CHAPTER 1

Introduction to Cisco MPLS VPN Technology

Technology Overview

The Cisco VPN Solutions Center: MPLS Solution, a modular suite of network and service management applications, is a network management system that defines and monitors virtual private network (VPN) services for service providers. VPN Solutions Center allows service providers to provision and manage intranet and extranet VPNs.

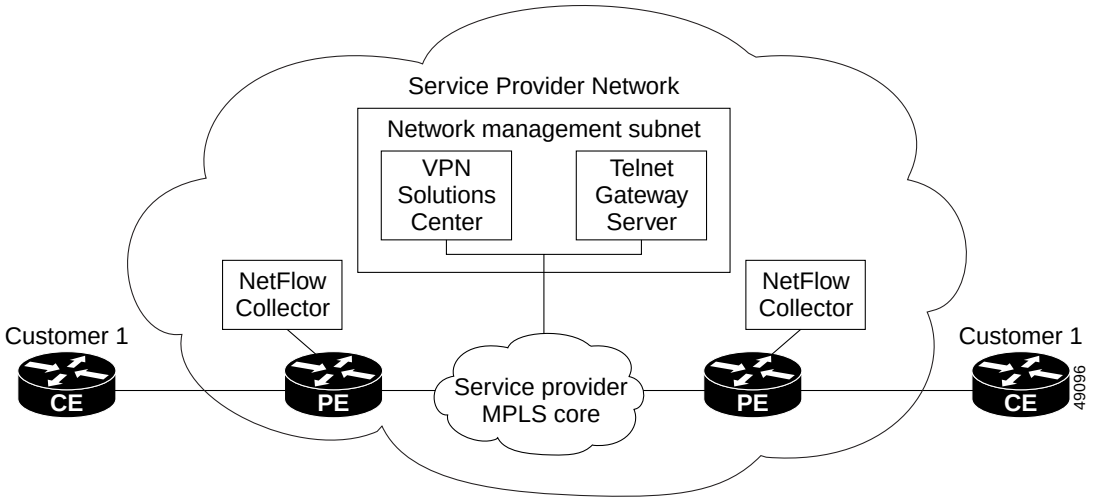
The product provides the aspect of operations management that addresses flow-through provisioning, service auditing, and Service Level Agreement (SLA) measurement of IP-based MPLS VPN environments. Multiprotocol Label Switching (MPLS) is an emerging industry standard upon which tag switching is based.

VPN Solutions Center is a scalable, provider-focused VPN technology that allows service providers to plan, provision, and manage for IP VPN services according to a customer's service level agreement. This product complements Cisco's MPLS-based VPN solutions by simplifying the provisioning, service assurance, and billing processes, thereby reducing the cost of deploying and operating VPN services.

VPN Solutions Center does not contain a billing application, but the product enables billing by providing the usage data on services that a billing engine can process.

VPN Solutions Center focuses on provisioning, auditing, and monitoring the links between the customer's routers through the provider's network. This product deals only with the provider's edge routers and the customer's edge routers.

Figure 1-1 VPN Solutions Center: MPLS Solution in the Service Provider Network



As shown in Figure 1-1, a customer edge router (CE) is connected to a provider edge router (PE) in such a way that the customer's traffic is encapsulated and transparently sent to other CEs, thus creating a virtual private network. CEs advertise routes to the VPN for all the devices in their site. The VPN Solutions Center provisioning engine accesses the configuration files on both the CE and PE to compute the necessary changes to those files that are required to support the service on the PE-CE link.

Using the VPN Solutions Center (VPNSC) software, service providers can do the following:

- Provision IP-based MPLS VPN services
- Generate audit reports for service requests
- Perform data collection to measure SLA performance
- Evaluate service usage for each VPN

An MPLS VPN consists of a set of sites that are interconnected by means of an MPLS provider core network. At each site, there are one or more CEs, which attach to one or more PEs. PEs use the Border Gateway Protocol-Multiprotocol (MP-BGP) to dynamically communicate with each other.

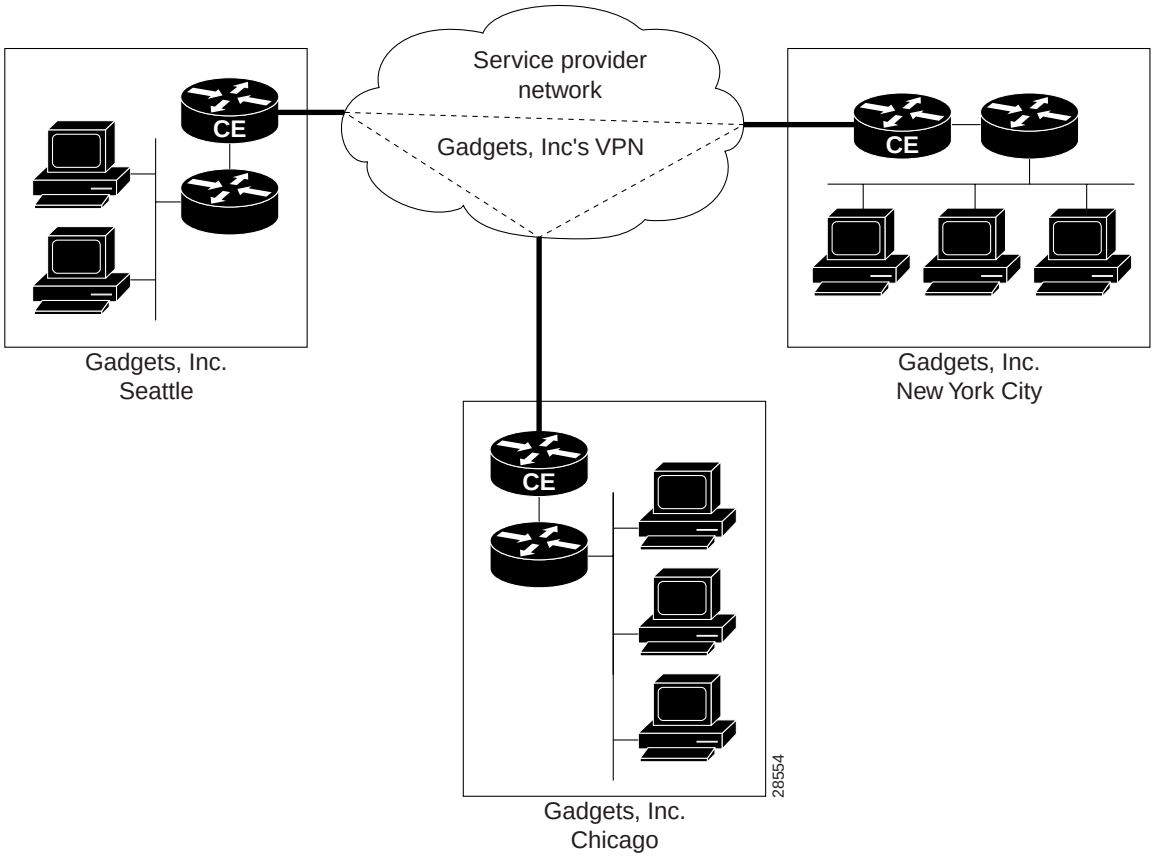
It is not required that the set of IPv4 addresses used in any two VPNs be mutually exclusive because the PEs translate IPv4 addresses into IPv4 VPN entities by using MP-BGP with extended community attributes.

The set of IP addresses used in a VPN, however, must be exclusive of the set of addresses used in the provider network. Every CE must be able to address the PEs to which it is directly attached. Thus, the IP addresses of the PEs must not be duplicated in any VPN.

The Customer's and Provider's View of the Network

From the customer's point of view, they see their internal routers communicating with their customer edge routers (CEs) from one site to another through a VPN managed by the service provider (see Figure 1-2).

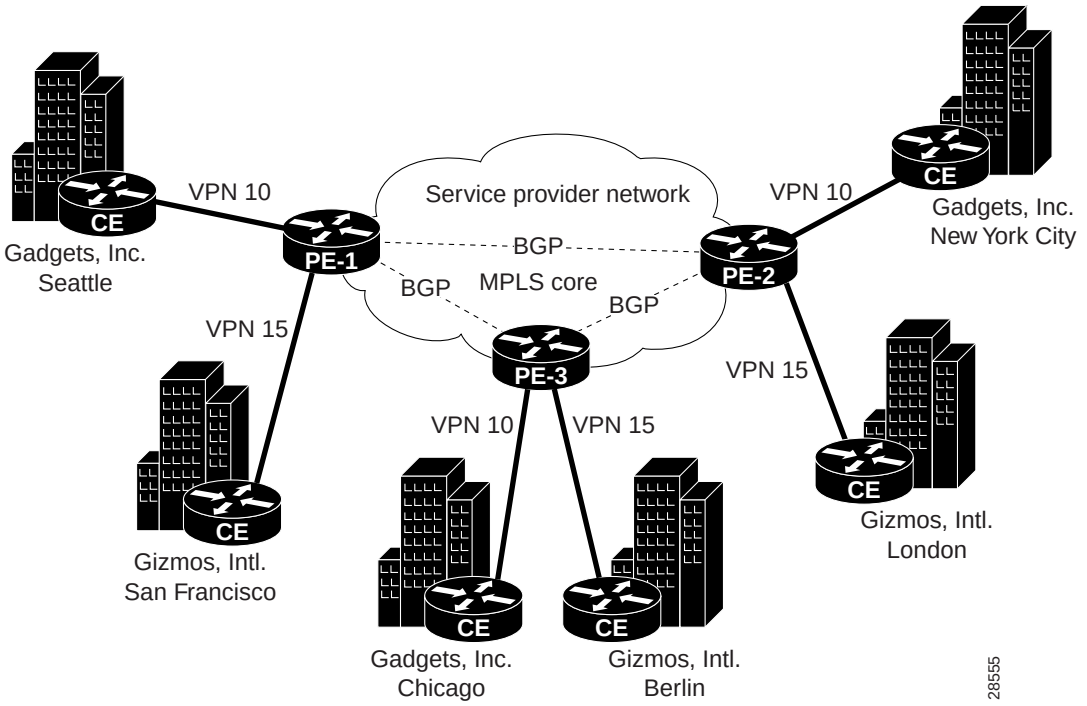
Figure 1-2 The Customer's View of the Network



This simple view of the customer's network is the advantage of employing VPNs: the customer experiences direct communication to their sites as though they had their own private network, even though their traffic is traversing a public network infrastructure and they are sharing that infrastructure with other businesses.

The service provider's view of the network is naturally very different, as shown in Figure 1-3. This illustration shows two different customers, with each customer having a single VPN. A customer can, however, have multiple VPNs.

Figure 1-3 Service Provider's View of the Network



About PEs

At the edge of the provider network are provider edge routers (PEs). Within the provider network are other provider routers as needed (often designated as P routers) that communicate with each other and the PEs via the Border Gateway Protocol-Multiprotocol (MP-BGP). Note that in this model, the service provider need only provision the links between the PEs and CEs.

PEs maintain separate routing tables called VPN routing and forwarding tables (VRFs). The VRFs contain the routes for directly connected VPN sites only. (For more information about VRFs, see the "VPN Routing and Forwarding Tables (VRFs)" section on page 1-15). PEs exchange VPN-IPv4 updates through MP-iBGP sessions. These updates contain VPN-IPv4 addresses and labels. The PE originating the route is the next hop of the route. PE addresses are referred to as host routes into the core interior gateway protocol.

Benefits

MPLS-based VPNs provide the following benefits:

- A platform for rapid deployment of additional value-added IP services, including intranets, extranets, voice, multimedia, and network commerce
- Privacy and security equal to Layer-2 VPNs by constraining the distribution of a VPN's routes to only those routers that are members of that VPN, and by using MPLS for forwarding
- Seamless integration with customer intranets
- Increased scalability with thousands of sites per VPN and hundreds of thousands of VPNs per service provider

- IP Class of Service (CoS) with support for multiple classes of service within a VPN, as well as priorities among VPNs
- Easy management of VPN membership and rapid deployment of new VPNs
- Scalable any-to-any connectivity for extended intranets and extranets that encompass multiple businesses

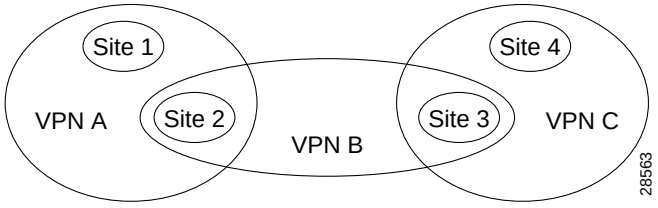
About MPLS VPNs

A virtual private network (VPN) is a network in which customer connectivity to multiple sites is deployed on a shared infrastructure with the same administrative policies as a private network.The path between two systems in a VPN, and the characteristics of that path, may also be determined (wholly or partially) by policy. Whether a system in a particular VPN is allowed to communicate with systems not in the same VPN is also a matter of policy.

In MPLS VPN, a VPN generally consists of a set of sites that are interconnected by means of an MPLS provider core network, but it is also possible to apply different policies to different systems that are located at the same site. Policies can also be applied to systems that dial in; the chosen policies would be based on the dial-in authentication processes.

A given set of systems can be in one or more VPNs. A VPN can consist of sites (or systems) that are all from the same enterprise (intranet), or from different enterprises (extranet); it may consist of sites (or systems) that all attach to the same service provider backbone, or to different service provider backbones.

Figure 1-4 VPNs Sharing Sites



MPLS-based VPNs are created in Layer 3 and are based on the peer model, which makes them more scalable and easier to build and manage than conventional VPNs. In addition, value-added services, such as application and data hosting, network commerce, and telephony services, can easily be targeted and deployed to a particular MPLS VPN because the service provider backbone recognizes each MPLS VPN as a secure, connectionless IP network.

The MPLS VPN model is a true peer VPN model that enforces traffic separations by assigning unique VPN route forwarding tables (VRFs) to each customer's VPN. Thus, users in a specific VPN cannot see traffic outside their VPN. Traffic separation occurs without tunneling or encryption because it is built directly into the network. (For more information on VRFs, see the "VPN Routing and Forwarding Tables (VRFs)" section on page 1-15.)

The service provider's backbone is comprised of the PE and its provider routers. MPLS VPN provides the ability that the routing information about a particular VPN be present *only* in those PE routers that attach to that VPN.

Characteristics of MPLS VPNs

MPLS VPNs have the following characteristics:

- Multiprotocol Border Gateway Protocol-Multiprotocol (MP-BGP) extensions are used to encode customer IPv4 address prefixes into unique VPN-IPv4 Network Layer Reachability Information (NLRI) values.

  NLRI refers to a destination address in MP-BGP, so NLRI is considered "one routing unit." In the context of IPv4 MP-BGP, NLRI refers to a network prefix/prefix length pair that is carried in the BGP4 routing updates.

- Extended MP-BGP community attributes are used to control the distribution of customer routes.
- Each customer route is associated with an MPLS label, which is assigned by the provider edge router that originates the route. The label is then employed to direct data packets to the correct egress customer edge router.

  When a data packet is forwarded across the provider backbone, two labels are used. The first label directs the packet to the appropriate egress PE; the second label indicates how that egress PE should forward the packet.

- Cisco MPLS CoS and QoS mechanisms provide service differentiation among customer data packets. For more information, see the "Quality of Service and Class of Service" section on page 1-25.
- The link between the PE and CE routers uses standard IP forwarding.

  The PE associates each CE with a per-site forwarding table that contains only the set of routes available to that CE.

Principal Technologies

There are four principal technologies that make it possible to build MPLS-based VPNs:

- Multiprotocol Border Gateway Protocol (MP-BGP) between PEs carries CE routing information
- Route filtering based on the VPN route target extended MP-BGP community attribute
- MPLS forwarding carries packets between PEs (across the service provider backbone)
- Each PE has multiple VPN routing and forwarding instances (VRFs)

Intranets and Extranets

If all the sites in a VPN are owned by the same enterprise, the VPN is a corporate *intranet*. If the various sites in a VPN are owned by different enterprises, the VPN is an *extranet*. A site can be in more than one VPN. Both intranets and extranets are regarded as VPNs.

While the basic unit of interconnection is the site, the MPLS VPN architecture allows a finer degree of granularity in the control of interconnectivity. For example, at a given site, it may be desirable to allow only certain specified systems to connect to certain other sites. That is, certain systems at a site may be members of an intranet as well as members of one or more extranets, while other systems at the same site may be restricted to being members of the intranet only.

A CE router can be in multiple VPNs, although it can only be in a single site. When a CE router is in multiple VPNs, one of these VPNs is considered its primary VPN. In general, a CE router's primary VPN is the intranet that includes the CE router's site. A PE router may attach to CE routers in any number of

different sites, whether those CE routers are in the same or in different VPNs. A CE router may, for robustness, attach to multiple PE routers. A PE router attaches to a particular VPN if it is a router adjacent to a CE router that is in that VPN.

Security Requirements for MPLS VPNs

This section discusses the security requirements for MPLS VPN architectures. This section concentrates on protecting the core network against attacks from the "outside," that is, the Internet and connected VPNs. Protection against attacks from the "inside," that is, when an attacker has logical or physical access to the core network is not discussed here, since any network can be attacked with access from the inside.

Address Space and Routing Separation

Between two non-intersecting VPNs of an MPLS VPN service, it is assumed that the address space between different VPNs is entirely independent. This means, for example, that two non-intersecting VPNs must be able to both use the 10/8 network without any interference. From a routing perspective, this means that each end system in a VPN has a unique address, and all routes to this address point to the same end system. Specifically:

- Any VPN must be able to use the same address space as any other VPN.
- Any VPN must be able to use the same address space as the MPLS core.
- Routing between any two VPNs must be independent.
- Routing between any VPN and the core must be independent.

Address Space Separation

From a security point of view, the basic requirement is to avoid that packets destined to a host a.b.c.d within a given VPN reach a host with the same address in another VPN or the core.

MPLS allows distinct VPNs to use the same address space, which can also be private address space. This is achieved by adding a 64-bit route distinguisher (RD) to each IPv4 route, making VPN-unique addresses also unique in the MPLS core. This "extended" address is also called a *VPN-IPv4 address*. Thus customers of an MPLS service do not need to change current addressing in their networks.

In the case of using routing protocols between CE and PE routers (for static routing this is not an issue), there is one exception—the IP addresses of the PE routers the CE routers are peering with. To be able to communicate to the PE router, routing protocols on the CE routers must configure the address of the peer router in the core. This address must be unique from the CE router's perspective. In an environment where the service provider manages also the CE routers as CPE (customer premises equipment), this can be made invisible to the customer.

Routing Separation

Routing separation between the VPNs can also be achieved. Every PE router maintains a separate Virtual Routing and Forwarding instance (VRF) for each connected VPN. Each VRF on the PE router is populated with routes from one VPN, through statically configured routes or through routing protocols that run between the PE and the CE router. Since every VPN results in a separate VRF, there are no interferences between the VPNs on the PE router.

Across the MPLS core to the other PE routers, this routing separation is maintained by adding unique VPN identifiers in multi-protocol BGP, such as the route distinguisher (RD). VPN routes are exclusively exchanged by MP-BGP across the core, and this BGP information is not redistributed to the core network, but only to the other PE routers, where the information is kept again in VPN-specific VRFs. Thus routing across an MPLS network is separate per VPN.

Given addressing and routing separation across an MPLS core network, MPLS offers in this respect the same security as comparable Layer 2 VPNs, such as ATM or Frame Relay. It is not possible to intrude into other VPNs through the MPLS core, unless this has been configured specifically.

Hiding the MPLS Core Structure

The internal structure of the MPLS core network (PE and Provider router devices) should not be visible to outside networks (either the Internet or any connected VPN). While a breach of this requirement does not lead to a security problem itself, it is generally advantageous when the internal addressing and network structure remains hidden to the outside world. The ideal is to not reveal any information of the internal network to the outside. This applies equally to the customer networks as to the MPLS core.

Denial-of-service attacks against a core router, for example, are much easier to carry out if an attacker knows the IP address. Where addresses are not known, they can be guessed, but when the MPLS core structure is hidden, attacks are more difficult to make. Ideally, the MPLS core should be as invisible to the outside world as a comparable Layer 2 infrastructure (for example, Frame Relay or ATM).

In practice, a number of additional security measures have to be taken, most of all *extensive packet filtering*. MPLS does not reveal unnecessary information to the outside, not even to customer VPNs. The addressing in the core can be done with either private addresses or public addresses. Since the interface to the VPNs, as well as potentially to the Internet, is BGP, there is no need to reveal any internal information. The only information required in the case of a routing protocol between a PE and CE is the address of the PE router. If this is not desired, you can configure static routing between the PE and CE. With this measure, the MPLS core can be kept completely hidden.

To ensure reachability across the MPLS cloud, customer VPNs will have to advertise their routes as a minimum to the MPLS core. While this could be seen as too open, the information known to the MPLS core is not about specific hosts, but networks (routes); this offers some degree of abstraction. Also, in a VPN-only MPLS network (that is, no shared Internet access), this is equal to existing Layer 2 models, where the customer has to trust the service provider to some degree. Also in a Frame Relay or ATM network, routing information about the VPNs can be seen on the core network.

In a VPN service with shared Internet access, the service provider typically announces the routes of customers that wish to use the Internet to his upstream or peer providers. This can be done via a network address translation (NAT) function to further obscure the addressing information of the customers' networks. In this case, the customer does not reveal more information to the general Internet than with a general Internet service. Core information is not revealed at all, except for the peering addresses of the PE router) that hold the peering with the Internet.

In summary, in a pure MPLS VPN service, where no Internet access is provided, the level of information hiding is as good as on a comparable Frame Relay or ATM network—no addressing information is revealed to third parties or the Internet. If a customer chooses to access the Internet via the MPLS core, he will have to reveal the same addressing structure as for a normal Internet service. NAT can be used for further address hiding.

If an MPLS network has no interconnections to the Internet, this is equal to Frame Relay or ATM networks. With Internet access from the MPLS cloud, the service provider has to reveal at least one IP address (of the peering PE router) to the next provider, and thus the outside world.

Resistance to Attacks

It is not possible to directly intrude into other VPNs. However, it is possible to attack the MPLS core, and try to attack other VPNs from there. There are two basic ways the MPLS core can be attacked:

- Attacking the PE routers directly.
- Attacking the signaling mechanisms of MPLS (mostly routing)

There are two basic types of attacks: *denial-of-service (DoS) attacks*, where resources become unavailable to authorized users, and *intrusion attacks*, where the goal is to gain unauthorized access to resources.

For intrusion attacks, give unauthorized access to resources, there are two basic ways to protect the network:

- Harden protocols that could be abused (for example, Telnet to a router)
- Make the network as inaccessible as possible. This is achieved by a combination of packet filtering or firewalling and hiding the IP addresses in the MPLS core.

Denial-of service attacks are easier to execute, since in the simplest case, a known IP address might be enough to attack a machine. The only way to be certain that you are not be vulnerable to this kind of attack is to make sure that machines are not reachable, again by packet filtering and pinging IP addresses.

MPLS networks must provide at least the same level of protection against both forms of attack as current Layer 2 networks provide.

To attack an element of an MPLS network it is first necessary to know this element, that is, its IP address. It is possible to hide the addressing structure of the MPLS core to the outside world, as discussed in the previous section. Thus, an attacker does not know the IP address of any router in the core that he wants to attack. The attacker could guess addresses and send packets to these addresses. However, due to the address separation of MPLS, each incoming packet is treated as belonging to the address space of the customer. It is therefore impossible to reach an internal router, even through guessing the IP addresses. There is only one exception to this rule—the peer interface of the PE router.

Securing the Routing Protocol

The routing between the VPN and the MPLS core can be configured two ways:

1. **Static**. In this case, the PE routers are configured with static routes to the networks behind each CE, and the CEs are configured to statically point to the PE router for any network in other parts of the VPN (usually a default route).

   The static route can point to the IP address of the PE router, or to an interface of the CE router (for example, serial0).

   Although in the static case the CE router does not know any IP addresses of the PE router, it is still attached to the PE router via some method, and could guess the address of the PE router and try to attack it with this address.

   In the case of a static route from the CE router to the PE router, which points to an interface, the CE router does not need to know any IP address of the core network, not even of the PE router. This has the disadvantage of a more extensive (static) configuration, but from a security point of view, it is preferable to the other cases.

2. **Dynamic**. A routing protocol (for example, RIP, OSPF, or BGP) is used to exchange the routing information between the CE and the PE at each peering point.

In all other cases, each CE router needs to know at least the router ID (RID; peer IP address) of the PE router in the MPLS core, and thus has a potential destination for an attack.

In practice, access to the PE router over the CE-PE interface can be limited to the required routing protocol by using access control lists (ACLs). This limits the point of attack to one routing protocol, for example BGP. A potential attack could send an extensive number of routes, or flood the PE router with routing updates. Both of these attacks could lead to a denial-of-service attack, however, not to an intrusion attack.

To restrict this risk it is necessary to configure the routing protocol on the PE router as securely as possible. This can be done in various ways:

- Use ACLs. Allow the routing protocol only from the CE router, not from anywhere else. Furthermore, no access other than that should be allowed to the PE router in the inbound ACL on each PE interface.

  ACLs must be configured to limit access only to the port(s) of the routing protocol, and only from the CE router.

- Where available, configure MD-5 authentication for routing protocols.

  This is available for BGP, OSPF, and RIP2. It avoids the possibility that packets could be spoofed from other parts of the customer network than the CE router. This requires that the service provider and customer agree on a shared secret between all CE and PE routers. The problem here is that it is necessary to do this for all VPN customers; it is not sufficient to do this only for the customer with the highest security requirements.

  MD5 authentication in routing protocols should be used on all PE-CE peers. It is easy to track the source of such a potential denial-of-service attack.

- Configure, where available, the parameters of the routing protocol to further secure this communication.

  In BGP, for example, it is possible to configure *dampening*, which limits the number of routing interactions. Also, a maximum number of routes accepted per VRF should be configured where possible.

In summary, it is not possible to intrude from one VPN into other VPNs or the core. However, it is theoretically possible to exploit the routing protocol to execute a denial-of-service attack against the PE router. This in turn might have negative impact on other VPNs. For this reason, PE routers must be extremely well secured, especially on their interfaces to the CE routers.

Label Spoofing

Assuming the address and routing separation as discussed above, a potential attacker might try to gain access to other VPNs by inserting packets with a label that he does not own. This is called *label spoofing*. This kind of attack can be done from the outside, that is, another CE router or from the Internet, or from within the MPLS core. The latter case (from within the core) is not discussed since the assumption is that the core network is provided in a secure manner. Should protection against an insecure core be required, it is necessary to run IPsec on top of the MPLS infrastructure.

Within the MPLS network, packets are not forwarded based on the IP destination address, but based on the labels that are prepended by the PE routers. Similar to IP spoofing attacks, where an attacker replaces the source or destination IP address of a packet, it is also possible to spoof the label of an MPLS packet.

The interface between any CE router and its peering PE router is an IP interface, that is, without labels. The CE router is unaware of the MPLS core, and is only aware of the destination router. The intelligence exits in the PE device, where based on the configuration, the PE chooses a label and prepends it to the packet. This is the case for all PE routers, toward CE routers, as well as to the upstream service provider. All interfaces into the MPLS cloud require IP packets without labels.

For security reasons, a PE router should never accept a packet with a label from a CE router. Cisco routers implementation is such that packets that arrive on a CE interface with a label are dropped. Thus, it is not possible to insert fake labels because no labels are accepted.

There remains the possibility to spoof the IP address of a packet that is being sent to the MPLS core. However, since there is strict addressing separation within the PE router, and each VPN has its own VRF, this can only do harm to the VPN the spoofed packet originated from, in other words, a VPN customer can attack himself. MPLS does not add any security risk here.

Securing the MPLS Core

The following is a list of recommendations and considerations on configuring an MPLS network securely.

Note The security of the overall solution depends on the security of its weakest link. This could be the weakest single interconnection between a PE and a CE, an insecure access server, or an insecure TFTP server.

Trusted Devices

The PE and P devices, as well as remote access servers and AAA servers must be treated as trusted systems. This requires strong security management, starting with physical building security and including issues such as access control, secure configuration management, and storage. There is ample literature available on how to secure network elements, so these topics are not discussed here in more detail.

CE routers are typically not under full control of the service provider and must be treated as “untrusted.”

PE-CE Interface

The interface between PE and CE routers is crucial for a secure MPLS network. The PE router should be configured as close as possible. From a security point of view, the best option is to configure the interface to the CE router unnumbered and route statically.

Packet filters (Access Control Lists) should be configured to permit only one specific routing protocol to the peering interface of the PE router, and only from the CE router. All other traffic to the router and the internal service provider network should be denied. This avoids the possibility that the PE and P routers can be attacked, since all packets to the corresponding address range are dropped by the PE router. The only exception is the peer interface on the PE router for routing purposes. This PE peer interface must be secured separately.

If private address space is used for the PE and P routers, the same rules with regard to packet filtering apply—it is required to filter all packets to this range. However, since addresses of this range should not be routed over the Internet, it limits attacks to adjacent networks.

Routing Authentication

All routing protocols should be configured with the corresponding authentication option toward the CEs and toward any Internet connection. Specifically: BGP, OSPF, and RIP2. All peering relationships in the network need to be secured this way:

- CE-PE link: use BGP MD-5 authentication
- PE-P link: use LDP MD5 authentication
- P-P

This prevents attackers from spoofing a peer router and introducing bogus routing information. Secure management is particularly important regarding configuration files, which often contain shared secrets in clear text (for example for routing protocol authentication).

Separation of CE-PE Links

If several CEs share a common Layer 2 infrastructure to access the same PE router (for example, an ethernet VLAN), a CE router can spoof packets as belonging to another VPN that also has a connection to this PE router. Securing the routing protocol is not sufficient, since this does not affect normal packets.

To avoid this problem, Cisco recommends that you implement separate physical connections between CEs and PEs. The use of a switch between various CE routers and a PE router is also possible, but it is strongly recommended to put each CE-PE pair into a separate VLAN to provide traffic separation. Although switches with VLANs increase security, they are not unbreakable. A switch in this environment must thus be treated as a trusted device and configured with maximum security.

LDP Authentication

The Label Distribution Protocol (LDP) can also be secured with MD-5 authentication across the MPLS cloud. This prevents hackers from introducing bogus routers, which would participate in the LDP.

Connectivity Between VPNs

MPLS provides VPN services with address and routing separation between VPNs. In many environments, however, the devices in the VPN must be able to reach destinations outside the VPN. This could be for Internet access or for merging two VPNs, for example, in the case of two companies merging. MPLS not only provides full VPN separation, but also allows merging VPNs and accessing the Internet.

To achieve this, the PE routers maintain various tables: A *routing context table* is specific to a CE router, and contains only routes from this particular VPN. From there, routes are propagated into the *VRF* (virtual routing and forwarding instance) *routing table*, from which a *VRF forwarding table* is calculated.

For separated VPNs, the VRF routing table contains only routes from one routing context. To merge VPNs, different routing contexts (from different VPNs) are put into one single VRF routing table. In this way, two or several VPNs can be merged to a single VPN. In this case, it is necessary that all merged VPNs have mutually exclusive addressing spaces; in other words, the overall address space must be unique for all included VPNs.

For a VPN to have Internet connectivity, the same procedure is used: Routes from the Internet VRF routing table (the default routing table) are propagated into the VRF routing table of the VPN that requires Internet access. Alternatively to propagating all Internet routes, a default route can be propagated. In this case, the address space between the VPN and the Internet must be distinct. The VPN must use private address space since all other addresses can occur in the Internet.

From a security point of view, the merged VPNs behave like one logical VPN, and the security mechanisms described above apply now between the merged VPN and other VPNs. The merged VPN must have unique address space internally, but further VPNs can use the same address space without interference. Packets from and to the merged VPNs cannot be routed to other VPNs. All the separation functions of MPLS apply also for merged VPNs with respect to other VPNs.

If two VPNs are merged in this way, hosts from either part can reach the other part as if the two VPNs were a common VPN. With the standard MPLS features, there is no separation or firewalling or packet filtering between the merged VPNs. Also, if a VPN receives Internet routes through MPLS/BGP VPN mechanisms, firewalling or packet filtering has to be engineered in addition to the MPLS features.

MP-BGP Security Features

Security in VPN Solutions Center MPLS-based networks is delivered through a combination of MP-BGP and IP address resolution. In addition, service providers can ensure that VPNs are isolated from each other.

Multiprotocol BGP is a routing information distribution protocol that, through employing multiprotocol extensions and community attributes, defines who can talk to whom. VPN membership depends upon logical ports entering the VPN, where MP-BGP assigns a unique Route Distinguisher (RD) value (see “Route Distinguishers and Route Targets” below).

RDs are unknown to end users, making it impossible to enter the network on another access port and spoof a flow. Only preassigned ports are allowed to participate in the VPN. In an MPLS VPN, MP-BGP distributes forwarding information base (FIB) tables about VPNs to members of the same VPN only, providing native security via logical VPN traffic separation. Furthermore, IBGP PE routing peers can perform TCP segment protection using the MD5 Signature Option when establishing IBGP peering relationships, further reducing the likelihood of introducing spoofed TCP segments into the IBGP connection stream among PE routers (for information on the MD5 Signature Option, see RFC 2385).

The service provider, not the customer, associates a specific VPN with each interface when provisioning the VPN. Users can only participate in an intranet or extranet if they reside on the correct physical or logical port and have the proper RD. This setup makes a Cisco MPLS VPN virtually impossible to enter.

Within the core, a standard Interior Gateway Protocol (IGP) such as OSPF or IS-IS distributes routing information. Provider edge routers set up paths among one another using LDP to communicate label-binding information. Label binding information for external (customer) routes is distributed among PE routers using MP-BGP multiprotocol extensions instead of LDP, because they easily attach to VPN IP information already being distributed.

The MP-BGP community attribute constrains the scope of reachability information. MP-BGP maps FIB tables to provider edge routers belonging to only a particular VPN, instead of updating all edge routers in the service provider network.

Security Through IP Address Resolution

MPLS VPN networks are easier to integrate with IP-based customer networks. Subscribers can seamlessly interconnect with a provider service without changing their intranet applications because MPLS-based networks have built-in application awareness. Customers can even transparently use their existing IP address space without Network Address Translator (NAT) because each VPN has a unique identifier.

MPLS VPNs remain unaware of one another. Traffic is separated among VPNs using a logically distinct forwarding table and RD for each VPN. Based on the incoming interface, the PE selects a specific forwarding table, which lists only valid destinations in the VPN. To create extranets, a provider explicitly configures reachability among VPNs.

The forwarding table for a PE contains only address entries for members of the same VPN. The PE rejects requests for addresses not listed in its forwarding table. By implementing a logically separate forwarding table for each VPN, each VPN itself becomes a private, connectionless network built on a shared infrastructure.

IP limits the size of an address to 32 bits in the packet header. The VPN IP address adds 64 bits in front of the header, creating an extended address in routing tables that classical IP cannot forward. MPLS solves this problem by forwarding traffic based on labels, so one can use MPLS to bind VPN IP routes to label-switched paths. PEs are concerned with reading labels, not packet headers. MPLS manages forwarding through the provider's MPLS core. Since labels only exist for valid destinations, this is how MPLS delivers both security and scalability.

When a virtual circuit is provided using the overlay model, the egress interface for any particular data packet is a function solely of the packet's ingress interface; the IP destination address of the packet does not determine its path in the backbone network. Thus, unauthorized communication into or out of a VPN is prevented.

In MPLS VPNs, a packet received by the backbone is first associated with a particular VPN by stipulating that all packets received on a certain interface (or subinterface) belong to a certain VPN. Then its IP address is looked up in the forwarding table associated with that VPN. The routes in that forwarding table are specific to the VPN of the received packet.

In this way, the ingress interface determines a set of possible egress interfaces, and the packet's IP destination address is used to choose from among that set. This prevents unauthorized communication into and out of a VPN.

Ensuring VPN Isolation

To maintain proper isolation of one VPN from another, it is important that the provider routers not accept a labeled packet from any adjacent PE unless the following conditions are met:

- The label at the top of the label stack was actually distributed by the provider router to the PE device.
- The provider router can determine that use of that label will cause the packet to exit the backbone before any labels lower in the stack and the IP header will be inspected.

These restrictions are necessary to prevent packets from entering a VPN where they do not belong.

The VRF tables in a PE are used only for packets arriving from a CE that is directly attached to the PE device. They are not used for routing packets arriving from other routers that belong to the service provider backbone. As a result, there may be multiple different routes to the same system, where the route followed by a given packet is determined by the site from which the packet enters the backbone. So one may have one route to a given IP network for packets from the extranet (where the route leads to a firewall), and a different route to the same network for packets from the intranet.

VPN Routing and Forwarding Tables (VRFs)

The VPN routing and forwarding table (VRF) is a key element in the MPLS VPN technology. VRFs exist on PEs only. A VRF is a routing table instance, and more than one VRF can exist on a PE. A VPN can contain one or more VRFs on a PE.The VRF contains routes that should be available to a particular set of sites. VRFs use CEF technology, therefore the VPN must be CEF-enabled.

A VRF is associated with the following elements:

- IP routing table
- Derived forwarding table, based on the Cisco Express Forwarding (CEF) technology
- A set of interfaces that use the derived forwarding table
- A set of routing protocols and routing peers that inject information into the VRF

Each PE maintains one or more VRFs. VPNSC software looks up a particular packet's IP destination address in the appropriate VRF only if that packet arrived directly through an interface that is associated with that VRF. The so-called "color" MPLS label tells the destination PE to check the VRF for the appropriate VPN so that it can deliver the packet to the correct CE and finally to the local host machine.

A VRF is named based on the VPN or VPNs it services, and on the role of the CE in the topology. The schemes for the VRF names are as follows:

The VRF name for a hub: `ip vrf V`*x:*`[`*VPN_name*`]`

The *x* parameter is a number assigned to make the VRF name unique.

For example, if we consider a VPN called Blue, then a VRF for a hub CE would be called:

```
ip vrf V1:blue
```

A VRF for a spoke CE in the Blue VPN would be called:

```
ip vrf V1:blue-s
```

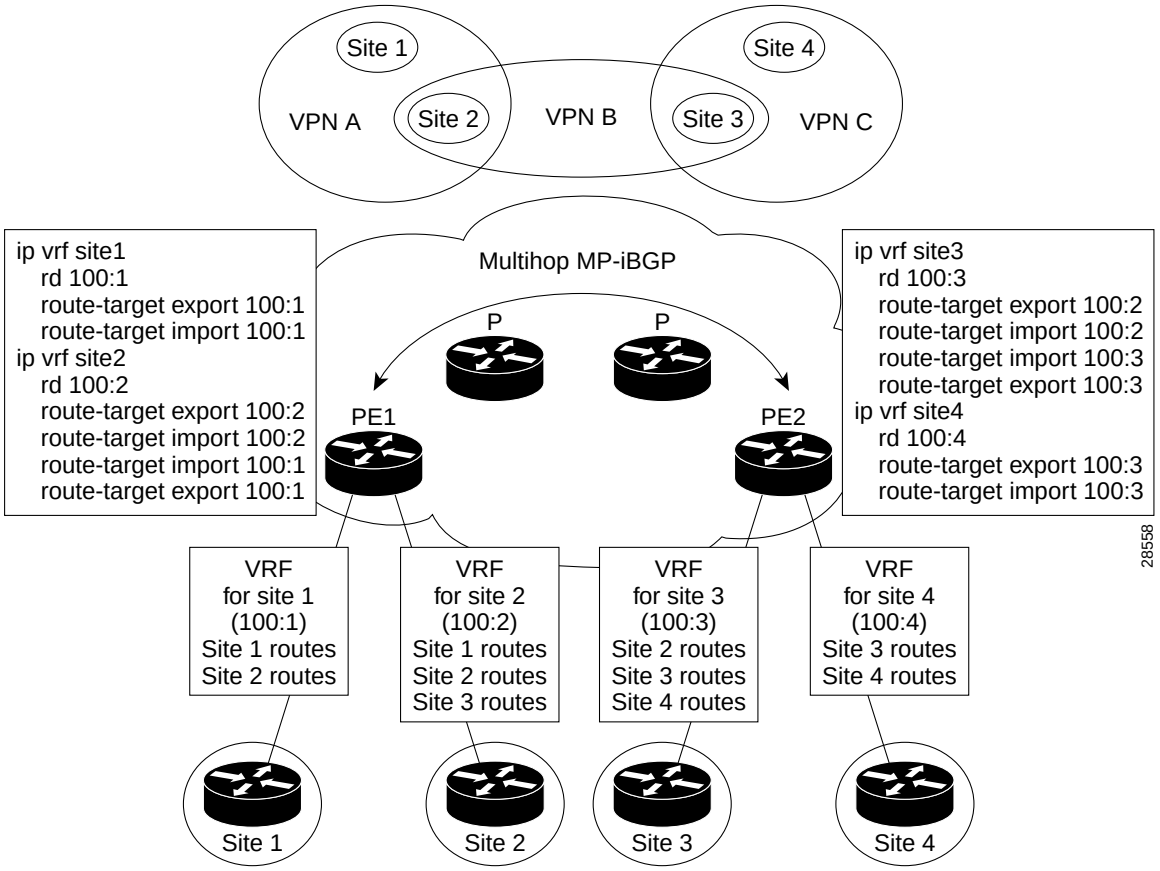
A VRF for an extranet VPN topology in the Green VPN would be called:

```
ip vrf V1:green-etc
```

Thus, you can read the VPN name and the topology type directly from the name of the VRF.

Figure 1-5 shows a network in which two of the four sites are members of two VPNs, and illustrates which routes are included in the VRFs for each site.

Figure 1-5 VRFs for Sites in Multiple VPNs



VRF Implementation Considerations

When implementing VPNs and VRFs, Cisco recommends you keep the following considerations in mind:

- A local VRF interface on a PE is not considered a directly-connected interface in a traditional sense. When you configure, for example, a Fast Ethernet interface on a PE to participate in a particular VRF/VPN, the interface no longer shows up as a directly-connected interface when you issue a **show ip route** command. To see that interface in a routing table, you must issue a **show ip route vrf** *vrf_name* command.
- The global routing table and the per-VRF routing table are independent entities. Cisco IOS commands apply to IP routing in a global routing table context. For example, `show ip route`, and other EXEC-level show commands—as well as utilities such as **ping**, **traceroute**, and **telnet**—all invoke the services of the Cisco IOS routines that deal with the global IP routing table.
- You can issue a standard Telnet command from a CE router to connect to a PE router. However, from that PE, you must issue the following command to connect from the PE to the CE:

  telnet *CE_RouterName* **/vrf** *vrf_name*

  Similarly, you can utilize the **Traceroute** and **Ping** commands in a VRF context.

- The MPLS VPN backbone relies on the appropriate Interior Gateway Protocol (IGP) that is configured for MPLS, for example, EIGRP, or OSPF. When you issue a **show ip route** command on a PE, you see the IGP-derived routes connecting the PEs together. Contrast that with the **show ip route vrf** *VRF_name* command, which displays routes connecting customer sites in a particular VPN.

Creating a VRF Instance

The configuration commands to create a VRF instance are as follows:

	Command	Description
Step 1	`Router# configure terminal` `Router(config)#`	Enter global configuration mode.
Step 2	`Router(config)# ip vrf` *vrf_name*	For example, `ip vrf` *CustomerA* initiates a VPN routing table and an associated CEF table named CustomerA. The command enters VRF configuration submode to configure the variables associated with the VRF.
Step 3	`Router(config-vrf)# rd` *RD_value*	Enter the eight-byte route descriptor (RD) or IP address. The PE prepends the RD to the IPv4 routes prior to redistributing the route into the MPLS VPN backbone.
Step 4	`Router(config-vrf)# route-target import | export | both` *community*	Enter the route-target information for the VRF.

For detailed information about these configuration commands, refer to Appendix C, "Cisco VPNSC: MPLS Solution Command Reference."

Route Distinguishers and Route Targets

MPLS-based VPNs employ BGP to communicate between PEs to facilitate customer routes. This is made possible through extensions to BGP that carry addresses other than IPv4 addresses. A notable extension is called the *route distinguisher* (RD).

The purpose of the route distinguisher (RD) is to make the prefix value unique across the backbone. Prefixes should use the same RD if they are associated with the same set of route targets (RTs) and anything else that is used to select routing policy. The community of interest association is based on the route target (RT) extended community attributes distributed with the Network Layer Reachability Information (NLRI).The RD value must be a globally unique value to avoid conflict with other prefixes.

The MPLS label is part of a BGP routing update. The routing update also carries the addressing and reachability information. When the RD is unique across the MPLS VPN network, proper connectivity is established even if different customers use non-unique IP addresses.

For the RD, every CE that has the same overall role should use a VRF with the same name, same RD, and same RT values. The RDs and RTs are *only* for route exchange between the PEs running BGP. That is, for the PEs to do MPLS VPN work, they have to exchange routing information with more fields than usual for IPv4 routes; that extra information includes (but is not limited to) the RDs and RTs.

The route distinguisher values are chosen by the VPN Solutions Center software.

- CEs with hub connectivity use `bgp_AS:`*value*.

- CEs with spoke connectivity use `bgp_AS:`*value* `+ 1`

Each spoke uses its own RD value for proper hub and spoke connectivity between CEs; therefore, the VPN Solutions Center software implements a new RD for each spoke that is provisioned.

VPN Solutions Center chooses route target values by default, but you can override the automatically assigned RT values if necessary when you first define a CERC in the VPN Solutions Center software (see the "Defining CE Routing Communities" section on page 3-15).

Route Target Communities

The mechanism by which MPLS VPN controls distribution of VPN routing information is through the VPN route-target extended MP-BGP communities. An extended MP-BGP community is an eight octet structure value. MPLS VPN uses route-target communities as follows:

- When a VPN route is injected into MP-BGP, the route is associated with a list of VPN route-target communities. Typically, this is set through an export list of community values associated with the VRF from which the route was learned.
- An import list of route-target communities is associated with each VRF. This list defines the values that should be matched against to decide whether a route is eligible to be imported into this VRF.

  For example, if the import list for a particular VRF is {A, B, C}, then any VPN route that carries community value A, B, or C is imported into the VRF.

CE Routing Communities

A VPN can be organized into subsets called *CE routing communities*, or CERCs. A CERC describes how the CEs in a VPN communicate with each other. Thus, CERCs describe the logical topology of the VPN. VPN Solutions Center can be employed to form a variety of VPN topologies between CEs by building hub and spoke or full mesh CE routing communities. CERCs are building blocks that allow you to form complex VPN topologies and CE connectivity.

The most common types of VPNs are *hub-and-spoke* and *full mesh*.

- A hub-and-spoke CERC is one in which one or a few CEs act as hubs, and all spoke CEs talk only to or through the hubs, never directly to each other.
- A full mesh CERC is one in which every CE connects to every other CE.

These two basic types of VPNs—full mesh and hub and spoke—can be represented with a single CERC.

Whenever you create a VPN, the VPN Solutions Center software creates one default CERC for you. This means that until you need advanced customer layout methods, you will not need to define new CERCs. Up to that point, you can think of a CERC as standing for the VPN itself—they are one and the same. If, for any reason, you need to override the software's choice of route target values, you can do so only at the time you create a CERC in the VPN Solutions Center software (see the "Defining CE Routing Communities" section on page 3-15).

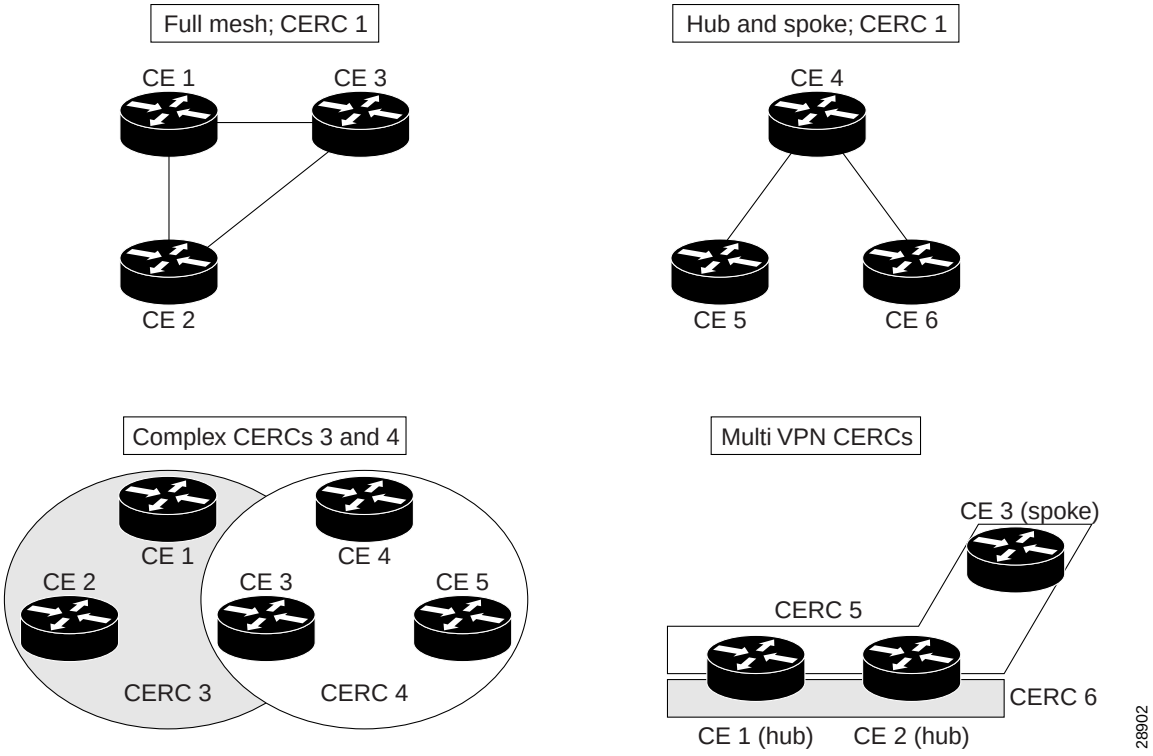
To build very complex topologies, it is necessary to break down the required connectivity between CEs into groups, where each group is either fully meshed, or has a hub and spoke pattern. (Note that a CE can be in more than one group at a time, so long as each group has one of the two basic patterns.) Each subgroup in the VPN needs its own CERC. Any CE that is only in one group just joins the corresponding CERC (as a spoke if necessary). If a CE is in more than one group, then you can use the Advanced Setup choice during provisioning to add the CE to all the relevant groups in one service request. Given this

information, the provisioning software does the rest, assigning route target values and VRF tables to arrange exactly the connectivity the customer requires. You can use the Topology tool to double-check the CERC memberships and resultant VPN connectedness.

VPN Solutions Center supports multiple CEs per site and multiple sites connected to the same PE. Each CERC has unique route targets (RT), route distinguisher (RD) and VRF naming. After provisioning a CERC, it is a good idea to run the audit reports to verify the CERC deployment and view the topologies created by the service requests. The product supports linking two or more CE routing communities in the same VPN.

Figure 1-6 shows several examples of the topologies that VPN Solutions Center CERCs can employ.

Figure 1-6 Examples of CERC Topologies



Hub and Spoke Considerations

In hub-and-spoke MPLS VPN environments, the spoke routers have to have unique Route Distinguishers (RDs). In order to use the hub site as a transit point for connectivity in such an environment, the spoke sites export their routes to the hub. Spokes can talk to hubs, but spokes never have routes to other spokes.

Due to the current MPLS VPN implementation, you must apply a different RD for each spoke VRF. The MP-BGP selection process applies to all the routes that have to be imported into the same VRF plus all routes that have the same RD of such a VRF. Once the selection process is done, only the best routes are imported. In this case this can result in a best route which is not imported. Thus, customers must have different RDs per spoke-VRF.

Full Mesh Considerations

Each CE Routing Community (CERC) has two distinct RTs: a hub RT and a spoke RT. When building a full mesh topology, always use the hub RT. Thus, when a need arises to add a spoke site for the current full mesh topology, you can easily add the spoke site without reconfiguring any of the hub sites. The existing spoke RT can be used for this purpose. This is a strategy to prevent having to do significant reprovisioning of a full mesh topology to a hub-and-spoke topology.

MPLS VPN Cable Feature Overview

Using MPLS VPN technology, service providers can create scalable and efficient private networks using a shared Hybrid Fiber Coaxial (HFC) network and Internet Protocol (IP) infrastructure. The cable MPLS VPN network consists of the following two major elements:

- The Multiple Service Operator (MSO) or cable company that owns the physical infrastructure and builds VPNs for the Internet Service Providers (ISPs) to move traffic over the cable and IP backbone.
- ISPs that use the HFC network and IP infrastructure to supply Internet service to cable customers.

You can find the complete description on how to use VPN Solutions Center software to provision cable MPLS VPNs in Chapter 7, “Provisioning MPLS VPN Cable Services.”

Benefits of Cable MPLS VPNs

Provisioning cable services with MPLS VPNs provides the following benefits:

- MPLS VPNs give cable MSOs and ISPs a manageable way of supporting multiple access to a cable plant.

  Service providers can create scalable and efficient VPNs across the core of their networks MPLS VPNs provide systems support scalability in cable transport infrastructure and management.
- Each ISP can support Internet access services from a subscriber’s PC through an MSO’s physical cable plant to their networks.
- MPLS VPNs allow MSOs to deliver value-added services through an ISP, and thus, deliver connectivity to a wider set of potential customers.

  MSOs can partner with ISPs to deliver multiple services from multiple ISPs and add value within the MSO’s own network using VPN technology.
- Subscribers can select combinations of services from various service providers.
- The Cisco IOS MPLS VPN cable feature sets build on Cable Modem Termination Server (CMTS) and DOCSIS 1.0 extensions to ensure services are reliably and optimally delivered over the cable plant.

  MPLS VPN provides systems support domain selection, authentication per subscriber, selection of QoS, policy-based routing, and ability to reach behind the cable modem to subscriber end-devices for QoS and billing, while preventing session-spoofing.
- MPLS VPN technology ensures both secure access across the shared cable infrastructure and service integrity.

The Cable MPLS VPN Network

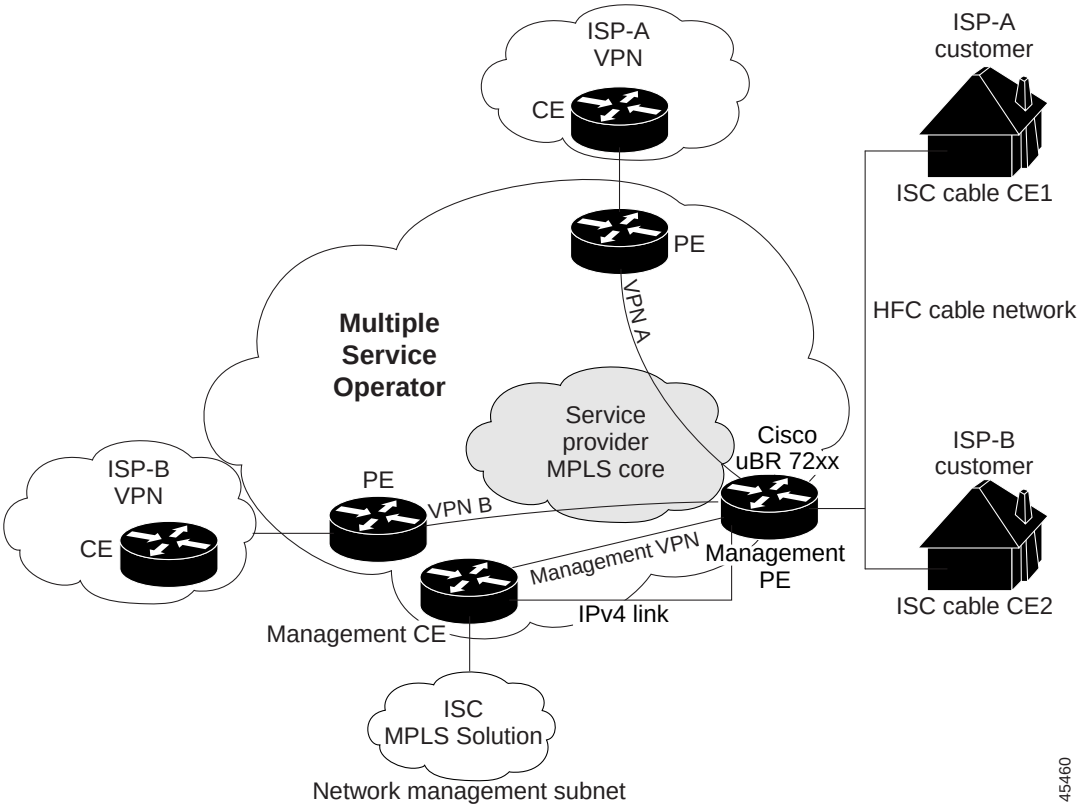
As shown in Figure 1-7, each ISP moves traffic to and from a subscriber's PC, through the MSO's physical network infrastructure, to the ISP's network. MPLS VPNs, created in Layer 3, provide privacy and security by constraining the distribution of a VPN's routes only to the routers that belong to its network. Thus, each ISP's VPN is insulated from other ISPs that use the same MSO infrastructure.

In the MPLS-based cable scheme, a VPN is a private network built over a shared cable plant and MPLS-core backbone. The public network is the shared cable plant or backbone connection points. A cable plant can support Internet access services and carry traffic for an MSO and its subscribers, as well as for multiple Internet Service Providers (ISPs) and their subscribers.

An MPLS VPN assigns a unique VPN Routing/Forwarding (VRF) instance to each VPN. A VRF instance consists of an IP routing table, a derived forwarding table, a set of interfaces that use the forwarding table, and a set of rules and routing protocols that determine the contents of the forwarding table.

Each PE router maintains one or more VRF tables. If a packet arrives directly through an interface associated with a particular VRF, the PE looks up a packet's IP destination address in the appropriate VRF table. MPLS VPNs use a combination of BGP and IP address resolution to ensure security.

Figure 1-7 Example of an MPLS VPN Cable Network



The routers in the cable network are as follows:

- Provider (P) router—Routers in the MPLS core of the service provider network. P routers run MPLS switching, and do not attach VPN labels (MPLS labels in each route assigned by the PE router) to routed packets. VPN labels direct data packets to the correct egress router.

- Provider Edge (PE) router—A router that attaches the VPN label to incoming packets based on the interface or subinterface on which they are received. A PE router attaches directly to a CE router. In the MPLS-VPN approach, each Cisco uBR72xx series router acts as a PE router.
- Customer (C) router—A router in the ISP or enterprise network.
- Customer Edge (CE) router—Edge router on the ISP's network that connects to the PE router on the MSO's network. A CE router must interface with a PE router.
- Cable CE—The cable CE is an object with the VPN Solutions Center only. In the VPN Solutions Center software, the cable CE represents the cable modem and its associated hosts for a particular site.
- Management CE (MCE) router—The MCE *emulates* the role of a customer edge router (CE), but the MCE is in provider space and serves as a network operations center gateway router. The network management subnet is connected to the Management CE (MCE). The MCE is part of a management site as defined in the VPN Solutions Center software.
- Management PE (MPE) router—The MPE *emulates* the role of a PE in the provider core network. The MPE connects the MCE to the provider core network. An MPE can have a dual role as both a PE and the MPE.

The shared cable plant supports Internet connectivity from ISP A to its subscribers and from ISP B to its subscribers.

The Management VPN in the Cable Network

The MPLS network has a unique VPN that exclusively manages the MSOs devices called the *management VPN*. It contains servers and devices that other VPNs can access. The management VPN connects the Management CE (MCE) router and the management subnet to the MSO PE router (a uBr72xx router or equivalent). VPN Solutions Center and the management servers, such as Dynamic Host Configuration Protocol (DHCP), Cisco Network Registrar (CNR) Time of Day (ToD) are part of the management subnet and are within the management VPN for ISP connectivity.

As shown in Figure 1-7, the management VPN is comprised of the network management subnet (where the VPN Solutions Center workstation resides), which is directly connected to the Management CE (MCE). The management VPN is a special VPN between the MCE and the cable VPN gateway. The cable VPN gateway is usually a Cisco uBR 72xx router that functions as both a regular PE and a Management PE. Notice that there is also a parallel IPv4 link between the MCE and the MPE.

Using VPNSC Templates to Customize Configuration Files

The Template Manager in the VPN Solutions Center software is a provisioning system that provides fast, flexible, and extensible Cisco IOS command generation capability. The Template Manager defines standard templates to generate Cisco IOS configurations for common provisioning tasks, such as common IPv4, QoS, and VPN provisioning. For details, see Chapter 8, "Provisioning with the VPN Solutions Center Template Manager."

- A *template file* is a file created by the Template Manager that stores a VPN Solutions Center template definition.
- A *template data file* is a text file that stores variable values to generate the template file. A valid data file contains name-value pairs for all the variables defined in a template. Each template file can be associated with multiple data files; however, note that each data file can only be associated with a single template. You can select which data file to use to generate a template. The filename suffix for data files is *.dat*.

- A *template configuration file* is an IOS configuration file that stores the Cisco IOS commands created by the Template Manager. A template configuration file can be either a partial or complete configuration file. When you generate a template configuration file using a particular data file, the template configuration filename is the same as the data file's name.

The template data files are tightly linked with its corresponding template. You can use a data file and its associated template to create a template configuration file. The template configuration file is merged with (either appended to or prepended to) the VPNSC configlet. VPN Solutions Center downloads the combined configlet to the edge device router.

You can apply the same template to multiple edge devices, assigning the appropriate template data file for each device. Each template data file includes the specific data for a particular device (for example, the management IP address or host name of each device).

The template files and data files are in XML format. The template file, its data files, and all template configuration file files are mapped to a single directory.

- VPN Solutions Center creates the initial VPNSC configlet. Through the Template Manager, you can create a template configuration file. You can then associate a template configuration file with a service request, which effectively merges the VPNSC configlet and the template configuration file. For details on this process, see the "Integrating VPN Solutions Center Templates with a Service Request" section on page 4-25. You can then download this merged VPNSC configlet to the target router (or routers).
- You can also create a template configuration file and download it directly to a router as described in the "Provisioning a Template Configuration File Directly to a Router" section on page 8-23.

Uses for the Templating Function

Service providers can use the Template Manager to enhance VPN Solutions Center functionality. Because the Telnet Gateway Server (TGS) supports console access to VPN Solutions Center targets, you can use the Template Manager to provide initial configuration for any service provider core device or edge device.

The Template Manager can be used as a stand-alone tool to generate complete configuration files that you can download to any VPN Solutions Center target.

Some of the additional uses for templating are as follows:

- IOS firewall provisioning
- Add a set of commands that VPN Solutions Center does not include to a service request; for example, provisioning ATM Class of Service.
- Use the templating feature to apply Class of Service using IP connectivity.
- Download a VPN Solutions Center service request and an Cisco IOS configuration file in one download operation through the console. This edge device staging method would create a template and apply the service request in one step.

Event Subscription Service

The Cisco VPN Solutions Center Event Subscription Service (ESS) is an event-notification service (for client-application developers) that allows you to track specific events that may be of interest to your application and your customers. Using the Event Subscription Service, client-application developers can support the following:

- Real-time response to system events
- Local caching of system data
- Synchronization of one or more tasks to create a process flow

While executing, the Cisco VPN Solutions Center software publishes events at the following times:

- Each time an element is created, modified, or destroyed in any of the four VPN Solutions Center repositories
- Each time a scheduled task begins or ends its execution
- When a Watch Dog event signals a change in execution status for any VPN Solutions Center server

Each event contains identifying information that appropriately corresponds with the event type. The ESS is supported by the following:

- Event Gateway server
- Cisco Event Gateway Callback interface (in the CiscoEventGateway.idl file)
- TIB®/Rendezvous™ software

For details on this feature, refer to “Part 5, Using the Event Subscription Service” in the *Cisco VPN Solutions Center: MPLS Solution API Programmer Guide*.

The Event Gateway Server

The Event Gateway server is a CORBA wrapper for the TIB/Rendezvous software that is used by VPN Solutions Center. The Event Gateway Server uses the client-oriented SDKs that are supplied by TIBCO to define its interaction with the TIB/Rendezvous software. The Cisco Event Gateway Callback interface, which is defined in the *CiscoEventGateway.idl* file, provides the client-development facility with which you can interact with the Event Gateway server.

There is no practical limit to the number of clients the Event Gateway server can support. Within the scope of each client, the Event Gateway server can support the Event Gateway Callback objects that subscribe to subjects of interest, which are events generated during the execution of the VPN Solutions Center software.

The Event Gateway Server complements the APIs that VPN Solutions Center provides to enable third party software access to VPNSC data. The TIB/Rendezvous software is the means by which VPNSC signals the occurrences of significant events within VPNSC (for example, the beginning and ending of tasks, the completion of data processing, and so on). If your third party software has special requirements, such as real-time notification of events within VPNSC software, you can use the Event Subscription Service to subscribe to those events.

Quality of Service and Class of Service

Quality of Service (QoS) and Class of Service (CoS) enable the service provider to offer differentiated IP-based service levels and tiered pricing. QoS refers to the ability of a network to provide better service to selected network traffic. In particular, QoS features provide better and more predictable network service by the following:

- Supporting dedicated bandwidth
- Improving loss characteristics
- Avoiding and managing network congestion
- Setting traffic priorities across the network

CoS refers to the methods that provide *differentiated service*, in which the network delivers a particular kind of service based on the class of service specified for each packet. CoS provides specific categories of service such as Gold, Silver, and Best-Effort service classes.

To properly deploy QoS, enforcement of QoS measurements and policies must be in place throughout the network, from the first internetwork forwarding device (such as a Layer 2 switch or router) to the last device that front-ends the ultimate IP destination station. QoS requires an end-to-end approach because it requires mechanisms both at the edge and in the core.

To service providers, QoS is desirable because it has the potential of helping them support many types of traffic (data, voice, and video) over the same network infrastructure. It allows them to offer business-quality IP VPN services, and the end-to-end service level agreements (SLAs) that customers demand.

In an MPLS VPN environment, the service provider must consider both packet and cell routers. In a packet environment, MPLS Class of Service is fairly straightforward. A PE simply copies the IP precedence to the MPLS Class of Service field. The CoS field can then be used as input to Weighted Random Early Detection (WRED), as well as Weighted Fair Queuing (WFQ). The challenge is to provide MPLS CoS in environments where PEs are connected to ATM. Class of Service is more involved on ATM interfaces and within the ATM PEs themselves. QoS is discussed in-depth in other resources available from Cisco. The emphasis in this section is to investigate differentiated services in MPLS intranet and extranet VPN environments.

In mega-scale VPNs, applying QoS on a flow-by-flow basis is not practical because of the number of IP traffic flows in carrier-sized networks. The key to QoS in large-scale VPNs is implementing controls on a set of service classes that applications are grouped into. For example, a service provider network may implement three service classes: a high-priority, low-latency “premium” class; a guaranteed-delivery “mission-critical” class; and a low-priority “best-effort” class. Each class of service is priced appropriately, and subscribers can buy the mix of services that suits their needs. For example, subscribers may wish to buy guaranteed-delivery, low-latency service for their voice and video conferencing applications, and best-effort service for e-mail traffic and bulk file transfers.

Because QoS requires intensive processing, the Cisco model distributes QoS duties between the PEs and core routers. This approach assumes a lower-speed, high-touch edge and a high-speed, lower-touch core for efficiency and scalability.

Cisco IOS QoS/CoS Toolkit

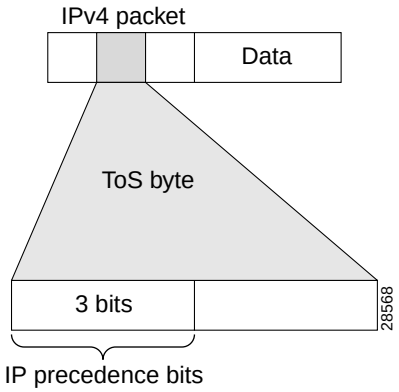
Cisco IOS software includes several Layer 3 QoS features that are particularly applicable to VPN provisioning and management. MPLS-enabled networks make use of the following Cisco IOS QoS features to build an end-to-end QoS architecture:

- IP Precedence
- Committed Access Rate (CAR)
- Weighted Random Early Detection (WRED)
- Weighted Fair Queuing (WFQ)
- Generic Traffic Shaping

IP Precedence

IP Precedence utilizes the three precedence bits in the IPv4 header Type-of-Service field to specify class of service for each packet, as shown in Figure 1-8. You can partition traffic in up to six classes of service using IP Precedence (two others are reserved for internal network use). Queuing technologies throughout the network can use this signal to provide the appropriate expedited handling.

Figure 1-8 Type of Service Field in the IP Precedence Header



Committed Access Rate (CAR)

Committed Access Rate (CAR) is Cisco's traffic policing tool for instituting a QoS policy at the edge of a network. CAR allows you to identify packets of interest for classification with or without rate limiting. CAR allows you to define a traffic contract in routed networks. You can classify and police traffic on an incoming interface, and set policies for handling traffic that exceeds a certain bandwidth allocation. CAR can be used to set IP precedence based on extended access list classification. This allows considerable flexibility for precedence assignment, including allocation by application, port, source address, destination address, and so on. As a rule-based engine, CAR classifies traffic based on flexible rules, including IP precedence, IP access lists, incoming interface, or MAC address. It limits the rate to the defined ingress thresholds to help allay congestion through the core.

For monitoring details, see the "Using CAR to Monitor Data" section on page 5-28.

VPN Solutions Centers software uses Committed Access Rate on the ingress or egress PE interfaces to perform two main tasks:

a. Classify traffic into a maximum of four classes of service

b. Rate limit traffic to a specified bandwidth

The PE can rate limit traffic to the subscribed bandwidth and mark the traffic that is within the specified bandwidth as *in-contract*, and mark traffic above the specified bandwidth as *out-of-contract*.

Marking a packet as in-contract or out-of-contract is done by setting the first bit of the precedence bits in the IP header. The appropriate class is indicated by the remaining two precedence bits (see). Traffic that exceeds any class is marked as out-of-contract, and this traffic can be dropped or mapped to a lower class of service. The out-of-contract bandwidth is initially set to the in-contract bandwidth, but you can set this in the product's VPN Console to the values appropriate for the customer (see the "Defining a Class of Service Profile" section on page 2-67).

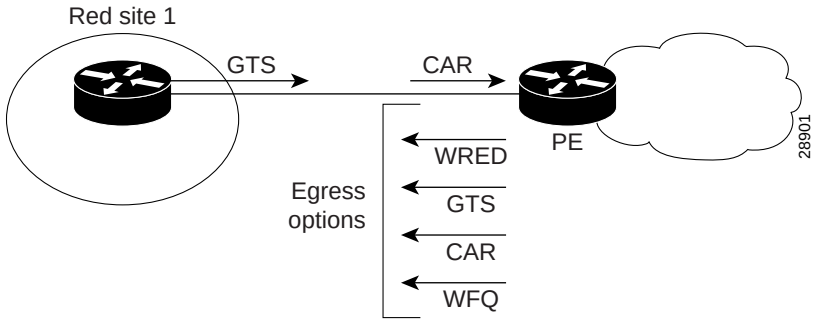
Table 1-1 Mapping IP Precedence to Class of Service

IP Precedence	Contract Status	Class of Service
111	In-contract	Class 1
110	In-contract	Class 2
101	In-contract	Class 3
100	In-contract	Class 4
011	Out-of-contract	Class 1
010	Out-of-contract	Class 2
001	Out-of-contract	Class 3
000	Out-of-contract	Class 4

The customer can initially "paint" the packets that leave the customer edge router (heading to the PE), and VPN Solutions Center allows policing or repainting of packets that enter the provider edge router.

Figure 1-9 shows GTS applied to the CE's egress interface (Red site 1) and CAR applied to the PE's ingress interface, as well as the CoS options available on the PE's egress interface.

Figure 1-9 CoS Options on the PE and CE



Generic Traffic Shaping (GTS)

Generic Traffic Shaping (GTS) shapes traffic by reducing outbound traffic flow to avoid congestion. It does this by constraining traffic to a particular bit rate using the token bucket mechanism. GTS applies on a per-interface basis and can use access lists to select the traffic to shape. GTS can also be applied to a specific access list on an interface.

GTS smooths out bandwidth peaks by class of service. GTS shapes by looking at bandwidth (for example, 40 kbps for “gold,” or best of service), and uses a buffering technique for handling excess (or out-of-contract) traffic. GTS is useful as a tool to protect the link between the PE and CE by limiting bursty traffic that exits the CE.

Generic Traffic Shaping can take place on the CE’s egress subinterface for traffic shaping and on the PE’s egress subinterface for congestion management.

VPN Solutions Center has the option to apply traffic shaping to either a) in-contract and out-of-contract packets leaving the CE interface, or b) out-of-contract traffic flow exiting the CE interface. GTS is provisioned so that traffic does not exceed a specified bandwidth and performs burst traffic control for the PE-CE link.

The out-of-contract bandwidth is, by default, equal to the in-contract bandwidth. You have the option to allow the out-of-contract bandwidth to be set to a percentage of the in-contract bandwidth. VPN Solutions Center also allows the application of adaptive traffic shaping for Frame Relay; the traffic shaping responds to Frame Relay traffic congestion control.

Weighted Random Early Detection (WRED)

WRED provides congestion avoidance. This technique monitors network traffic load in an effort to anticipate and avoid congestion at common network bottlenecks, as opposed to congestion management techniques that operate to control congestion once it occurs.

WRED is designed to avoid congestion in internetworks before it becomes a problem. It leverages the flow monitoring capabilities of TCP. It monitors traffic load at points in the network and discards packets if the congestion begins to increase. The result is that the source detects the dropped traffic and slows its transmission. WRED interacts with other QoS mechanisms to identify class of service in packet flows. It selectively drops packets from low-priority flows first, ensuring that high-priority traffic gets through. WRED is supported on the same interface as WFQ. You should run both of these queueing algorithms on every interface where congestion is likely to occur. In the service provider core, apply WRED by IP precedence and WFQ by service class.

Weighted Fair Queuing (WFQ)

WFQ addresses situations where it is desirable to provide consistent response time to heavy and light network users alike without adding excessive bandwidth. WFQ is a flow-based queuing algorithm that does two things simultaneously: it schedules interactive traffic to the front of the queue to reduce response time, and it fairly shares the remaining bandwidth among lower-priority flows.

Weighted Fair Queuing (WFQ) employs a differential scheduling policy that results in packets of different classes getting different amounts of link bandwidth during outbound congestion. WFQ is the differentially-oriented counterpart to a first-in, first-out (FIFO) scheduling policy.

WFQ ensures that queues are not starved for bandwidth and that traffic achieves predictable service so that mission-critical traffic receives highest priority to ensure guaranteed delivery and latency. Lower-priority traffic streams share the remaining capacity proportionally among them. The WFQ algorithm also addresses the problem of round-trip delay variability. If multiple high-volume conversations are active, their transfer rates and inter-arrival periods are made much more predictable.

Algorithms such as the Transmission Control Protocol (TCP) congestion control and slow-start features are much enhanced by WFQ. The result of WFQ is more predictable throughput and response time for each active flow.

WFQ is IP precedence-aware; that is, it is able to detect higher priority packets marked with precedence by the IP forwarder and schedule them faster, providing superior response time for this traffic. The IP precedence field has values between 0 (the default) and 7. As the precedence value increases, the algorithm allocates more bandwidth to that conversation to make sure that it gets served more quickly when congestion occurs. WFQ assigns a weight to each flow, which determines the transmit order for queued packets. It provides the ability to reorder packets and control latency at the edge and in the core. By assigning different weights to different service classes, a switch can manage buffering and bandwidth for each service class. This mechanism constrains delay bounds for time-sensitive traffic such as voice or video.

Service providers can tailor each class to the specific service needs of their customers. For example, a service provider can offer a “Gold class” for voice traffic. Here, a large bandwidth allocation policy ensures that sufficient bandwidth is available for all the cells in the voice queue while a moderately-sized buffer limits the potential cell delay. Since these shares are relative weights, allocating a large share to gold means that a minimum is guaranteed. If the gold class is under utilized, the bandwidth is shared by the remaining classes in proportion to their weights. This ensures maximum efficiency and that paying customer traffic is sent if bandwidth is available.

Proper QoS/CoS Placement in the Network

QoS/CoS application is easy to implement in a non-ATM MPLS environment. When QoS must be implemented in an end-to-end fashion, two areas of implementation need to be looked at— the ingress and egress edges of the network and the core network.

At the edges of the network, traffic enforcement and policing need to be present. Therefore, at the edges of the network, Cisco’s Committed Access Rate (CAR) is required.

In the core of the network, techniques such as WRED and WFQ need to be considered.

The IP precedence setting, if policy calls for it, is modified at the ingress of a network. It is also possible, for certain environments, to adjust the IP precedence field at the egress of the network.

NetFlow Collector and VPN Solutions Center Software

Although NetFlow is not part of the VPN Solutions Center software suite, it is an important element in the MPLS VPN network scheme, and operators are required to specify the NetFlow Collector devices in the service provider’s network (see the “Configuring NetFlow Accounting in VPN Solutions Center” section on page 5-5). Cisco recommends that service providers schedule VPN Solutions Center to collect data from NetFlow Collector devices every three hours.

The NetFlow data is stored on the NetFlow workstations in binary flat files. Because NetFlow sends data from the router in User Datagram Protocol (UDP) packets, Cisco recommends that the NetFlow Collector 3.0 device be located on a LAN connected directly to the PE or the Management PE (MPE) device.

NetFlow services consist of high-performance IP switching features that capture a rich set of traffic statistics exported from routers and switches while they perform their functions. The exported NetFlow data consists of traffic *flows*, which are unidirectional sequences of packets between a particular source device and destination device that share the same protocol and transport-layer information. The captured traffic statistics can be used for a wide variety of purposes, such as network analysis and planning, network management, accounting, billing, and data mining.

Because of their unidirectional nature, flows from a client to a server are differentiated from flows from the server to a client. Flows are also differentiated on the basis of protocol. For example, Hypertext Transfer Protocol (HTTP) Web packets from a source device to a destination device constitute a separate flow from File Transfer Protocol (FTP) packets between the same pair of devices.

NetFlow works by recording the initial IP packet attributes in a flow such as IP protocol type, type of service (ToS), and interface identifiers. In this way, NetFlow enables subsequent packets that belong to the same flow to be efficiently matched and counted. Likewise, it streamlines services appropriate to that traffic flow, such as security filtering, quality of service (QoS) policy, or traffic engineering. This real-time information flow is held in the NetFlow Cache, where it can be retrieved with a NetFlow data export operation.

A Cisco IOS service called NetFlow Policy Routing (NPR) integrates policy routing with NetFlow services. Because it is supported in conjunction with the Cisco Express Forwarding (CEF) architecture, NPR's performance can be scaled across the distributed platforms.

NetFlow FlowCollector 3.0 provides fast, scalable, and economical data collection from multiple NetFlow Export-enabled devices. A UNIX or Windows NT application, the FlowCollector reduces data volume through selective filtering and aggregation. The FlowCollector also stores flow information in flat files on disk for post-processing.

The NetFlow Data Analyzer is a network traffic analysis tool that works with the NetFlow FlowCollector. The Data Analyzer produces graphs, sorts, and builds tables from the data sets exported by NetFlow FlowCollector 3.0.