard enable** interface configuration mode command. The **spanning-tree portfast bpduguard default** global configuration command enables BPDU guard on all PortFast-enabled ports.

To verify that PortFast and BPDU guard has been enabled for a switch port, use the **show running-config** command, as shown in Figure 3. PortFast and BPDU guard are disabled, by default, on all interfaces.

Use the Syntax Checker in Figure 4 to configure and verify switches S1 and S2 with PortFast and BPDU guard.

Refer to **Online Course** for Illustration

2.3.1.4 PVST+ Load Balancing

The topology in Figure 1 shows three switches with 802.1Q trunks connecting them. There are two VLANs, 10 and 20, that are being trunked across these links. The goal is to configure S3 as the root bridge for VLAN 20 and S1 as the root bridge for VLAN 10. Port F0/3 on S2 is the forwarding port for VLAN 20 and the blocking port for VLAN 10. Port F0/2 on S2 is the forwarding port for VLAN 10 and the blocking port for VLAN 20.

In addition to establishing a root bridge, it is also possible to establish a secondary root bridge. A secondary root bridge is a switch that may become the root bridge for a VLAN if the primary root bridge fails. Assuming the other bridges in the VLAN retain their default STP priority, this switch becomes the root bridge if the primary root bridge fails.

The steps to configure PVST+ on this example topology are:

Step 1. Select the switches you want for the primary and secondary root bridges for each VLAN. For example, in Figure 1, S3 is the primary bridge for VLAN 20 and S1 is the secondary bridge for VLAN 20.

Step 2. Configure the switch to be a primary bridge for the VLAN by using the **spanning-tree vlan** number **root primary** command, as shown in Figure 2.

Step 3. Configure the switch to be a secondary bridge for the VLAN by using the **spanning-tree vlan** number **root secondary** command.

Another way to specify the root bridge is to set the spanning tree priority on each switch to the lowest value so that the switch is selected as the primary bridge for its associated VLAN.

Notice that in Figure 2, S3 is configured as the primary root bridge for VLAN 20, S1 is configured as the primary root bridge for VLAN 10. S2 retained its default STP priority.

The figure also shows that S3 is configured as the secondary root bridge for VLAN 10, and S1 is configured as the secondary root bridge for VLAN 20. This configuration enables spanning tree load balancing, with VLAN 10 traffic passing through S1 and VLAN 20 traffic passing through S3.

Another way to specify the root bridge is to set the spanning tree priority on each switch to the lowest value so that the switch is selected as the primary bridge for its associated VLAN, as shown in Figure 3. The switch priority can be set for any spanning tree instance. This setting affects the likelihood that a switch is selected as the root bridge. A lower value increases the probability that the switch is selected. The range is 0 to 61,440 in increments of 4,096; all other values are rejected. For example, a valid priority value is 4,096 x 2 = 8,192.

As shown in Figure 4, the **`show spanning-tree active`** command displays spanning tree configuration details for the active interfaces only. The output shown is for S1 configured with PVST+. There are a number of Cisco IOS command parameters associated with the **`show spanning-tree`** command.

In Figure 5, the output shows that the priority for VLAN 10 is 4,096, the lowest of the three respective VLAN priorities.

Use the Syntax Checker in Figure 6 to configure and verify spanning tree for S1 and S3.

Refer to **Packet Tracer Activity** for this chapter

2.3.1.5 Packet Tracer - Configuring PVST+

Background/Scenario

In this activity, you will configure VLANs and trunks, and examine and configure the Spanning Tree Protocol primary and secondary root bridges. You will also optimize the switched topology using PVST+, PortFast, and BPDU guard.

Refer to **Online Course** for Illustration

2.3.2 Rapid PVST+ Configuration

2.3.2.1 Spanning Tree Mode

Rapid PVST+ is the Cisco implementation of RSTP. It supports RSTP on a per-VLAN basis. The topology in Figure 1 has two VLANs: 10 and 20.

Note The default spanning tree configuration on a Catalyst 2960 Series switch is PVST+. A Catalyst 2960 switch supports PVST+, Rapid PVST+, and MST, but only one version can be active for all VLANs at any time.

Rapid PVST+ commands control the configuration of VLAN spanning tree instances. A spanning tree instance is created when an interface is assigned to a VLAN and is removed when the last interface is moved to another VLAN. As well, you can configure STP switch

and port parameters before a spanning tree instance is created. These parameters are applied when a spanning tree instance is created.

Figure 2 displays the Cisco IOS command syntax needed to configure Rapid PVST+ on a Cisco switch. The **spanning-tree mode rapid-pvst** global configuration mode command is the one required command for the Rapid PVST+ configuration. When specifying an interface to configure, valid interfaces include physical ports, VLANs, and port channels. The VLAN ID range is 1 to 4094 when the enhanced software image (EI) is installed and 1 to 1005 when the standard software image (SI) is installed. The port-channel range is 1 to 6.

Figure 3 shows Rapid PVST+ commands configured on S1.

In Figure 4, the **show spanning-tree vlan 10** command shows the spanning tree configuration for VLAN 10 on switch S1. Notice that the BID priority is set to 4,096. In the output, the statement "Spanning tree enabled protocol rstp" indicates that S1 is running Rapid PVST+. Because S1 is the root bridge for VLAN 10, all of its interfaces are designated ports.

In Figure 5, the **show running-config** command is used to verify the Rapid PVST+ configuration on S1.

Note Generally, it is unnecessary to configure the point-to-point *link-type* parameter for Rapid PVST+, because it is unusual to have a shared *link-type*. In most cases, the only difference between configuring PVST+ and Rapid PVST+ is the **spanning-tree mode rapid-pvst** command.

Refer to **Packet Tracer Activity** for this chapter

2.3.2.2 Packet Tracer - Configuring Rapid PVST+

Background/Scenario

In this activity, you will configure VLANs and trunks, and examine and configure the Spanning Tree primary and secondary root bridges. You will also optimize it by using rapid PVST+, PortFast, and BPDU guard.

Refer to **Lab Activity** for this chapter

2.3.2.3 Lab - Configuring Rapid PVST+, PortFast and BPDU Guard

In this lab, you will complete the following objectives:

- Part 1: Build the Network and Configure Basic Device Settings
- Part 2: Configure VLANs, Native VLAN, and Trunks
- Part 3: Configure the Root Bridge and Examine PVST+ Convergence
- Part 4: Configure Rapid PVST+, PortFast, BPDU Guard, and Examine Convergence

Refer to **Online Course** for Illustration

2.3.3 STP Configuration Issues

2.3.3.1 Analyzing the STP Topology

To analyze the STP topology, follow these steps:

Step 1. Discover the Layer 2 topology. Use network documentation if it exists or use the **`show cdp neighbors`** command to discover the Layer 2 topology.

Step 2. After discovering the Layer 2 topology, use STP knowledge to determine the expected Layer 2 path. It is necessary to know which switch is the root bridge.

Step 3. Use the **`show spanning-tree vlan`** command to determine which switch is the root bridge.

Step 4. Use the **`show spanning-tree vlan`** command on all switches to find out which ports are in blocking or forwarding state and confirm your expected Layer 2 path.

Refer to **Online Course** for Illustration

2.3.3.2 Expected Topology versus Actual Topology

In many networks, the optimal STP topology is determined as part of the network design and then implemented through manipulation of STP priority and cost values. Situations may occur where STP was not considered in the network design and implementation, or where it was considered or implemented before the network underwent significant growth and change. In such situations, it is important to know how to analyze the actual STP topology in the operational network.

A big part of troubleshooting consists of comparing the actual state of the network against the expected state of the network and spotting the differences to gather clues about the troubleshooting problem. A network professional should be able to examine the switches and determine the actual topology, and be able to understand what the underling spanning tree topology should be.

Refer to **Online Course** for Illustration

2.3.3.3 Overview of Spanning Tree Status

Using the **`show spanning-tree`** command without specifying any additional options provides a quick overview of the status of STP for all VLANs that are defined on a switch. If interested only in a particular VLAN, limit the scope of this command by specifying that VLAN as an option.

Use the **`show spanning-tree vlan`** vlan_id command to get STP information for a particular VLAN. Use this command to get information about the role and status of each port on the switch. The example output on switch S1 shows all three ports in the forwarding (FWD) state and the role of the three ports as either designated ports or root ports. Any ports being blocked display the output status as “BLK”.

The output also gives information about the BID of the local switch and the root ID, which is the BID of the root bridge.

Refer to **Online Course** for Illustration

2.3.3.4 Spanning Tree Failure Consequences

With many protocols, a malfunction means that you lose the functionality which the protocol was providing. For example, if OSPF malfunctions on a router, connectivity to networks that are reachable via that router might be lost. This would generally not affect the rest of the OSPF network. If connectivity to the router is still available, it is possible to troubleshoot to diagnose and fix the problem.

With STP, there are two types of failure. The first is similar to the OSPF problem; STP might erroneously block ports that should have gone into the forwarding state. Connectivity might be lost for traffic that would normally pass through this switch, but the rest of the network remains unaffected. The second type of failure is much more disruptive, as shown in Figure 1. It happens when STP erroneously moves one or more ports into the forwarding state.

Remember that an Ethernet frame header does not include a TTL field, which means that any frame that enters a bridging loop continues to be forwarded by the switches indefinitely. The only exceptions are frames that have their destination address recorded in the MAC address table of the switches. These frames are simply forwarded to the port that is associated with the MAC address and do not enter a loop. However, any frame that is flooded by a switch enters the loop (Figure 2). This may include broadcasts, multicasts, and unicasts with a globally unknown destination MAC address.

What are the consequences and corresponding symptoms of STP failure (Figure 3)?

The load on all links in the switched LAN quickly starts increasing as more and more frames enter the loop. This problem is not limited to the links that form the loop, but also affects any other links in the switched domain because the frames are flooded on all links. When the spanning tree failure is limited to a single VLAN only links in that VLAN are affected. Switches and trunks that do not carry that VLAN operate normally.

If the spanning tree failure has created a bridging loop, traffic increases exponentially. The switches will then flood the broadcasts out multiple ports. This creates copies of the frames every time the switches forward them.

When control plane traffic starts entering the loop (for example, OSPF Hellos or EIGRP Hellos), the devices that are running these protocols quickly start getting overloaded. Their CPUs approach 100 percent utilization while they are trying to process an ever-increasing load of control plane traffic. In many cases, the earliest indication of this broadcast storm in progress is that routers or Layer 3 switches are reporting control plane failures and that they are running at a high CPU load.

The switches experience frequent MAC address table changes. If a loop exists, a switch may see a frame with a certain source MAC address coming in on one port and then see the another frame with the same source MAC address coming in on a different port a fraction of a second later. This will cause the switch to update the MAC address table twice for the same MAC address.

Due to the combination of very high load on all links and the switch CPUs running at maximum load, these devices typically become unreachable. This makes it very difficult to diagnose the problem while it is happening.

Refer to **Online Course** for Illustration

2.3.3.5 Repairing a Spanning Tree Problem

One way to correct spanning tree failure is to manually remove redundant links in the switched network, either physically or through configuration, until all loops are eliminated from the topology. When the loops are broken, the traffic and CPU loads should quickly drop to normal levels, and connectivity to devices should be restored.

Although this intervention restores connectivity to the network, it is not the end of the troubleshooting process. All redundancy from the switched network has been removed, and now the redundant links must be restored.

If the underlying cause of the spanning tree failure has not been fixed, chances are that restoring the redundant links will trigger a new broadcast storm. Before restoring the redundant links, determine and correct the cause of the spanning tree failure. Carefully monitor the network to ensure that the problem is fixed.

Refer to **Interactive Graphic** in online course.

2.3.3.6 Activity - Troubleshoot STP Configuration Issues

Refer to **Online Course** for Illustration

2.4 First Hop Redundancy Protocols

2.4.1 Concept of First Hop Redundancy Protocols

2.4.1.1 Default Gateway Limitations

Spanning tree protocols enable physical redundancy in a switched network. However, a host at the access layer of a hierarchical network also benefits from alternate default gateways. If a router or router interface (that serves as a default gateway) fails, the hosts configured with that default gateway are isolated from outside networks. A mechanism is needed to provide alternate default gateways in switched networks where two or more routers are connected to the same VLANs.

Note For the purposes of the discussion on router redundancy, there is no functional difference between a multilayer switch and a router at the distribution layer. In practice, it is common for a multilayer switch to act as the default gateway for each VLAN in a switched network. This discussion focuses on the functionality of *routing*, regardless of the physical device used.

In a switched network, each client receives only one default gateway. There is no way to configure a secondary gateway, even if a second path exists to carry packets off the local segment.

In the figure, R1 is responsible for routing packets from PC1. If R1 becomes unavailable, the routing protocols can dynamically converge. R2 now routes packets from outside networks that would have gone through R1. However, traffic from the inside network associated with R1, including traffic from workstations, servers, and printers configured with R1 as their default gateway, are still sent to R1 and dropped.

End devices are typically configured with a single IP address for a default gateway. This address does not change when the network topology changes. If that default gateway IP address cannot be reached, the local device is unable to send packets off the local network

segment, effectively disconnecting it from the rest of the network. Even if a redundant router exists that could serve as a default gateway for that segment, there is no dynamic method by which these devices can determine the address of a new default gateway.

Refer to **Online Course** for Illustration

2.4.1.2 Router Redundancy

One way prevent a single point of failure at the default gateway, is to implement a virtual router. To implement this type of router redundancy, multiple routers are configured to work together to present the illusion of a single router to the hosts on the LAN, as shown in the figure. By sharing an IP address and a MAC address, two or more routers can act as a single virtual router.

The IP address of the virtual router is configured as the default gateway for the workstations on a specific IP segment. When frames are sent from host devices to the default gateway, the hosts use ARP to resolve the MAC address that is associated with the IP address of the default gateway. The ARP resolution returns the MAC address of the virtual router. Frames that are sent to the MAC address of the virtual router can then be physically processed by the currently active router within the virtual router group. A protocol is used to identify two or more routers as the devices that are responsible for processing frames that are sent to the MAC or IP address of a single virtual router. Host devices send traffic to the address of the virtual router. The physical router that forwards this traffic is transparent to the host devices.

A redundancy protocol provides the mechanism for determining which router should take the active role in forwarding traffic. It also determines when the forwarding role must be taken over by a standby router. The transition from one forwarding router to another is transparent to the end devices.

The ability of a network to dynamically recover from the failure of a device acting as a default gateway is known as first-hop redundancy.

Refer to **Online Course** for Illustration

2.4.1.3 Steps for Router Failover

When the active router fails, the redundancy protocol transitions the standby router to the new active router role. These are the steps that take place when the active router fails:

1. The standby router stops seeing Hello messages from the forwarding router.
2. The standby router assumes the role of the forwarding router.
3. Because the new forwarding router assumes both the IP and MAC addresses of the virtual router, the host devices see no disruption in service.

Refer to **Interactive Graphic** in online course.

2.4.1.4 Activity - Identify FHRP Terminology

Refer to **Online Course** for Illustration

2.4.2 Varieties of First Hop Redundancy Protocols

2.4.2.1 First Hop Redundancy Protocols

The following list defines the options available for First Hop Redundancy Protocols (FHRPs), as shown in the figure.

- **Hot Standby Router Protocol (HSRP)**- A Cisco-proprietary FHRP designed to allow for transparent failover of a first-hop IPv4 device. HSRP provides high network avail-

ability by providing first-hop routing redundancy for IPv4 hosts on networks configured with an IPv4 default gateway address. HSRP is used in a group of routers for selecting an active device and a standby device. In a group of device interfaces, the active device is the device that is used for routing packets; the standby device is the device that takes over when the active device fails, or when pre-set conditions are met. The function of the HSRP standby router is to monitor the operational status of the HSRP group and to quickly assume packet-forwarding responsibility if the active router fails.

- **HSRP for IPv6**- Cisco-proprietary FHRP providing the same functionality of HSRP, but in an IPv6 environment. An HSRP IPv6 group has a virtual MAC address derived from the HSRP group number and a virtual IPv6 link-local address derived from the HSRP virtual MAC address. Periodic router advertisements (RAs) are sent for the HSRP virtual IPv6 link-local address when the HSRP group is active. When the group becomes inactive these RAs stop after a final RA is sent.
- **Virtual Router Redundancy Protocol version 2 (VRRPv2)**- A non-proprietary election protocol that dynamically assigns responsibility for one or more virtual routers to the VRRP routers on an IPv4 LAN. This allows several routers on a multiaccess link to use the same virtual IPv4 address. A VRRP router is configured to run the VRRP protocol in conjunction with one or more other routers attached to a LAN. In a VRRP configuration, one router is elected as the virtual router master, with the other routers acting as backups, in case the virtual router master fails.
- **VRRPv3**- Provides the capability to support IPv4 and IPv6 addresses. VRRPv3 works in multi-vendor environments and is more scalable than VRRPv2.
- **Gateway Load Balancing Protocol (GLBP)**- Cisco-proprietary FHRP that protects data traffic from a failed router or circuit, like HSRP and VRRP, while also allowing load balancing (also called load sharing) between a group of redundant routers.
- **GLBP for IPv6**- Cisco-proprietary FHRP providing the same functionality of GLBP, but in an IPv6 environment. GLBP for IPv6 provides automatic router backup for IPv6 hosts configured with a single default gateway on a LAN. Multiple first-hop routers on the LAN combine to offer a single virtual first-hop IPv6 router while sharing the IPv6 packet forwarding load.
- **ICMP Router Discovery Protocol (IRDP)**- Specified in RFC 1256, is a legacy FHRP solution. IRDP allows IPv4 hosts to locate routers that provide IPv4 connectivity to other (nonlocal) IP networks.

Refer to **Interactive Graphic** in online course.

2.4.2.2 Activity - Identify the Type of FHRP

Refer to **Online Course** for Illustration

2.4.3 FHRP Verification

2.4.3.1 HSRP Verification

An HSRP active router has the following characteristics:

- Responds to default gateway's ARP requests with the virtual router's MAC.
- Assumes active forwarding of packets for the virtual router.

- Sends Hello messages.
- Knows the virtual router IP address.

An HSRP standby router has the following characteristics:

- Listens for periodic Hello messages.
- Assumes active forwarding of packets if it does not hear from the active router.

Use the **show standby** command to verify the HSRP state. In the figure, the output shows that the router is in the active state.

Refer to **Online Course** for Illustration

2.4.3.2 GLBP Verification

Although HSRP and VRRP provide gateway resiliency, for the standby members of the redundancy group, the upstream bandwidth is not used while the device is in standby mode.

Only the active router in HSRP and VRRP groups forwards traffic for the virtual MAC address. Resources that are associated with the standby router are not fully utilized. You can accomplish some load balancing with these protocols by creating multiple groups and assigning multiple default gateways, but this configuration creates an administrative burden.

GLBP is a Cisco proprietary solution to allow automatic selection and simultaneous use of multiple available gateways in addition to automatic failover between those gateways. Multiple routers share the load of frames that, from a client perspective, are sent to a single default gateway address, as shown in Figure 1.

With GLBP, you can fully utilize resources without the administrative burden of configuring multiple groups and managing multiple default gateway configurations. GLBP has the following characteristics:

- Allows full use of resources on all devices without the administrative burden of creating multiple groups.
- Provides a single virtual IP address and multiple virtual MAC addresses.
- Routes traffic to single gateway distributed across routers.
- Provides automatic rerouting in the event of any failure.

Use the **show glbp** command to verify the GLBP status. Figure 2 shows that GLBP group 1 is in the active state with virtual IP address 192.168.2.100.

Refer to **Online Course** for Illustration

2.4.3.3 Syntax Checker - HSRP and GLBP

Configuration of HSRP and GLBP are beyond the scope of this course. However, familiarity with the commands used to enable HSRP and GLBP aid in understanding the configuration output. For this reason, the syntax checker and subsequent lab are available as optional exercises.

Refer to
Lab Activity
for this chapter

2.4.3.4 Lab - Configuring HSRP and GLBP

In this lab, you will complete the following objectives:

- Part 1: Build the Network and Verify Connectivity
- Part 2: Configure First Hop Redundancy Using HSRP
- Part 3: Configure First Hop Redundancy Using GLBP

Refer to
Online Course
for Illustration

2.5 Summary

Refer to
Lab Activity
for this chapter

2.5.1.1 Class Activity - Documentation Tree

Documentation Tree

The employees in your building are having difficulty accessing a web server on the network. You look for the network documentation that the previous network engineer used before he transitioned to a new job; however, you cannot find any network documentation whatsoever.

Therefore, you decide to create your own network record-keeping system. You decide to start at the access layer of your network hierarchy. This is where redundant switches are located, as well as the company servers, printers, and local hosts.

You create a matrix to record your documentation and include access layer switches on the list. You also decide to document switch names, ports in use, cabling connections, root ports, designated ports, and alternate ports.

Refer to
Online Course
for Illustration

2.5.1.2 Summary

Problems that can result from a redundant Layer 2 network include broadcast storms, MAC database instability, and duplicate unicast frames. STP is a Layer 2 protocol that ensures that there is only one logical path between all destinations on the network by intentionally blocking redundant paths that could cause a loop.

STP sends BPDU frames for communication between switches. One switch is elected as the root bridge for each instance of spanning tree. An administrator can control this election by changing the bridge priority. Root bridges can be configured to enable spanning tree load balancing by VLAN or by a group of VLANs, depending on the spanning tree protocol used. STP then assigns a port role to each participating port using a path cost. The path cost is equal to the sum of all the port costs along the path to the root bridge. A port cost is automatically assigned to each port; however, it can also be manually configured. Paths with the lowest cost become preferred, and all other redundant paths are blocked.

PVST+ is the default configuration of IEEE 802.1D on Cisco switches. It runs one instance of STP for each VLAN. A newer, faster-converging spanning tree protocol, RSTP, can be implemented on Cisco switches on a per-VLAN basis in the form of Rapid PVST+. Multiple Spanning Tree (MST) is the Cisco implementation of Multiple Spanning Tree Protocol (MSTP), where one instance of spanning tree runs for a defined group of VLANs. Features such as PortFast and BPDU guard ensure that hosts in the switched environment are provided immediate access to the network without interfering with spanning tree operation.

First Hop Redundancy Protocols, such as HSRP, VRRP, and GLBP provide alternate default gateways for hosts in the redundant router or multilayer switched environment. Multiple routers share a virtual IP address and MAC address that is used as the default gateway on a client. This ensures that hosts maintain connectivity in the event of the failure of one device serving as a default gateway for a VLAN or set of VLANs. When using HSRP or VRRP, one router is active or forwarding for a particular group while others are in standby mode. GLBP allows the simultaneous use of multiple gateways in addition to providing automatic failover.

Go to the online course to take the quiz and exam.

Chapter 2 Quiz

This quiz is designed to provide an additional opportunity to practice the skills and knowledge presented in the chapter and to prepare for the chapter exam. You will be allowed multiple attempts and the grade does not appear in the gradebook.

Chapter 2 Exam

The chapter exam assesses your knowledge of the chapter content.

Your Chapter Notes

CHAPTER 3

Link Aggregation

3.0 Introduction

3.0.1.1 Introduction

Link aggregation is the ability to create one logical link using multiple physical links between two devices. This allows load sharing among the physical links, rather than having STP block one or more of the links. EtherChannel is a form of link aggregation used in switched networks.

This chapter describes EtherChannel and the methods used to create an EtherChannel. An EtherChannel can be manually configured or can be negotiated by using the Cisco-proprietary protocol Port Aggregation Protocol (PAgP) or the IEEE 802.3ad-defined protocol Link Aggregation Control Protocol (LACP). The configuration, verification, and troubleshooting of EtherChannel are discussed.

Refer to **Lab Activity** for this chapter

3.0.1.2 Class Activity - Imagine This

Imagine This

It is the end of the work day. In your small- to medium-sized business, you are trying to explain to the network engineers about EtherChannel and how it looks when it is physically set up. The network engineers have difficulty envisioning how two switches could possibly be connected via several links that collectively act as one channel or connection. Your company is definitely considering implementing an EtherChannel network.

Therefore, you end the meeting with an assignment for the engineers. To prepare for the next day's meeting, they are to perform some research and bring to the meeting one graphic representation of an EtherChannel network connection. They are tasked with explaining how an EtherChannel network operates to the other engineers.

When researching EtherChannel, a good question to search for is "What does EtherChannel look like?" Prepare a few slides to demonstrate your research that will be presented to the network engineering group. These slides should provide a solid grasp of how EtherChannels are physically created within a network topology. Your goal is to ensure that everyone leaving the next meeting will have a good idea as to why they would consider moving to a network topology using EtherChannel as an option.

Refer to **Interactive Graphic** in online course.

3.1 Link Aggregation Concepts

3.1.1 Link Aggregation

3.1.1.1 Introduction to Link Aggregation

In the figure, traffic coming from several links (usually 100 or 1000 Mb/s) aggregates on the access switch and must be sent to distribution switches. Because of the traffic aggregation, links with higher bandwidth must be available between the access and distribution switches.

It may be possible to use faster links, such as 10 Gb/s, on the aggregated link between the access and distribution layer switches. However, adding faster links is expensive. Additionally, as the speed increases on the access links, even the fastest possible port on the aggregated link is no longer fast enough to aggregate the traffic coming from all access links.

It is also possible to multiply the number of physical links between the switches to increase the overall speed of switch-to-switch communication. However, by default, STP is enabled on switch devices. STP will block redundant links to prevent routing loops.

For these reasons, the best solution is to implement an EtherChannel configuration.

Refer to **Online Course** for Illustration

3.1.1.2 Advantages of EtherChannel

EtherChannel technology was originally developed by Cisco as a LAN switch-to-switch technique of grouping several Fast Ethernet or Gigabit Ethernet ports into one logical channel. When an EtherChannel is configured, the resulting virtual interface is called a port channel. The physical interfaces are bundled together into a port channel interface.

EtherChannel technology has many advantages:

- Most configuration tasks can be done on the EtherChannel interface instead of on each individual port, ensuring configuration consistency throughout the links.
- EtherChannel relies on existing switch ports. There is no need to upgrade the link to a faster and more expensive connection to have more bandwidth.
- Load balancing takes place between links that are part of the same EtherChannel. Depending on the hardware platform, one or more load-balancing methods can be implemented. These methods include source MAC to destination MAC load balancing, or source IP to destination IP load balancing, across the physical links.
- EtherChannel creates an aggregation that is seen as one logical link. When several EtherChannel bundles exist between two switches, STP may block one of the bundles to prevent switching loops. When STP blocks one of the redundant links, it blocks the entire EtherChannel. This blocks all the ports belonging to that EtherChannel link. Where there is only one EtherChannel link, all physical links in the EtherChannel are active because STP sees only one (logical) link.
- EtherChannel provides redundancy because the overall link is seen as one logical connection. Additionally, the loss of one physical link within the channel does not create a change in the topology; therefore a spanning tree recalculation is not required. Assuming at least one physical link is present; the EtherChannel remains functional, even if its overall throughput decreases because of a lost link within the EtherChannel.

Refer to **Online Course** for Illustration

3.1.2 EtherChannel Operation

3.1.2.1 Implementation Restrictions

EtherChannel can be implemented by grouping multiple physical ports into one or more logical EtherChannel links.

Note Interface types cannot be mixed; for example, Fast Ethernet and Gigabit Ethernet cannot be mixed within a single EtherChannel.

The EtherChannel provides full-duplex bandwidth up to 800 Mb/s (Fast EtherChannel) or 8 Gb/s (Gigabit EtherChannel) between one switch and another switch or host. Currently each EtherChannel can consist of up to eight compatibly-configured Ethernet ports. The Cisco IOS switch can currently support six EtherChannels. However, as new IOSs are developed and platforms change, some cards and platforms may support increased numbers of ports within an EtherChannel link, as well as support an increased number of Gigabit EtherChannels. The concept is the same no matter the speeds or number of links that are involved. When configuring EtherChannel on switches, be aware of the hardware platform boundaries and specifications.

The original purpose of EtherChannel is to increase speed capability on aggregated links between switches. However, this concept was extended as EtherChannel technology became more popular, and now many servers also support link aggregation with EtherChannel. EtherChannel creates a one-to-one relationship; that is, one EtherChannel link connects only two devices. An EtherChannel link can be created between two switches or an EtherChannel link can be created between an EtherChannel-enabled server and a switch. However, traffic cannot be sent to two different switches through the same EtherChannel link.

The individual EtherChannel group member port configuration must be consistent on both devices. If the physical ports of one side are configured as trunks, the physical ports of the other side must also be configured as trunks within the same native VLAN. Additionally, all ports in each EtherChannel link must be configured as Layer 2 ports.

Note Layer 3 EtherChannels can be configured on Cisco Catalyst multilayer switches, such as the Catalyst 3560, but these are not explored in this course. A Layer 3 EtherChannel has a single IP address associated with the logical aggregation of switch ports in the EtherChannel.

Each EtherChannel has a logical port channel interface, illustrated in the figure. A configuration applied to the port channel interface affects all physical interfaces that are assigned to that interface.

Refer to **Online Course** for Illustration

3.1.2.2 Port Aggregation Protocol

EtherChannels can be formed through negotiation using one of two protocols, PAgP or LACP. These protocols allow ports with similar characteristics to form a channel through dynamic negotiation with adjoining switches.

Note It is also possible to configure a static or unconditional EtherChannel without PAgP or LACP.

PAgP

PAgP is a Cisco-proprietary protocol that aids in the automatic creation of EtherChannel links. When an EtherChannel link is configured using PAgP, PAgP packets are sent between EtherChannel-capable ports to negotiate the forming of a channel. When PAgP identifies matched Ethernet links, it groups the links into an EtherChannel. The EtherChannel is then added to the spanning tree as a single port.

When enabled, PAgP also manages the EtherChannel. PAgP packets are sent every 30 seconds. PAgP checks for configuration consistency and manages link additions and failures between two switches. It ensures that when an EtherChannel is created, all ports have the same type of configuration.

Note In EtherChannel, it is mandatory that all ports have the same speed, duplex setting, and VLAN information. Any port modification after the creation of the channel also changes all other channel ports.

PAgP helps create the EtherChannel link by detecting the configuration of each side and ensuring that links are compatible so that the EtherChannel link can be enabled when needed. The figure shows the modes for PAgP.

- **On**- This mode forces the interface to channel without PAgP. Interfaces configured in the on mode do not exchange PAgP packets.
- **PAgP desirable**- This PAgP mode places an interface in an active negotiating state in which the interface initiates negotiations with other interfaces by sending PAgP packets.
- **PAgP auto**- This PAgP mode places an interface in a passive negotiating state in which the interface responds to the PAgP packets that it receives, but does not initiate PAgP negotiation.

The modes must be compatible on each side. If one side is configure to be in auto mode, it is placed in a passive state, waiting for the other side to initiate the EtherChannel negotiation. If the other side is also set to auto, the negotiation never starts and the EtherChannel does not form. If all modes are disabled by using the `no` command, or if no mode is configured, then the EtherChannel is disabled.

The on mode manually places the interface in an EtherChannel, without any negotiation. It works only if the other side is also set to on. If the other side is set to negotiate parameters through PAgP, no EtherChannel forms, because the side that is set to on mode does not negotiate.

Refer to **Online Course** for Illustration

3.1.2.3 Link Aggregation Control Protocol

LACP

LACP is part of an IEEE specification (802.3ad) that allows several physical ports to be bundled to form a single logical channel. LACP allows a switch to negotiate an automatic bundle by sending LACP packets to the peer. It performs a function similar to PAgP

with Cisco EtherChannel. Because LACP is an IEEE standard, it can be used to facilitate EtherChannels in multivendor environments. On Cisco devices, both protocols are supported.

Note LACP was originally defined as IEEE 802.3ad. However, LACP is now defined in the newer IEEE 802.1AX standard for local and metropolitan area networks.

LACP provides the same negotiation benefits as PAgP. LACP helps create the EtherChannel link by detecting the configuration of each side and making sure that they are compatible so that the EtherChannel link can be enabled when needed. The figure shows the modes for LACP.

- **On**- This mode forces the interface to channel without LACP. Interfaces configured in the on mode do not exchange LACP packets.
- **LACP active**- This LACP mode places a port in an active negotiating state. In this state, the port initiates negotiations with other ports by sending LACP packets.
- **LACP passive**- This LACP mode places a port in a passive negotiating state. In this state, the port responds to the LACP packets that it receives, but does not initiate LACP packet negotiation.

Just as with PAgP, modes must be compatible on both sides for the EtherChannel link to form. The on mode is repeated, because it creates the EtherChannel configuration unconditionally, without PAgP or LACP dynamic negotiation.

Refer to **Interactive Graphic** in online course.

3.1.2.4 Activity - Identify the PAgP and LACP Modes

Refer to **Online Course** for Illustration

3.2 Link Aggregation Configuration

3.2.1 Configuring EtherChannel

3.2.1.1 Configuration Guidelines

The following guidelines and restrictions are useful for configuring EtherChannel:

- **EtherChannel support**- All Ethernet interfaces on all modules must support EtherChannel with no requirement that interfaces be physically contiguous, or on the same module.
- **Speed and duplex**- Configure all interfaces in an EtherChannel to operate at the same speed and in the same duplex mode, as shown in the figure.
- **VLAN match**- All interfaces in the EtherChannel bundle must be assigned to the same VLAN, or be configured as a trunk (also shown in the figure).
- **Range of VLAN**- An EtherChannel supports the same allowed range of VLANs on all the interfaces in a trunking EtherChannel. If the allowed range of VLANs is not the same, the interfaces do not form an EtherChannel, even when set to **`auto`** or **`desirable`** mode.

If these settings must be changed, configure them in port channel interface configuration mode. After the port channel interface is configured, any configuration that is applied to the port channel interface also affects individual interfaces. However, configurations that are applied to the individual interfaces do not affect the port channel interface. Therefore, making configuration changes to an interface that is part of an EtherChannel link may cause interface compatibility issues.

Refer to **Online Course** for Illustration

3.2.1.2 Configuring Interfaces

Configuring EtherChannel with LACP is based on two steps:

Step 1. Specify the interfaces that compose the EtherChannel group using the **interface range** interface global configuration mode command. The **range** keyword allows you to select several interfaces and configure them all together. A good practice is to start by shutting down those interfaces, so that any incomplete configuration does not create activity on the link.

Step 2. Create the port channel interface with the **channel-group** identifier **mode active** command in interface range configuration mode. The identifier specifies a channel group number. The **mode active** keywords identify this as an LACP EtherChannel configuration.

Note EtherChannel is disabled by default.

In Figure 1, FastEthernet0/1 and FastEthernet0/2 are bundled into EtherChannel interface port channel 1.

To change Layer 2 settings on the port channel interface, enter port channel interface configuration mode using the interface port-channel command, followed by the interface identifier. In the example, the EtherChannel is configured as a trunk interface with allowed VLANs specified. Also shown in Figure 1, interface port channel 1 is configured as a trunk with allowed VLANs 1, 2, and 20.

Use the Syntax Checker in Figure 2 to configure EtherChannel on switch S1.

Refer to **Packet Tracer Activity** for this chapter

3.2.1.3 Packet Tracer - Configuring EtherChannel

Background/Scenario

Three switches have just been installed. There are redundant uplinks between the switches. Usually, only one of these links could be used; otherwise, a bridging loop might occur. However, using only one link utilizes only half of the available bandwidth. EtherChannel allows up to eight redundant links to be bundled together into one logical link. In this lab, you will configure Port Aggregation Protocol (PAgP), a Cisco EtherChannel protocol, and Link Aggregation Control Protocol (LACP), an IEEE 802.3ad open standard version of EtherChannel.

Refer to
Lab Activity
for this chapter

3.2.1.4 Lab - Configuring EtherChannel

In this lab, you will complete the following objectives:

- Part 1: Configure Basic Switch Settings
- Part 2: Configure PAgP
- Part 3: Configure LACP

Refer to
Online Course
for Illustration

3.2.2 Verifying and Troubleshooting EtherChannel

3.2.2.1 Verifying EtherChannel

There are a number of commands to verify an EtherChannel configuration. First, the **`show interface port-channel`** command displays the general status of the port channel interface. In Figure 1, the Port Channel 1 interface is up.

When several port channel interfaces are configured on the same device, use the **`show etherchannel summary`** command to simply display one line of information per port channel. In Figure 2, the switch has one EtherChannel configured; group 1 uses LACP.

The interface bundle consists of the FastEthernet0/1 and FastEthernet0/2 interfaces. The group is a Layer 2 EtherChannel and that it is in use, as indicated by the letters SU next to the port channel number.

Use the **`show etherchannel port-channel`** command to display information about a specific port channel interface, as shown in Figure 3. In the example, the Port Channel 1 interface consists of two physical interfaces, FastEthernet0/1 and FastEthernet0/2. It uses LACP in active mode. It is properly connected to another switch with a compatible configuration, which is why the port channel is said to be in use.

On any physical interface member of an EtherChannel bundle, the **`show interfaces etherchannel`** command can provide information about the role of the interface in the EtherChannel, as shown in Figure 4. The interface FastEthernet 0/1 is part of the EtherChannel bundle 1. The protocol for this EtherChannel is LACP.

Use the Syntax Checker in Figure 5 to verify EtherChannel on switch S1.

Refer to
Online Course
for Illustration

3.2.2.2 Troubleshooting EtherChannel

All interfaces within an EtherChannel must have the same configuration of speed and duplex mode, native and allowed VLANs on trunks, and access VLAN on access ports:

- Assign all ports in the EtherChannel to the same VLAN, or configure them as trunks. Ports with different native VLANs cannot form an EtherChannel.
- When configuring an EtherChannel from trunk ports, verify that the trunking mode is the same on all the trunks. Inconsistent trunk modes on EtherChannel ports can cause EtherChannel not to function and ports to be shut down (errdisable state).

- An EtherChannel supports the same allowed range of VLANs on all the ports. If the allowed range of VLANs is not the same, the ports do not form an EtherChannel even when PAgP is set to the **auto** or **desirable** mode.
- The dynamic negotiation options for PAgP and LACP must be compatibly configured on both ends of the EtherChannel.

Note It is easy to confuse PAgP or LACP with DTP, because they both are protocols used to automate behavior on trunk links. PAgP and LACP are used for link aggregation (EtherChannel). DTP is used for automating the creation of trunk links. When an EtherChannel trunk is configured, typically EtherChannel (PAgP or LACP) is configured first and then DTP.

In Figure 1, interfaces F0/1 and F0/2 on switches S1 and S2 are connected with an EtherChannel. The output indicates that the EtherChannel is down.

In Figure 2, more detailed output indicates that there are incompatible PAgP modes configured on S1 and S2.

In Figure 3, the PAgP mode on the EtherChannel is changed to desirable and the EtherChannel becomes active.

Note EtherChannel and spanning tree must interoperate. For this reason, the order in which EtherChannel-related commands are entered is important, which is why (in Figure 3) you see interface Port-Channel 1 removed and then re-added with the **channel-group** command, as opposed to directly changed. If one tries to change the configuration directly, spanning tree errors cause the associated ports to go into blocking or errdisabled state.

Refer to **Packet Tracer Activity** for this chapter

3.2.2.3 Packet Tracer - Troubleshooting EtherChannel

Background/Scenario

Four switches were recently configured by a junior technician. Users are complaining that the network is running slow and would like you to investigate.

Refer to **Lab Activity** for this chapter

3.2.2.4 Lab - Troubleshooting EtherChannel

In this lab, you will complete the following objectives:

- Part 1: Build the Network and Load Device Configurations
- Part 2: Troubleshoot EtherChannel

Refer to **Online Course** for Illustration

3.3 Summary

Refer to **Lab Activity** for this chapter

3.3.1.1 Class Activity - Linking Up

Linking Up

Many bottlenecks occur on your small- to medium-sized business network, even though you have configured VLANs, STP, and other network traffic options on the company's switches.

Instead of keeping the switches as they are currently configured, you would like to try EtherChannel as an option for, at least, part of the network to see if it will decrease traffic congestion between your access and distribution layer switches.

Your company uses Catalyst 3560 switches at the distribution layer and Catalyst 2960 and 2950 switches at the access layer of the network. To verify if these switches can perform EtherChannel, you visit the System Requirements to Implement EtherChannel on Catalyst Switches. This site allows you to gather more information to determine if EtherChannel is a good option for the equipment and network currently in place.

After researching the models, you decide to use a simulation software program to practice configuring EtherChannel before implementing it live on your network. As a part of this procedure, you ensure that the equipment simulated in Packet Tracer will support these practice configurations.

Refer to **Packet Tracer Activity** for this chapter

3.3.1.2 Packet Tracer - Skills Integration Challenge

Background/Scenario

In this activity, two routers are configured to communicate with each other. You are responsible for configuring subinterfaces to communicate with the switches. You will configure VLANs, trunking, and EtherChannel with PVST. The Internet devices are all preconfigured.

Refer to **Online Course** for Illustration

3.3.1.3 Summary

EtherChannel aggregates multiple switched links together to load balance over redundant paths between two devices. All ports in one EtherChannel must have the same speed, duplex setting, and VLAN information on all interfaces on the devices at both ends. Settings configured in the port channel interface configuration mode will also be applied to the individual interfaces in that EtherChannel. Settings configured on individual interfaces will not be applied to the EtherChannel or to the other interfaces in the EtherChannel.

PAgP is a Cisco-proprietary protocol that aids in the automatic creation of EtherChannel links. PAgP modes are on, PAgP desirable, and PAgP auto. LACP is part of an IEEE specification that also allows multiple physical ports to be bundled into one logical channel. The LACP modes are on, LACP active and LACP passive. PAgP and LACP do not interoperate. The on mode is repeated in both PAgP and LACP because it creates an EtherChannel unconditionally, without the use of PAgP or LACP. The default for EtherChannel is that no mode is configured.

Go to the online course to take the quiz and exam.

Chapter 3 Quiz

This quiz is designed to provide an additional opportunity to practice the skills and knowledge presented in the chapter and to prepare for the chapter exam. You will be allowed multiple attempts and the grade does not appear in the gradebook.

Chapter 3 Exam

The chapter exam assesses your knowledge of the chapter content.

Your Chapter Notes