Connected Roadways System
Cisco Validated Design (CVD)

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Connected Roadways System Cisco Validated Design

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System Overview

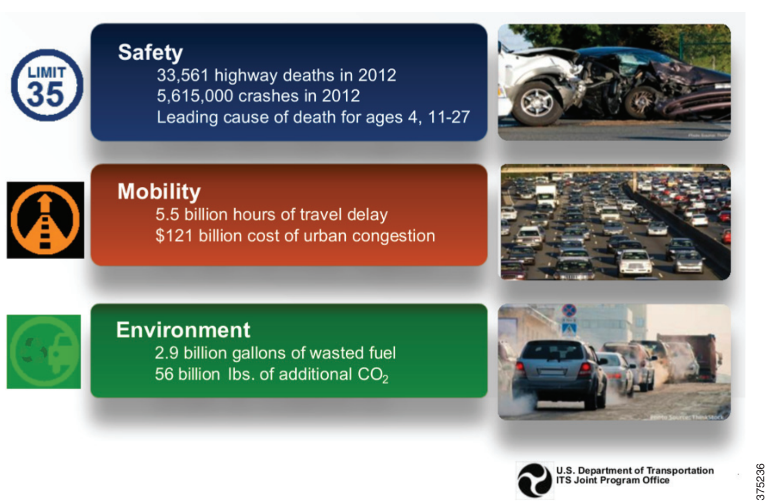
This document defines a system architecture for Connected Roadways as part of the Cisco Connected Transportation System (CTS) portfolio. It includes design and best practice recommendations for a scalable and resilient multi-service transport infrastructure for any size and scale of deployment. Previous releases of CTS focused on Positive Train Control (PTC) in CTS 1.0, and Connected Rail in CTS 1.5.

The Connected Roadways System design is based on a proven architecture deployed by dozens of major service providers around the world: Unified MPLS Transport. This design addresses the requirements of both legacy and next-generation services in a converged, scalable, and operationally simplified design. It provides transport of any service to any location over any type of access, providing maximum flexibility. It eliminates the need for service-specific networks or protocols, optimizing both capital and operating expenditures for the network infrastructure.

Connected Roadways

The transportation industry is changing radically. As Figure 1-1 depicts, competitive pressure, innovation, and regulation require transport authorities to adopt new standards and infrastructure investments.

Figure 1-1 Today's Transportation Challenges



A safe, interoperable wireless communications network that links cars, buses, trucks, trains, transportation infrastructure, and personal mobile devices transforms the way we travel. Technology will fundamentally change the transportation system paradigm by giving people the tools to avoid crashes, and make travel faster, easier, more accessible, and friendlier to the environment. These investments aim to tackle some of the biggest challenges in the surface transportation industry-safety, mobility, and environment:

- **Safety—**According to USDOT, 5.6 million crashes were reported in 2012 alone, resulting in over 33,000 fatalities. While mass transit is already one of the safest modes for travel, connected vehicle technologies will give mass transit drivers tools to anticipate potential crashes and significantly reduce the number of lives lost each year.
- **Mobility—**Connected vehicle mobility applications will enable system operators and travelers to make informed decisions that reduce travel delay. In addition, communication between mass transit and traffic management infrastructures will optimize routing of vehicles, further reducing potential delays.
- **Environment—**According to the American Public Transportation Association (APTA), transit systems can collectively reduce carbon dioxide (Co2) emissions by 16.2 million metric tons each year by reducing private vehicle miles. Connected vehicle environmental applications will give all travelers the real-time information they need to make "green" transportation choices.

The following megatrends have emerged which have a profound impact on the future of transportation:

- **Population Growth**—By 2025, an estimated 1 billion additional people will inhabit the earth, with 87% of this growth coming from Asia and Africa. The estimated impact on logistics is equally staggering. Freight transportation, measured in freight ton kilometers (ftk), is forecasted to increase by 60% between 2010 and 2025, reaching up to 31.1 trillion ftk.
- **Grand Economic Shift**—The World Economic Forum projects that by 2030 a radical change in the socioeconomic makeup of global population may occur—with a strong increase in the middle-class. This fundamental shift in demography will influence all types of middle-class expectations about mobility, automobile ownership, civil aviation, and global commerce.
- **Great Urban Shift**—By 2025, nearly half of the world's population will live in cities of more than 1 million inhabitants. In addition, the total number of megacities—those with more than 10 million inhabitants—is projected to increase from 23 in 2011 to 37 by 2025, with nine new megacities emerging in Asia alone.
- **Global Aging**—It is another important development to consider. Individuals aged 55 or older will account for 20% of world population (or 1.6 billion out of 8 billion) in 2025. This "silver segment" is even expected to reach 35% in G7 countries by 2025, a situation that will call for age-appropriate mobility solutions.

While streamlined operations, safe travel, integrated infrastructures, and intelligent networks are of the utmost importance, the transportation industry continues to face many challenges:

- Increased government regulations, including safety mandates and requirements for driver/operator credentials and workplace standards for employees.
- Congestion on roadways and overcrowded mass transit and railway systems.
- The impact of rising fuel costs on many sectors within the transportation industry, including passenger vehicles, commercial fleets, and emergency response and public safety vehicles.
- Environmental concerns further highlight the importance of reducing pollution and carbon footprints while the demand for travel continues to rise.

Currently, infrastructure upgrades and funding lag behind the demand for travel services over roads, rail, and in the air. It is more important than ever for government agencies and transit operators to find better ways to increase capacity without having to build new infrastructures in the traditional manner.

Policy Trends

The policy initiatives to address the growing needs of transportation are well underway in both the United States and Europe. Similar initiatives are taking shape in Japan, Korea, China, and India. Intelligent Transport Systems is defined by the US Department of Transportation and the European Commission in the following way:

- **USDoT**—ITS improves transportation safety and mobility and enhances American productivity through the integration of advanced communications technologies into the transportation infrastructure and in vehicles. Intelligent transportation systems (ITS) encompass a broad range of wireless and wireline communications-based information and electronics technologies.
- **European Commission—**Intelligent Transport Systems (ITS) apply information and communications technologies to transport. Computers, electronics, satellites, and sensors are playing an increasingly important role in our transport systems. The main innovation is the integration of existing technologies to create new services. ITS as such are instruments that can be used for different purposes under different conditions. ITS can be applied in every transport mode (road, rail, air, water) and services can be used by both passenger and freight transport.

USDoT Action Plan and Directives

The following is a synopsis of USDoT action plan and policy directives:

- On January 8, 2001, the Final Rule on ITS Architecture and Standards Conformity (Final Rule) and the Final Policy on Architecture and Standards Conformity (Final Policy) were enacted by the FHWA and FTA, respectively. The Final Rule/Final Policy ensures that ITS projects carried out using funds from the Highway Trust Fund, including the Mass Transit Account, conform to the National ITS Architecture and applicable ITS standards. This will be accomplished through the development of regional ITS architectures and using a systems engineering process for ITS project development.
- FHWA Rule on ITS Architecture and Standards Conformity. This new rule is provided to ensure that intelligent transportation system projects carried out using funds made standards.
  - HTML: http://www.ops.fhwa.dot.gov/its_arch_imp/policy_1.htm
  - PDF: http://www.ops.fhwa.dot.gov/its_arch_imp/docs/20010108.pdf
- FTA Policy on ITS Architecture and Standards Conformity. This new policy is provided to ensure that intelligent transportation system projects carried out using Mass Transit Funds from the Highway Trust Fund to conform to the National ITS Architecture and applicable standards.
  - HTML: http://www.ops.fhwa.dot.gov/its_arch_imp/policy_2.htm
  - PDF: http://www.ops.fhwa.dot.gov/its_arch_imp/docs/fta-pol.pdf
- NHTSA Decision on V2 Communication (February 3, 2014). This decision is targeted at light vehicle drivers to be receive collision warnings prior to the crash. Decision on heavy vehicles is expected by the end of 2014.
  - HTML: http://www.nhtsa.gov/About+NHTSA/Press+Releases/2014/USDOT+to+Move+Forward+with+Vehicle-to-Vehicle+Communication+Technology+for+Light+Vehicles

European Commission Action Plan and Directives

The following is a synopsis of European Commission action plan and policy directives:

- ITS can significantly contribute to a cleaner, safer and more efficient transport system. A new legal framework (Directive 2010/40/EU) was adopted on 7 July 2010 to accelerate the deployment of these innovative transport technologies across Europe. This Directive is an important instrument for the coordinated implementation of ITS in Europe. It aims to establish interoperable and seamless ITS services while leaving Member States the freedom to decide which systems to invest in.
  - HTML: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32010L0040
- Under this Directive, the European Commission has to adopt within the next seven years specifications (i.e., functional, technical, organizational, or services provisions) to address the compatibility, interoperability, and continuity of ITS solutions across the EU. The first priorities will be traffic and travel information, the eCall emergency system, and intelligent truck parking.
- The Commission already took a major step towards the deployment and use of ITS in road transport (and interfaces to the other transport modes) on 16 December 2008 by adopting an Action Plan. The Action Plan suggested a number of targeted measures and included the proposal for this Directive. The goal is to create the momentum necessary to speed up market penetration of rather mature ITS applications and services in Europe.
- The initiative is supported by five cooperating Directorates General: DG Mobility and Transport (lead), DG Information Society and Media, DG Research, DG Enterprise, and Industry and DG Climate Action.

System Architecture

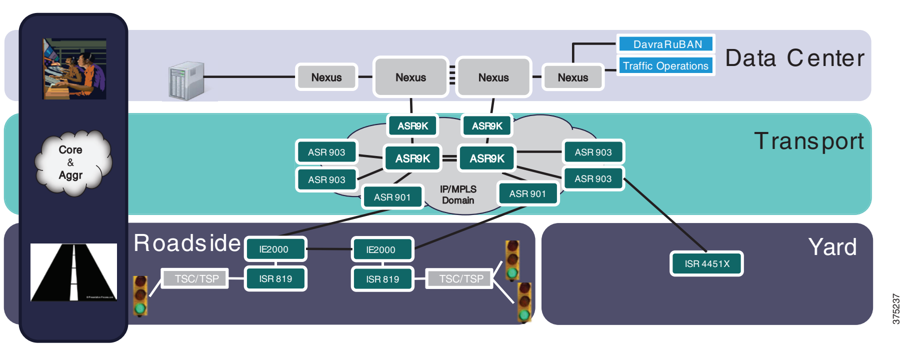
This chapter includes the following major topics:

The Connected Roadways System design follows a layered approach. Each layer builds on the previous one by adding new functionalities and capabilities into the system. This design approach results in a network that easily scales to any deployment size, from a metro area deployment to a statewide deployment. It provides the flexibility to position the right platforms at the right locations to match specific deployment criteria.

The system design incorporates a Unified MPLS-based "core" network design for transport. To extend the reach of this transport network to smaller equipment locations, such as roadside cabinets, Ethernet access networks, and time-division multiplexing (TDM) access off of the MPLS transport network are also incorporated. This provides the flexibility to address service transport to any required location.

This chapter provides a detailed description of the Connected Roadways System architecture design and the components of which it is comprised. Figure 2-1 illustrates the high level architecture of the Connected Roadways System.

Figure 2-1 Connected Roadways System Architecture



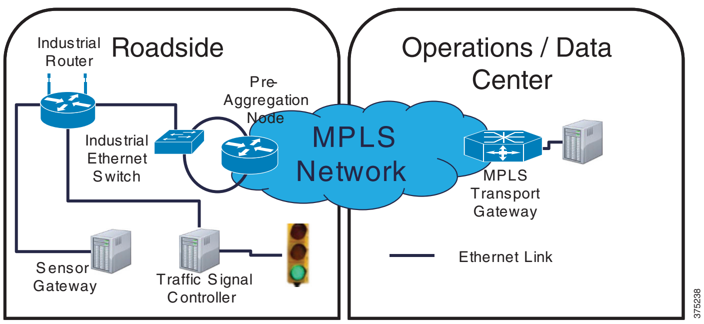
This document focuses on the transport layers and their connections to the roadside, yard, and data center layers.

Roadside Network Design

The goal of the Connected Roadways System is to provide an infrastructure interconnecting devices deployed at the roadside with backend systems and centralized control. As nearly all roadside equipment is deployed in cabinets subject to harsh conditions, and even equipment exposed directly to the elements on poles and other locations, special considerations need to be taken when designing a transport infrastructure to accommodate this environment.

The roadside network, as depicted in Figure 2-2, design employs a hardened Cisco router, such as the ISR 819, to provide Layer 3 routing of IP traffic to and from equipment in the curbside cabinet, such as a traffic signal controller, sensor gateway, or any other IP-enabled device. This router is a "customer edge" (CE) routing device, configured to peer with the "provider edge" (PE) devices at the edge of the MPLS network, interworking with Layer 3 virtual private networking (L3VPN) transport. Utilizing L3VPN transport is what allows for a converged infrastructure to support multiple services with proper service separation.

Figure 2-2 Roadside Network Overview



If a single uplink from the roadside cabinet to the citywide MPLS transport network is desired, then the gigabit Ethernet wide area network (WAN) port Cisco router may be connected directly to the pre-aggregation node (PAN) at the edge of the MPLS network.

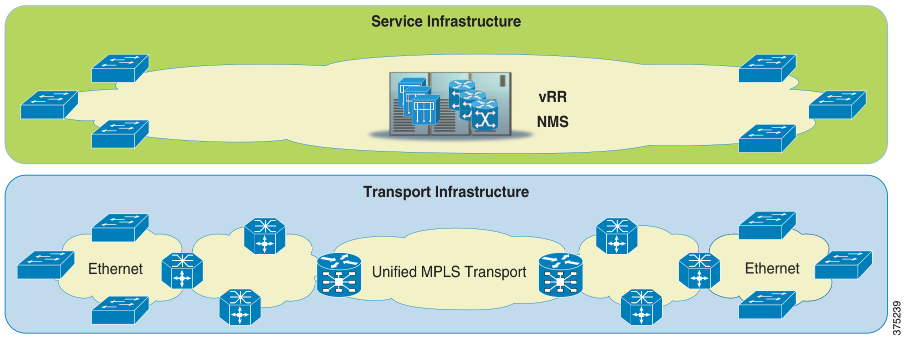
In many cases, redundant connectivity to the roadside cabinet equipment is desired. This may be achieved through connectivity to two PANs in a hub-and-spoke fashion from each roadside cabinet; however, having fiber runs and gigabit Ethernet ports consumed on the PANs is very expensive. A more likely network topology is to deploy fiber rings that connect several roadside cabinets to a pair of PANs. In either topology, the gigabit Ethernet WAN port of the hardened Cisco router is connected to a Cisco Industrial Ethernet switch, such as the IE2000.

The Ethernet switch has multiple uplink ports to support the redundant connectivity to the citywide MPLS transport network, and implements topology control functionality to manage traffic flow and avoid loops. For hub-and-spoke deployments, Link Aggregation Control Protocol (LACP) provides management of traffic over the redundant uplinks. For ring deployments, Cisco's Resilient Ethernet Protocol (REP) is used to manage traffic flow around the ring to avoid switching loops and manage traffic rerouting in the event of a link or node failure within the ring. In either deployment scenario, virtual local area network (VLAN) tagging is implemented to maintain service separation over the native Ethernet access network.

Citywide MPLS Transport

The Connected Roadways System design follows a layered approach for the citywide deployment of an MPLS transport network. Each layer builds on the previous one by adding new functionalities and capabilities into the system. See Figure 2-3.

Figure 2-3 Cisco Connected Roadways System Concept



Layer One

Starting from the first layer, the system's transport infrastructure provides a framework to achieve connectivity among any two or more nodes in the network, whether locations are roadside cabinets, departmental buildings, or centralized infrastructure components. It also enables the virtualization and convergence of multiple services over a common network architecture.

Based on a Unified MPLS transport design, this layer allows for the integration of any access technology and topology into the architecture to meet service requirements and operator preferences. Last mile networks supported include legacy TDM access and Ethernet access over hub-and-spoke and ring topologies made of fiber, copper, or microwave links, as described in the previous section on Roadside Network deployment.

Through automated processes and virtualization, the first layer also aims to minimize or facilitate user intervention at different stages of the network setup:

- Insertion and initial configuration of nodes in the network
- Intelligent route filtering based on route tagging and service activation events
- Optimal centralization of functions in the data center

Layer Two

The second layer, the service infrastructure, builds upon those capabilities to instantiate services between nodes in the architecture. This layer is concerned with the ubiquitous setup of transport services over any access and any device, supporting legacy TDM transport via circuit emulation, L2VPN transport, and L3VPN transport. This document focuses on the deployment of L3VPN transport, but it is important to note that L2VPN and circuit emulation service transport are supported concurrently on the same infrastructure.

The service infrastructure is also involved in the integration and virtualization of certain network functions to ensure their optimal placement in the network, resulting in maximized resource utilization and minimized costs, while guaranteeing stipulated service level agreements. Thus, service edge functions are typically integrated in the network nodes, while other control plane or less performance-demanding tasks may be virtualized in computing resources centralized or distributed in the network, such as route reflectors (RRs) for implementation of Border Gateway Protocol (BGP) for L3VPN service deployment.

Transport Infrastructure

Enabled by the Unified MPLS technology, the Connected Roadways System incorporates a network architecture designed to consolidate transport of multiple services in a single network.

Such converged infrastructure must conform to the SLAs demanded by each of these services, ranging from resiliency requirements, to guaranteed bandwidth, to jitter and delay boundaries. Operations, Administration, and Maintenance (OAM) and Performance Management (PM) aspects, as well as granular QoS assurance, assume a pivotal role in these new networks and become key aspects fully integrated into the system.

Certain services may benefit or even require accurate timing distribution and synchronization across all endpoint equipment in the network. While a number of approaches are possible, including the installation of Global Positioning System (GPS) receivers at each endpoint or dedicated timing equipment in several locations throughout the network, the Connected Roadways System takes advantage of the network fabric as a timing transport infrastructure. By selecting a hybrid approach involving a combination of physical and packet-oriented technologies and a multi-layer hierarchy of clock functions optimally co-located with network equipment, the system is capable of delivering accurate frequency and time throughout the network.

Lastly, as providers convert more and more applications requiring multipoint communication to use a more efficient multicast transport, the industry expectation is that the infrastructure is capable of leveraging the intelligent replication logic built into multicast forwarding increases and becomes a requirement. The Connected Roadways System supports multicast delivered across all services supported, using a combination of multicast Label Distribution Protocol (mLDP) in the aggregation network, and Protocol Independent Multicast (PIM) in the access network.

Unified MPLS

Unified MPLS is the foundation upon which the Evolved Programmable Network (EPN) system, which serves as the basis for the Connected Roadways System, was originally developed and it continues to evolve today. It is an efficient MPLS-based transport that employs a hierarchical approach to solve scaling and convergence issues associated with a large-scale MPLS deployment, while ensuring ease of end-to-end service provisioning and monitoring. End-to-end provisioning implies that service configuration should only happen at the service edges and nowhere else in the network. Similarly, end-to-end monitoring enables the use of service OAM and PM tools to evaluate the state of service "edge-to-edge."

MPLS is the clear winner as a technology that satisfies the requisites for convergence in Next Generation Networks (NGN) while preserving existing network investments. It supports legacy circuit (Asynchronous Transfer Mode (ATM)/TDM) and packet-based (Ethernet) access technologies and easily enables virtualization of multiple services, including Layer 2 and Layer 3 VPNs, over a single infrastructure.

In its simplest form, MPLS is a technology based on Interior Gateway Protocols (IGPs) and, as such, every node must be capable of reaching any other node in the network. Label Distribution Protocol (LDP) is used for MPLS label distribution to build label-switched paths (LSPs) based on these IGP routes for service transport. For the vast majority of Connected Roadways deployments, this is the recommended deployment model. Only in the case of extremely large MPLS domain deployments with over 1000 MPLS nodes in the network, does this ubiquitous connectivity requirement become a limiting factor. In this case, Unified MPLS implements a divide-and-conquer strategy, partitioning the network into smaller IGP domains, and implementing RFC3017 compliant BGP to build hierarchical LSP across IGP domains for service transport. This is considered to be a corner case of deployment scenarios, and is not covered in the scope of this document. It is covered in the scope of the EPN system DIGs.

Unified MPLS also distances itself from the traditional MPLS Fast Re-Route (FRR) technologies based on Traffic Engineered (TE) tunnels, which required manual setup of the protection mode and possibly the tunnels, toward totally automated mechanisms.

For LSPs, Loop Free Alternate (LFA) and Remote LFA (rLFA) FRR are used for unicast MPLS/IP traffic in hub-and-spoke and ring topologies. LFA FRR technologies pre-calculate a backup path for every prefix in the IGP routing table, allowing the node to rapidly switch to the backup path when a failure occurs, providing recovery times on the order of 50 msec or less.

For L3VPN services configured in BGP, network re-convergence is accomplished via BGP core and edge Prefix Independent Convergence (PIC) throughout the system. This allows for deterministic network re-convergence on the order of 100 msec, regardless of the number of BGP prefixes. BGP FRR technologies pre-calculate a loop free backup path for every prefix in the BGP forwarding table, and rely on the structure and entries in the Label Forwarding Information Base (LFIB) to allow for a fast transition to the alternate paths.

Network Topology

This chapter includes the following major topics:

MPLS Transport Network Model

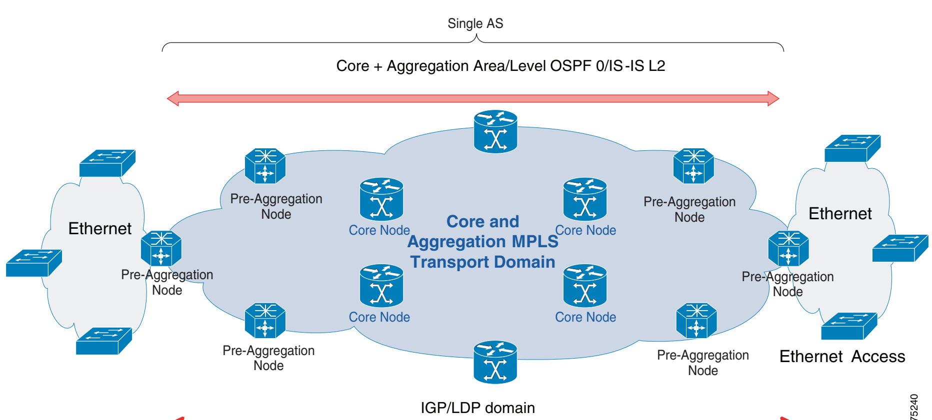
The Connected Roadways System design incorporates a native Ethernet access network, and a combined core and aggregation network that implements Unified MPLS.

The Ethernet access network supports point-to-point or ring topologies over fiber and newer Ethernet microwave-based access. Ring topologies can be Layer 3 enabled or Layer 2 only with REP protection.

The MPLS transport services are enabled by the core and aggregation network and include L3VPN, L2VPN, and CES.

The MPLS core/aggregation domain has a single physical topology with a design combining all network nodes in a single MPLS-enabled IGP/LDP region. The access domain is then integrated as a Layer 1 or a Layer 2 cloud made up of Ethernet or TDM links. Figure 3-1 depicts the case of a Layer 1 or a Layer 2 access network. Since no segmentation exists between network layers, a flat LDP LSP provides end-to-end reachability across the network. Aggregation and pre-aggregation nodes are in charge of enabling all mobile and wireline services.

Figure 3-1 MPLS Transport Network Model



The Connected Roadways System design recommends either Intermediate System to Intermediate System (IS-IS) or Open Shortest Path First (OSPF) for the IGP. The single IGP domain can be implemented as an OSPF Area 0 or as an IS-IS L2 backbone. Since there is no segmentation between network layers, a flat LDP LSP provides end-to-end reachability across the network.

Transport Network Model Roles

Table 3-1 lists the names of the network node roles within the Connected Roadways System design and the definition of each role,

Table 3-1 Transport Network Model Roles

Network Role	Role Definition
Roadside Router	Provides network connectivity, routing, and facilitates IP address management and network address translation (NAT) for endpoint devices. Performs CE role and peers to PE node for L3VPN service transport.
Ethernet Access Node (EAN)/Fixed Access Node (FAN)	Provides ruggedized, resilient access from the Roadside Router (and potentially other devices) to the edge of the MPLS network. Maintains service separation by VLANs.
Pre-Aggregation Node (PAN)	Connects Ethernet Access Networks and TDM circuits for transport across the MPLS network. Implements service edge functions needed for service transport, such as PE role for L3VPN services.
Core Node (CN)	Provides scalable and resilient transport of MPLS Label Switched Paths (LSPs) between PANs and MTGs. Typically will be the location of the route reflector for the L3VPN service deployment.
MPLS Transport Gateway (MTG)	Provides MPLS transport network connectivity to centralized network infrastructure and backend systems, such as data centers and Internet peering gateways. Implements service edge functions needed for service transport, such as PE role for L3VPN services to a CE device within the data center. Provides large-scale circuit emulation termination and TDM interconnects.
Route reflector (RR)	Control-plane only role that maintains table of all possible L3VPN service endpoints in the MPLS transport network. All endpoints within the MPLS transport network simple peer with the RR, instead of having to have all endpoints maintain all peering information with each other.

Transport Control Plane

The Connected Roadways System design implements a single IGP/LDP core/aggregation domain, and thus all control plane management is performed by the IGP and LDP protocols. The Connected Roadways System proposes the use of IS-IS or OSPF for the IGP, as these two protocols implement the necessary resiliency and filtering functions for Unified MPLS to operate properly.

BGP is only used for L3VPN service management, and thus the Connected Roadways System design only requires a single RR in the core of the network. Since BGP is not involved in the transport plane, discussion of RR implementation is in Chapter 4, "Service Infrastructure."

Ethernet Access Network

This section describes the different designs implemented by the Connected Roadways System design for Ethernet-based access network.

Hub-and-Spoke Access Network

Hub-and-spoke topologies are the simplest way of connecting devices, or spokes, to a common aggregation node or hub. These topologies can be single or dual homed, with the latter entailing each spoke node to be connected to a pair of hub devices.

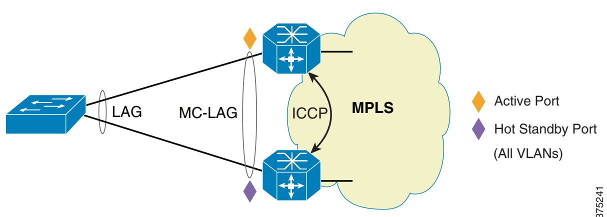
The Connected Roadways System supports the following dual-homed hub-and-spoke topologies:

- Per Node Active/Standby Multichassis Link Aggregation Groups (MC-LAG)
- Per VLAN Active/Active Multichassis Link Aggregation Groups (Pseudo mLACP)

Per Node Active/Standby Multichassis Link Aggregation Groups

Multichassis Link Aggregation Groups (MC-LAG), or Multichassis LACP (mLACP), provides a flexible redundancy mechanism emulating a single homing environment to a dual-homed access device in hub-and-spoke topologies. The access node is connected to the network via a single Ethernet bundle interface with member links terminating into two different service edge devices. These edge nodes synchronize bundle-related protocol states via Inter-Chassis Control Protocol (ICCP) in order to appear as a single entity to the access node. The ICCP protocol runs over MPLS. mLACP mandates that all the bundle members link toward a specific SE node run in either active or standby mode. See Figure 3-2.

Figure 3-2 Multichassis Link Aggregation



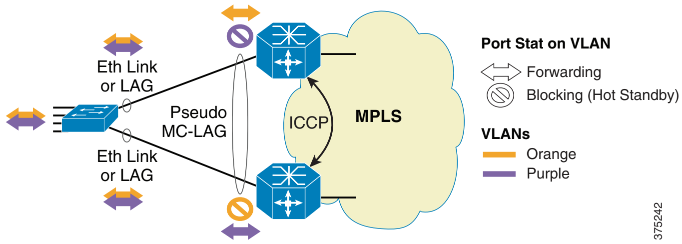
Per VLAN Active/Active Multichassis Link Aggregation Groups (Pseudo MC-LAG)

Pseudo MC-LAG enhances standard MC-LAG by load-balancing traffic across PANs, maintaining all inter-chassis links active at the same time on a per-VLAN basis. See Figure 3-3.

The access node is connected to each service edge device via standalone Ethernet links or bundle interfaces that are part of the same bridge domain(s). All the links terminate in a common multi-chassis bundle interface at the SE nodes and are placed in active or hot-standby state based on node and VLAN.

ICCP is used again for the correlation required between the PANs.

Figure 3-3 Pseudo Multichassis Link Aggregation



Ethernet Access Rings

Ring topologies allow for ubiquitous connectivity among networks nodes while achieving the highest degree of sharing of physical resources such as the links that interconnect the various nodes.

The dominant interconnection technology over ring topologies has historically been SONET, capable of delivering up to 40 Gbps speeds and sub-50ms failover time.

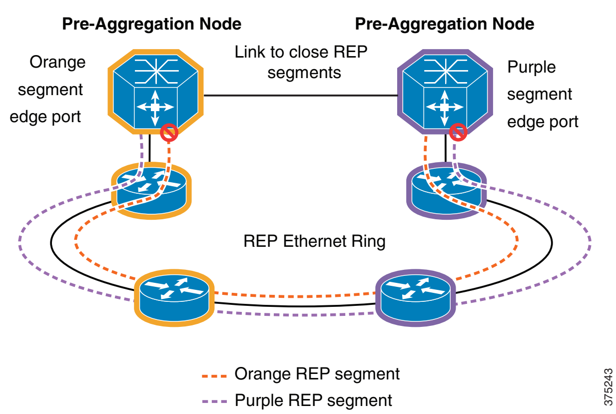
With the move to NGNs and the wide adoption of Ethernet as the latest interconnection technology for the delivery of cost effective network infrastructure, operators are looking into new ring fault detection mechanisms that are once again standardized, predictable, and fast. Under those premises, the Connected Roadways System design has selected REP to provide protection for Ethernet traffic in a ring topology.

The REP protocol has been developed as a standard alternative to slow converging spanning tree protocol (STP) to achieve faster (~50ms) protection switching in ring topologies without any extensive information exchange, overprovisioning, or complex computation. Loop avoidance is achieved by guaranteeing that at any time, traffic within the ring will flow on all but one of the ring links. Under normal conditions, REP blocks this link to data traffic, only allowing traffic to pass over it if there is a Topology Change Notification (TCN).

The REP protocol allows super-imposing multiple logical rings over the same physical topology by using different instances. Each instance contains an inclusion list of VLAN IDs, thus allowing for per-VLAN load balancing on a single ring. Load sharing between PANs is achieved by implementing two REP instances for different VLAN ranges.

As shown in Figure 3-4, the system design implements a design with the PANs at the ring edges acting as the owners for two different REP instances, blocking the access ring-facing port in their respective instance.

Figure 3-4 REP-enabled Ethernet Access Ring



Service Infrastructure

This chapter includes the following major topics:

The service infrastructure layer of the Connected Roadways System focuses on the deployment and implementation of the full set of services supported by the system. The service infrastructure layer also introduces the next level of convergence in the architecture.

From a service standpoint, the meaning of convergence is multi-fold. Convergence may happen at different levels of the service infrastructure, from the network functions to access technology agnosticism, and can be achieved by network integration.

All services supported by the Connected Roadways System are *Integrated Network Functions*, meaning those functionalities that are optimally embedded in the network transport devices to optimize traffic patterns while reducing power consumption and real estate requirements through consolidation.

The additional computing capacity and better hardware performances of today's equipment have made multi-service capabilities within a single network node possible. Consolidation of functionalities enables economies of scale by decreasing the infrastructure, either installed base or spares. By lowering the power consumption, CAPEX and OPEX are inevitably reduced. In addition, consolidation of transport and service functions within a single device allows for an optimal placement of the service edge based upon service distribution, which, in turn, results in a better use of network resources as well as an improved service experience.

All transport services are supported across a combination of access technologies that include native Ethernet and TDM access. Native Ethernet access is further segmented into hub-and-spoke and ring topologies, depending upon the requirements and deployed network topology.

The various services the Connected Roadways System supports are:

- **L3VPN Services**—Provides Layer 3 routing of IP traffic from numerous remote locations to centralized backend systems.
- **Circuit Emulation Services**—Provides both structured and unstructured emulation of legacy TDM circuits, allowing for convergence of all services into a single infrastructure.

Due to the vast majority of service scenarios being covered by these two service categories, this document focuses on only these. The system also supports:

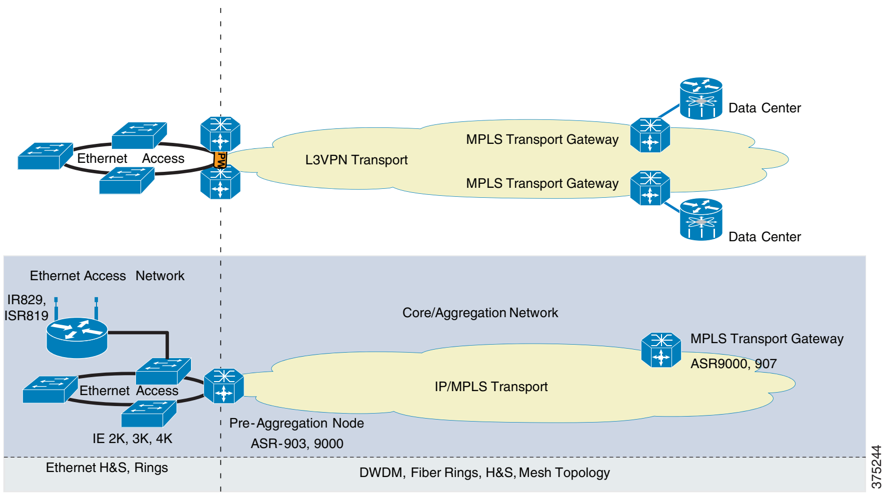
- **L2VPN Services**—Provides Layer 2 switching of Ethernet frames, analogous to a LAN infrastructure emulated by the MPLS transport. Supports both point-to-point and multipoint deployments, as defined by the Metro Ethernet Forum (MEF).

A future version of the Connected Roadways System may include these L2VPN services as well if sufficient need is identified.

L3VPN Services

The vast majority of services deployed in Connected Roadways use case scenarios are supported by L3VPN service transport. Supporting both IPv4 and IPv6 transport, the L3VPN services implemented by the system design can support both existing and next-generation routed transport simultaneously. In addition, multicast transport support ensures that any multicast-reliant services are also supported. The VPN aspect of L3VPN transport services ensures proper service separation, allowing for multiple services and multitenant deployments on a converged infrastructure. An overview of the models supported for the transport of mobile services is illustrated in Figure 4-1 and Figure 4-1.

Figure 4-1 MPLS Transport Services Architecture-TDM and Ethernet Access



The L3VPN model allows for roadside network infrastructure to be deployed easily at any location in the network. Likewise, data centers and backend systems can be deployed in multiple locations connected to the MPLS Transport network, and have instant connectivity to each other without additional configuration overhead.

Connectivity between roadside routers associated to Ethernet access nodes and PANs providing service edge functionality for MPLS transport is based on Ethernet links in point-to-point or ring topologies over fiber connectivity. Ring topologies made of Ethernet links are secured by REP ring protection technology to ensure sub-50msec recovery from network ring failures.

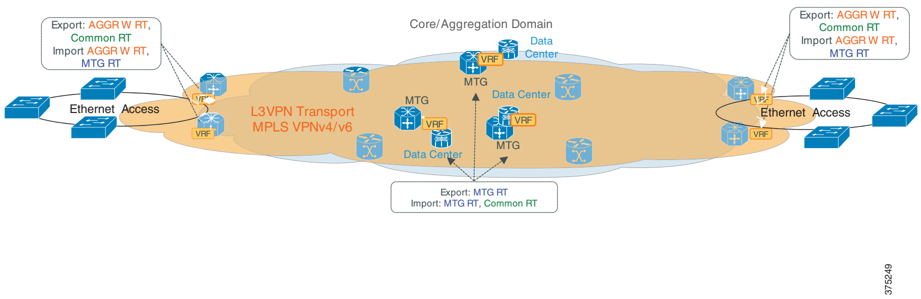
Additionally, the L3VPN model provides the required transport virtualization for multiservice deployment on a converged infrastructure, and even provides for multi-tenant deployments that can support multiple departments or agencies on a single infrastructure. It is also capable of providing mesh connectivity for services that may require direct endpoint-to-endpoint communication.

Simple L3VPN route-target import/export mechanisms allow enabling multipoint connectivity while keeping the VPN route scale under control in the following ways:

- Within the local Ethernet access network, enabling communications between devices in that access network
- With adjacent Ethernet access networks, enabling communications between devices in different access networks

- With centralized infrastructure elements located behind the MTGs in the MPLS transport network

Figure 4-2 MPLS Transport Service Routes Filtering Architecture



As shown in Figure 4-2, the system defines the following route targets to satisfy all possible connectivity requirements while achieving the following optimal traffic patterns:

- A unique route target (RT) denoted as a Common RT is assigned to the transport L3VPN service. It is exported by all PANs across the core/aggregation domain and it is imported by the MTGs. This provides reachability from the centralized backend systems to all roadway endpoints in the network.
- A unique RT denoted by MTG RT is assigned to the MTG. It is imported by all PANs across the MPLS Transport network. This provides reachability from all roadside endpoints via the PANs to the centralized backend systems.
- Each aggregation region in the network is assigned a unique PAN RT. Each PAN in a given domain exports the local PAN RT and imports the PAN RT of neighboring aggregations domains. This provides direct communication between roadside infrastructures.

The rapid migration of IP networking for Connected Roadways deployments is leading to an exponential increase in IP address requirements. In order to minimize the requirements for public IPv4 address usage, the Cisco Connected Roadways System enables carrying IPv6 traffic over an IPv4 Unified MPLS Transport infrastructure, using 6VPE as defined in RFC 4659. The network endpoints can be IPv6 only or dual-stack enabled to support IPv6 for service transport while using IPv4 for network management functions, if desired. The dual-stack network endpoints connect to PANs and MTGs configured with a dual stack VRF carrying VPNv4 and VPNv6 routes. IPv6 reachability between the network endpoints is exchanged between the PANs and MTGs using the BGP MPLS VPN IPv6 address family.

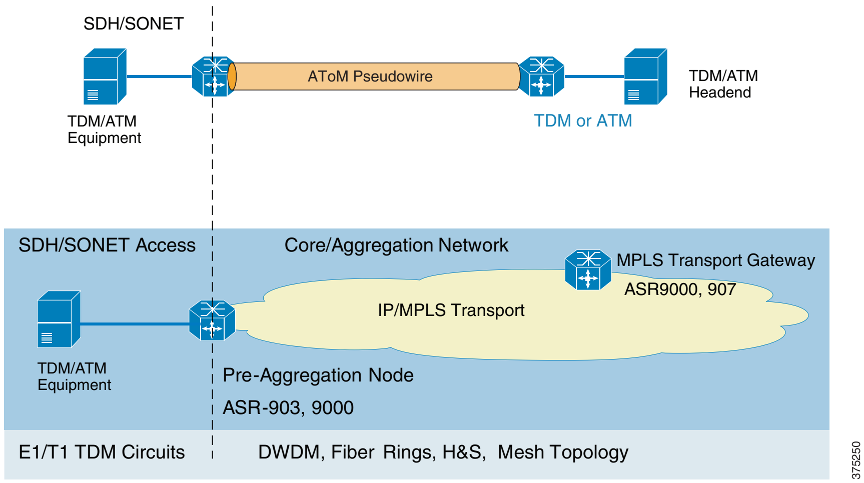
Some services deployed in a Connected Roadways System may require identical data to be distributed to many endpoints. A multicast-based transport mechanism may be implemented for these services, minimizing packet duplication within the transport network.

The multicast mechanism used for transporting multicast service traffic depends upon the network location. In the MPLS transport network domains, transport happens via Label Switched Multicast (LSM) and multicast Label Distribution Protocol (mLDP)-Global in-band signaling profile, which provide efficient and resilient transport of the multicast traffic within these regions. In the Ethernet access domain, native IP Multicast is used to provide efficient and resilient transport

Circuit Emulation Services

Service virtualization with MPLS-based service transport allows for legacy circuit-based transport to co-exist with L3VPNs on the same MPLS transport infrastructure. The Connected Roadways System supports customers wishing to remove, reduce, or cap investments in point-to-point TDM, SONET/SDH, and even ATM transport infrastructure by using MPLS-based circuit emulation over packet (CEoP) services. See Figure 4-3.

Figure 4-3 Circuit Emulation Services



For customers who want to reduce SONET/SDH infrastructure use, the system enables Pseudowire Emulation End-to-End (PWE3) transport of emulated TDM circuits. Structured circuit emulation is achieved with Circuit Emulation Services over Packet Switched Networks (CESoPSN), maintaining the TDM structure of the circuit to the DS0 channel level. Services that do not require DS0 channel level structure use Structure Agnostic Transport over Packet (SAToP) for unstructured circuit emulation. E1/T1 circuits to be emulated are connected to the PAN and are carried across the MPLS transport network to the MTG, where the circuits are bundled into channelized STM1/OC-3 interfaces or larger for handoff to the legacy backend systems.

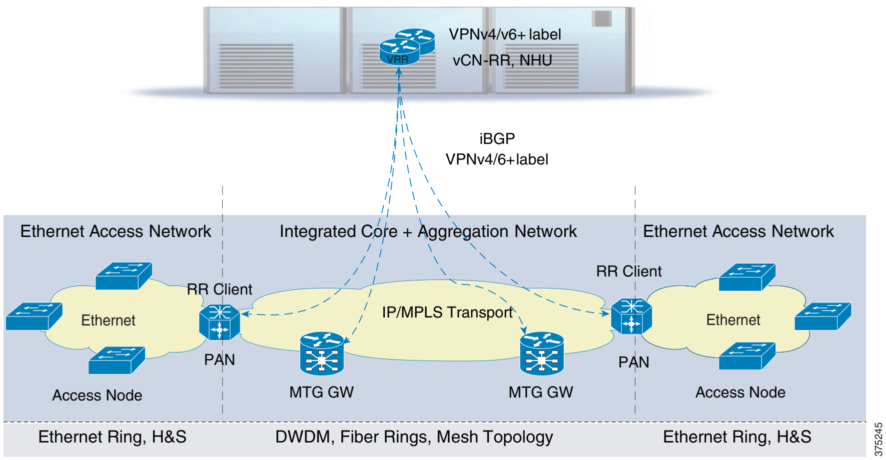
For the less common customer that may have an existing ATM infrastructure, the Connected Roadways System enables ATM VC (AAL0 or AAL5) or VP (AAL0) PWE3-based transport. ATM E1/T1 interfaces from legacy equipment is connected to the PAN and transported to the MTG, where the circuits are bundled into STM1 ATM interfaces for handoff to the legacy backend equipment. Cell packing may be used to optimize the bandwidth used for this transport.

For all the above service models, the system supports physical layer synchronization of frequency based on SyncE, or packet-based synchronization of frequency as well as phase.

Service Control Plane

To optimize the network infrastructure costs, the Connected Roadways System proposes the integration of BGP Service RRs and Network Management System (NMS) as virtualized functions running over a common pool of standard server systems in the customer's data center. See Figure 4-4.

Figure 4-4 Virtualized Service Route Reflector Architecture



In the case of the Connected Roadways System where the MPLS Transport network is based on a single IGP/LDP core and aggregation domain, the virtual Route Reflector (vRR) design applies to the core RRs only, which provides RR connectivity to all other nodes in the network.

System Components

For each role in the Connected Roadways System architecture, the system selects devices from different Cisco product families to provide operators with the best-of-breed selection of fully interoperable products available in the market.

The various network components and their architectural role are described in Table 5-1.

Table 5-1 Connected Roadways System Components

Architectural Role	Hardware
Aggregation node + service edge	ASR 9006
Pre-aggregation node	ASR 903 RSP1 and RSP2
Access node	ASR 901 and ASR 920
Business CPE	Small Branch—ISR G2 for enterprise and ME1200 NID for MEF transport services Large Branch—ASR1000, Virtual-CSR1000V
Residential CPE	ME4600 RG, Virtual: Quantum virtual Broadband Network (Q-vBN)
DHCP Server	Prime Network Registrar
Network Management System	Prime Provisioning, Prime Performance Manager

System Functional Considerations

This chapter includes the following major topics:

- Multicast, page 6-1
- Quality of Service (QoS), page 6-2
- Redundancy and High Availability, page 6-3
- Operations, Administration, and Maintenance (OAM), page 6-4

Multicast

The Connected Roadways System supports services delivered via unicast transport as well as multicast transport for any service that requires multicast.

A citywide network may carry multiple multicast services concurrently on a single infrastructure, which requires proper transport organization in order to meet the different communication needs for the disparate services while providing the required separation at the same time.

While standard efforts exist to address transport of multicast services using multicast GRE (mGRE) tunnels and PIM, a more desirable approach aims to consolidate both unicast and multicast traffic forwarding on a common data plane based on label switched paths (LSPs). These new Label Switched Multicast (LSM) paths are created via multicast Label Distribution Protocol (mLDP), which provides extensions to LDP to enable the setup of multiprotocol LSPs (MP LSPs) without requiring additional multicast routing protocols, such as PIM, in the MPLS infrastructure.

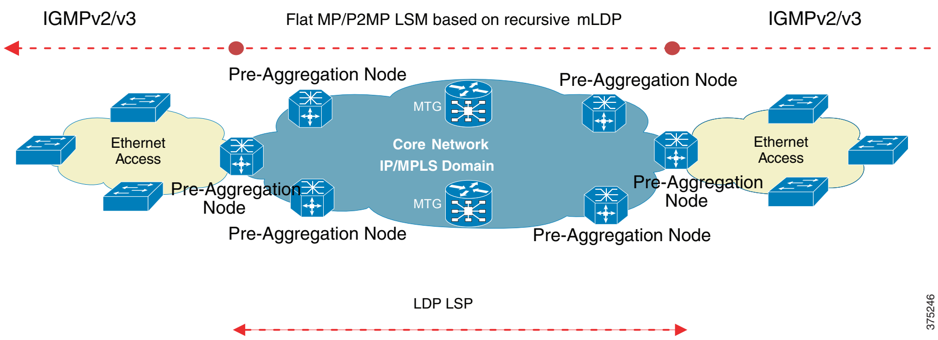
As an example of a multicast service, contribution and distribution of broadcast video services involves a limited number of multicast groups and sources, thus only requiring a reasonably low number of LSM trees. A hierarchical approach, built upon LSP nesting to reduce the total number of LSPs and routes to multicast sources that each domain must maintain, is not required for this type of service, and a flat architecture with redistribution of multicast source addresses across all domains is thus used.

Similarly, multipoint-to-multipoint multicast VPNs have historically been centralized in the core domain, also requiring a flat LSP topology.

The scale of multicast service deployment typically encountered in a Connected Roadways System deployment focuses on enabling an end-to-end flat LSM tree across the unified MPLS domains without redistribution. RFC 6512, in particular, defines recursive mLDP behaviors to enable the creation of LSM paths when a given domain has no reachability to the multicast source or root node.

Figure 6-1 illustrates the end-to-end deployment of multicast transport implemented by the system design and based on RFC 6512.

Figure 6-1 Unified MPLS Multicast



Multicast service edge nodes add an additional opaque time-length-value (TLV) to the mLDP requests they originate to reach the multicast source. Since the system design incorporates a single core/aggregation area, the multicast source is reachable from throughout the domain.

In the case of Layer 3 access, multicast source addresses are redistributed into the access network IGP according to the multicast address family, and PIM is enabled to build multicast delivery trees that are rooted at the redistribution nodes.

In the case of Layer 2 Ethernet access, IGMPv2/3 or MLDv2 snooping is enabled throughout the access domain to ensure optimal replication of multicast frames.

Quality of Service (QoS)

Although congestion is more likely where statistical estimates of peak demand are conservative (that is, under-provisioned), such as in access and aggregation links, it can occur anywhere in a transport network. Therefore, all nodes in a transport network are required to implement congestion management techniques, which involve classification and proper scheduling functions.

The Connected Roadways System design applies the Differentiated Services (DiffServ) Architecture defined by the IETF in RFC 2475 across all network layers, utilizing classification mechanisms like MPLS Experimental (EXP) bits, IP Differentiated Services Code Point (DSCP), and IEEE 802.1p Class of Service (CoS) for implementing the DiffServ Per-Hop Behaviors (PHBs) in use.

Within the aggregation and core networks, where strict control over SLAs is not required, a flat QoS policy with a single-level scheduler is sufficient for the desired DiffServ functionality among the different classes of traffic, as all links are operated at full line rate transmission.

H-QoS policies are required whenever the physical bandwidth of an access link is lower than the line-rate of the interface on the node. An example of this would be a Gigabit Ethernet link transmitted over a point-to-point wireless carrier that only supports approximately 400 Mbps. In this case, a parent policy with a shaper configured to at or just below the speed of the physical bandwidth available, combined with a child policy providing per-class PHB treatments, ensures proper SLA guarantees.

Services in the Connected Roadways System are typically divided into three main categories:

- **Expedited Forwarding (EF)**—Traffic marked as EF is grouped in a single class, serviced with priority treatment to satisfy stringent latency and delay variation requirements. The EF PHB defines a scheduling logic able to guarantee an upper limit to the per-hop delay variation caused by packets from non-EF services. Examples of these services are Voice-over-IP (VoIP), Network Timing Synchronization, and Circuit Emulation Services (CES) traffic.

- **Assured Forwarding (AF)**—Traffic marked as AF is divided over multiple classes. Each class is guaranteed a predefined amount of bandwidth, thus establishing relative priorities while maintaining fairness among classes, and somewhat limiting the amount of latency traffic that each class may experience.
- **Best Effort (BE)—**The best effort category encompasses all traffic that can be transmitted only after all other classes have been served. Traffic in this class is not delay sensitive, and can experience some packet loss without being adversely affected.

Redundancy and High Availability

The Connected Roadways System architecture implements high availability at the transport network level and the service level. By utilizing a combination of several technologies throughout the network, the design is capable of meeting stringent availability SLAs.

High availability at the transport network layer is provided through the combination of several technologies:

- Loop-Free Alternate Fast Reroute (LFA FRR)
- Bidirectional Forwarding Detection (BFD) at the IGP

In addition, the following mechanisms improve resiliency in dual-homing scenarios for Ethernet access, which have been previously discussed in this document.

- Multichassis Link Aggregation Groups (MC-LAG) and pseudo MC-LAG for multi-homed Ethernet access nodes in hub-and-spoke topologies
- REP protection for Ethernet access nodes in ring topologies

Loop-Free Alternate Fast Reroute with BFD

LFA FRR pre-calculates a backup path for every prefix in the IGP routing table, allowing the node to rapidly switch to the backup path when a failure is encountered, with recovery times on the order of 50 msec. Remote LFA FRR functionality extends LFA FRR functionality to ring networks and other topologies.

Also integrated are BFD rapid failure detection and IS-IS/OSPF extensions for incremental shortest-path first (SPF) and link-state advertisement (LSA)/SPF throttling.

More information regarding LFA FRR can be found in IETF RFC 5286, 5714, and 6571.

Microloop Avoidance in Remote LFA FRR

In a network comprised of different platforms, some of which converge faster than others, this difference in convergence time can lead to a condition where a node is forwarding traffic to the same neighbor from which traffic was being received prior to the topology change. This is referred to as a *microloop* within the topology.

With remote LFA-FRR activated, the backup path is used until the computing node learns about the topology change and reinstalls new paths for the prefix. If the computing node converges before its neighbors, microloops can occur. To prevent this from happening, a microloop avoidance mechanism is provided to postpone the protected prefixes by an additional delay to allow for convergence in its neighbors.

BGP Fast Reroute (FRR) Edge Protection

For L3VPN services, BGP Edge protection and BGP FRR Edge protection mechanisms are supported, and VRRP is enabled on the MTGs for redundant connectivity to the data center infrastructure. The combination of these technologies combined with the transport layer mechanisms ensures a recovery time on the order of sub-200 milliseconds for all L3VPN services due to any node or link failure within the network.

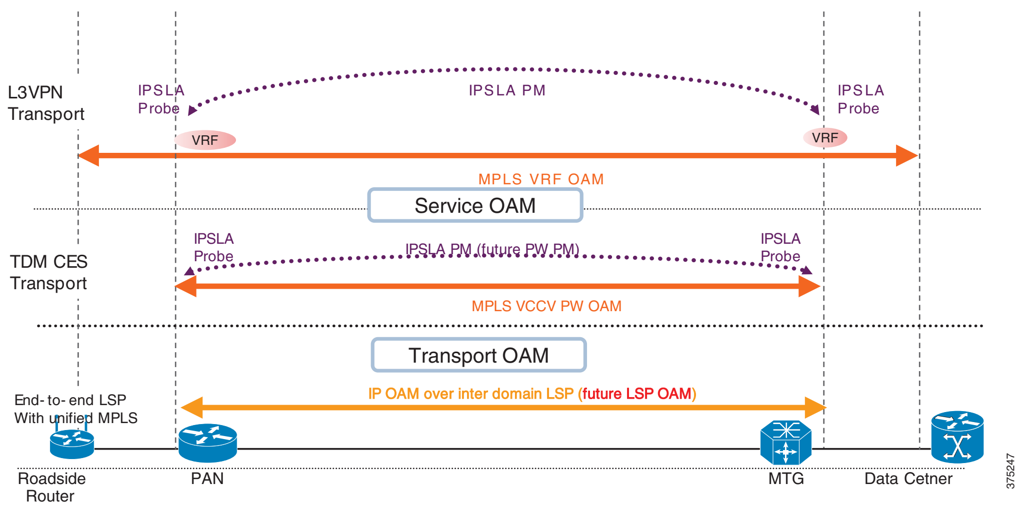
Pseudowire Redundancy

For TDM pseudowire-based services, pseudowire redundancy is supported for protection across the MPLS Transport network. For redundant connectivity to TDM headend connections, Multirouter Automatic Protection Switching (MR-APS) is enabled. This provides a similar recovery target time of sub-200 milliseconds for any infrastructure failure encountered.

Operations, Administration, and Maintenance (OAM)

For transport services, the Connected Roadways System design uses a combination of protocols to provide the required service and transport OAM and PM functionality between the PAN and the MTG. The details of the required mechanism are highlighted in Figure 6-2.

Figure 6-2 OAM Implementation for Service Transport



At a high level, for Service OAM, the Connected Roadways System employs:

- MPLS VPN OAM and MPLS VCCV PW OAM for services carried over MPLS VPNs or pseudowires, respectively. Specifically MPLS VPN OAM is used for IP-based services, while MPLS VCCV PW OAM applies to Non-IP services, such as TDM circuit emulation.
- Cisco IP SLA tools for any service configured between IP-enabled end points

For transport OAM, the system design employs MPLS LSP OAM to monitor the health of the Unified MPLS Transport. Performance monitoring is based on Cisco IP SLA tools running between service end points or between any two points in the unified MPLS domain to find performance bottlenecks.

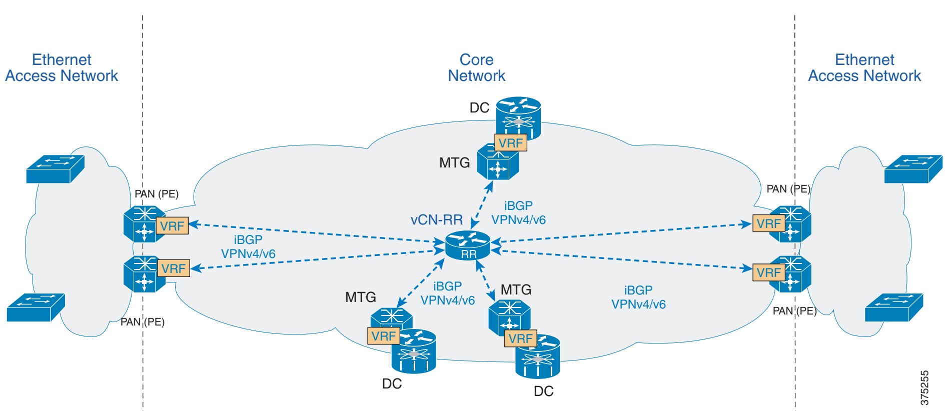
System Implementation

This chapter includes the following major topics:

Transport Network Implementation

In this model, the core and aggregation networks are integrated with a flat IGP and LDP control plane from the core to the PANs in the aggregation domain. See Figure 7-1.

Figure 7-1 Flat IGP/LDP Network with Ethernet Access



All nodes (MTG, Core, AGN, and PAN) in the combined core-aggregation domain make up the IS-IS Level-2 domain or OSPF backbone area.

In this model, the access network could be one of the following options:

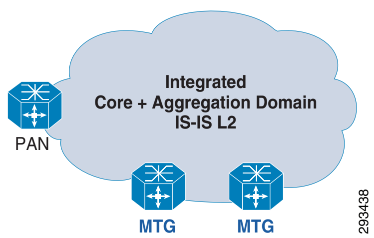
- Routers configured as Customer Edge (CE) devices in point-to-point or ring topologies over fiber Ethernet running native IP transport, supporting L3VPN services. In this case, the CEs pair with PANs configured as L3VPN PEs, enabling Layer 3 backhaul. Any TDM circuits connected directly to the PANs, which provide circuit emulation services via pseudowire-based circuit emulation to the MTG.
- Ethernet Access Nodes in point-to-point and REP-enabled ring topologies over fiber access running native Ethernet. In this case, the PANs provide service edge functionality for the services from the access nodes and connect the services to the proper L2VPN or L3VPN service backhaul mechanism. The MPLS services are always enabled by the PANs in the aggregation network.

MPLS Transport Implementation

MPLS Transport Gateway Configuration

This section shows the IGP/LDP configuration required to build the LSPs to the PANs. See Figure 7-2.

Figure 7-2 MPLS Transport Gateway (MTG)




```
Interface Configuration
interface Loopback0
  description Global Loopback
  ipv4 address 100.111.15.1 255.255.255.255
!
!***Core-facing Interface***
interface TenGigE0/0/0/0
  description To CN-K0201 Ten0/0/0/0
  cdp
  service-policy output PMAP-NNI-E
  ipv4 address 10.2.1.9 255.255.255.254
  carrier-delay up 2000 down 0
  load-interval 30
  transceiver permit pid all
!
!***Core-facing Interface***
interface TenGigE0/0/0/1
  description To CN-K0401 Ten0/0/0/1
  cdp
  service-policy output PMAP-NNI-E
  ipv4 address 10.4.1.5 255.255.255.254
  carrier-delay up 2000 down 0
  load-interval 30
  transceiver permit pid all
!
```

IGP Configuration

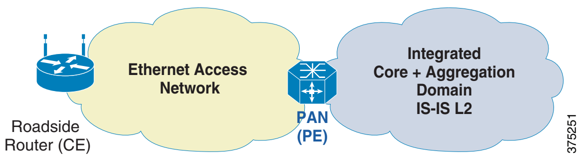
```
router isis core-agg
  set-overload-bit on-startup 250
```

```
  net 49.0100.1001.1101.5001.00
  nsf cisco
  log adjacency changes
  lsp-gen-interval maximum-wait 5000 initial-wait 50 secondary-wait 200
  lsp-refresh-interval 65000
  max-lsp-lifetime 65535
  address-family ipv4 unicast
    metric-style wide
    ispf
    spf-interval maximum-wait 5000 initial-wait 50 secondary-wait 200
  !
  interface Loopback0
    passive
    point-to-point
    address-family ipv4 unicast
    !
  !
  interface TenGigE0/0/0/0
    circuit-type level-2-only
    bfd minimum-interval 15
    bfd multiplier 3
    bfd fast-detect ipv4
    point-to-point
    address-family ipv4 unicast
      fast-reroute per-prefix level 2
      metric 10
      mpls ldp sync
    !
  !
  interface TenGigE0/0/0/1
    circuit-type level-2-only
    bfd minimum-interval 15
    bfd multiplier 3
    bfd fast-detect ipv4
    point-to-point
    address-family ipv4 unicast
      fast-reroute per-prefix level 2
      metric 10
      mpls ldp sync
    !
  !
!
mpls ldp
  router-id 100.111.15.1
  discovery targeted-hello accept
  nsr
  graceful-restart
  session protection
  igp sync delay 10
  log
    neighbor
    graceful-restart
    session-protection
    nsr
  !
  interface TenGigE0/0/0/0
  !
  interface TenGigE0/0/0/1
  !
!
```

Pre-Aggregation Node Configuration

This section shows the IGP/LDP configuration required to build the intra-domain LSPs. Minimal BGP configuration is shown as the basis for building the transport MPLS VPN. The actual service configuration is in L3VPN Service Implementation, page 7-13. See Figure 7-3.

Figure 7-3 Pre-Aggregation Node (PAN)




```
Interface Configuration
interface Loopback0
  ip address 100.111.14.3 255.255.255.255
!
!***Redundant PAN interface***
interface TenGigabitEthernet0/0/0
  description To PAN-K1404 Ten0/0/0
  ip address 10.14.3.0 255.255.255.254
  ip router isis core
  load-interval 30
  carrier-delay msec 0
  mpls ip
  mpls ldp igp sync delay 10
  bfd interval 50 min_rx 50 multiplier 3
  no bfd echo
  cdp enable
  isis network point-to-point
  isis metric 10
  isis csnp-interval 10
  service-policy output PMAP-NNI-E
  hold-queue 1500 in
  hold-queue 2000 out
!
!***Uplink interface***
interface TenGigabitEthernet0/1/0
  description To AGN-K1102 Ten0/0/0/1
  ip address 10.11.2.1 255.255.255.254
  ip router isis core
  load-interval 30
  carrier-delay msec 0
  mpls ip
  mpls ldp igp sync delay 10
  bfd interval 50 min_rx 50 multiplier 3
  no bfd echo
  cdp enable
  isis circuit-type level-2-only
  isis network point-to-point
  isis metric 10
  service-policy output PMAP-NNI-E
  hold-queue 1500 in
  hold-queue 2000 out
!
!***Interface toward native IP CE device in MPLS VPN VRFS***
!***Shown here for reference. Not part of Unified MPLS config.*** interface
GigabitEthernet0/4/2
description To CE Router
 vrf forwarding RFS
```

```
ip address 10.13.14.1 255.255.255.254
ip ospf network point-to-point load-interval 30
negotiation auto
bfd interval 50 min_rx 50 multiplier 3 no bfd echo
hold-queue 350 in
hold-queue 2000 out
!
```

IGP/LDP Configuration

```
router isis core-agg
  net 49.0100.1001.1101.4003.00
  !***PAN is a IS-IS Level-1-2 node***
  ispf level-1-2
  metric-style wide
  fast-flood
  set-overload-bit on-startup 180
  max-lsp-lifetime 65535
  lsp-refresh-interval 65000
  spf-interval 5 50 200
  prc-interval 5 50 200
  lsp-gen-interval 5 5 200
  no hello padding
  log-adjacency-changes
  nsf cisco
  passive-interface Loopback0
  bfd all-interfaces
  mpls ldp sync
!
mpls label protocol ldp
mpls ldp graceful-restart
mpls ldp discovery targeted-hello accept
mpls ldp router-id Loopback0 force
```

Small Network Non-IP/MPLS Access Network Implementation

Dual-homed Hub-and-Spoke Ethernet Access

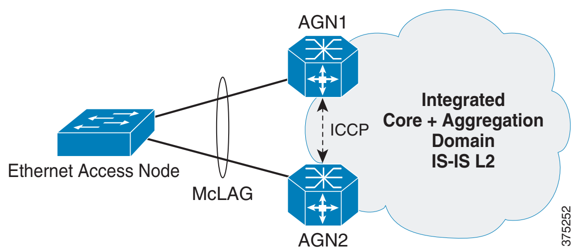
Dual-homed topologies for hub-and-spoke access have been implemented in the following modes:

- Per Node Active/Standby MC-LAG
- Per VLAN Active/Active MC-LAG (pseudo mLACP)

Per Node Active/Standby MC-LAG

Figure 7-4 illustrates the implementation of hub-and-spoke Ethernet access with MC-LAG operating in Per Node Active and Standby Mode.

Figure 7-4 Per Node Active/Standby MC-LAG



The Ethernet access node is dual-homed to the AGN nodes using a bundle interface. The AGN node establishes an inter-chassis bundle and correlates the states of the bundle member ports using ICCP.

At steady state, links connected to AGN1 are selected as active, while links to AGN2 are kept in standby state ready to take over in case of a failure.

The following configuration shows the implementation of the AGN nodes, AGN-K1101 and AGN-K1102, and the Ethernet Access Node.

Aggregation Node Configuration

AGN1: Active Point-of-Attachment (PoA) AGN-K1101: ASR9000

NNI Interfaces

For reference throughout this document, the following is a list of settings used for MC-LAG configuration. The access-facing virtual bundle interface is configured as follows:

- Suppress-flaps timer set to 300 ms. This prevents the bundle interface from flapping during a LACP failover.
- Associated with ICCP redundancy group 300
- Lowest possible port-priority (to ensure node serves as active point of attachment (PoA) initially)
- MAC address for bundle interface. This needs to match the MAC address configured on the other PoA's bundle interface.
- Wait-while timer set to 100 ms to minimize LACP failover time
- Maximum links allowed in the bundle limited to 1. This configuration ensures that the access node will never enable both links to the PoAs simultaneously if ICCP signaling between the PoAs fails.

```
!*** Interface configuration towards the OLT ***
interface TenGigE0/2/0/1
 bundle id 102 mode active
!
interface Bundle-Ether102
 mlacp iccp-group 102
 mlacp switchover type revertive
 mlacp switchover recovery-delay 300
 mlacp port-priority 10
 mac-address 0.1101.1102
!
```

ICCP and Multichassis LACP

For reference throughout this document, the following is a list of settings used for ICCP configuration. The ICCP redundancy group is configured as follows:

- Group ID
- mLACP node ID (unique per node)

- mLACP system MAC address and priority (same for all nodes). These two values are concatenated to form the system ID for the virtual LACP bundle.
- ICCP peer address. Since ICCP works by establishing an LDP session between the PoAs, the peer's LDP router ID should be configured.
- Backbone interfaces. If all interfaces listed go down, core isolation is assumed and a switchover to the standby PoA is triggered.

```
!*** ICCP configuration ***
redundancy
 iccp
  group 102
   mlacp node 1
   mlacp system mac 0000.1101.1111
   mlacp system priority 20
   member
    neighbor 100.111.11.2
   !
   backbone
    interface TenGigE0/0/0/0
    interface TenGigE0/0/0/2
   !
  !
 !
!
```

AGN2: Active Point-of-Attachment (PoA) AGN-A9K-K1102: ASR9000

NNI Interfaces

```
interface Bundle-Ether300
!*** Interface configuration towards the OLT ***
interface TenGigE0/1/1/1
 bundle id 102 mode active
!
interface Bundle-Ether102
 mlacp iccp-group 102
 mlacp switchover type revertive
 mlacp switchover recovery-delay 300
 mlacp port-priority 20
 mac-address 0.1101.1102
!
```

ICCP and Multichassis LACP

The ICCP redundancy group is configured as follows:

- Group ID
- mLACP node ID (unique per node)
- mLACP system MAC address and priority (same for all nodes). These two values are concatenated to form the system ID for the virtual LACP bundle.
- ICCP peer address. Since ICCP works by establishing an LDP session between the PoAs, the peer's LDP router ID should be configured.
- Backbone interfaces. If all interfaces listed go down, core isolation is assumed and a switchover to the standby PoA is triggered.

```
!*** ICCP Configuration ***
redundancy
 iccp
  group 102
   mlacp node 2
```

```
    mlacp system mac 0000.1101.1111
    mlacp system priority 20
    member
     neighbor 100.111.11.1
     !
    backbone
     interface TenGigE0/0/0/0
     interface TenGigE0/0/0/2
     !
   !
  !
 !
```

Ethernet Access Node Configuration

The following configuration is taken from a Cisco router running IOS. Configurations for Ethernet switches and other access nodes can be easily derived from the following configuration.

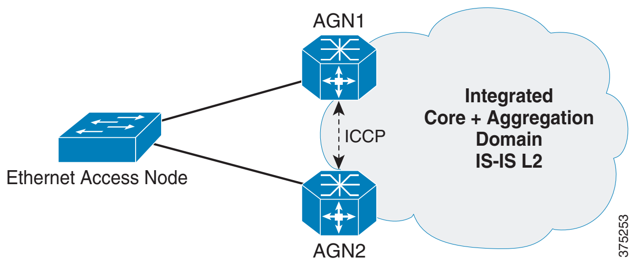
NNI Interfaces

```
!*** Interface configuraton towards the AGN nodes ***
interface GigabitEthernet0/8
 description por to 1101 gi 0/0/1/16
 no ip address
 load-interval 30
 negotiation auto
 channel-protocol lacp
 channel-group 6 mode active
!
interface GigabitEthernet0/6
 description por to 1102 gi 0/0/1/17
 no ip address
 load-interval 30
 negotiation auto
 channel-protocol lacp
 channel-group 6 mode active
!
!*** Port-Channel configuration towards the AGN nodes ***
interface Port-channel6
 no ip address
 load-interval 30
 no negotiation auto
 ethernet dot1ad nni
  !
!
```

Per VLAN Active/Active MC-LAG (pseudo MC-LAG)

Figure 7-5 illustrates the implementation of hub-and-spoke Ethernet access with MC-LAG operating in per VLAN active/active load balancing.

Figure 7-5 Per VLAN Active/Active MC-LAG



The Ethernet access node connects to each AGN via standalone Ethernet links or Bundle interfaces that are part of a common bridge domain(s). All the links terminate in a common multi-chassis bundle interface at the AGN and are placed in active or hot-standby state based on node and VLAN via ICCP-SM negotiation.

In steady state conditions, each AGN node forwards traffic only for the VLANs it is responsible for, but takes over forwarding responsibility for all VLANs in case of peer node or link failure.

The following configuration shows the implementation of active/active per VLAN MC-LAG for VLANs 100 and 101, on the AGN nodes, AGN-K1101 and AGN-K1102, and the FAN, ME-K0904.

Aggregation Nodes Configuration

AGN1: Active Point-of-Attachment (PoA) AGN-A9K-K1101: ASR9000

NNI Interfaces

```
interface Bundle-Ether1
!
interface Bundle-Ether1.100 l2transport
 encapsulation dot1q 100
!
interface Bundle-Ether1.101 l2transport
 encapsulation dot1q 101
!
interface GigabitEthernet0/0/1/1
  bundle id 1 mode on
```

ICCP and ICCP-SM and Multichassis LACP

For reference throughout this document, here is a list of settings used for ICCP-SM configuration. The ICCP-SM redundancy group is configured as follows:

- Group ID
- Multi-homing node ID (1 or 2 unique per node)
- ICCP peer address. Since ICCP works by establishing an LDP session between the PoAs, the peer's LDP router ID should be configured.
- Backbone interfaces. If all interfaces listed go down, core isolation is assumed and a switchover to the standby PoA is triggered.

```
redundancy
  iccp
    group 1
      member
        neighbor 100.111.11.2
      !
      backbone
        interface TenGigE0/0/0/0
        interface TenGigE0/0/0/2
```

```
      !
    !
  !
!

l2vpn
  redundancy
    iccp group 1
      multi-homing node-id 1
      interface Bundle-Ether1
        primary vlan 100
        secondary vlan 101
        recovery delay 60
      !
    !
  !
```

Standby Point-of-Attachment (PoA) AGN-A9K-K1102: ASR9000

NNI Interfaces

```
interface GigabitEthernet0/3/1/12
 bundle id 1 mode on
!
interface Bundle-Ether1
!
interface Bundle-Ether1.100 l2transport
 encapsulation dot1q 100
!
interface Bundle-Ether1.101 l2transport
 encapsulation dot1q 101
!
```

ICCP and Multichassis LACP

The ICCP redundancy group is configured as follows:

```
redundancy
 iccp
  group 1
   member
    neighbor 100.111.11.1
   !
   backbone
    interface TenGigE0/0/0/0
    interface TenGigE0/0/0/2
   !
  !
 !
!*** ICCP-SM configuration ***
l2vpn
 redundancy
  iccp group 1
   multi-homing node-id 2
   interface Bundle-Ether1
    primary vlan 101
    secondary vlan 100
    !
  !
!
```

Ethernet Access Node

In this example, the Ethernet access node is a Cisco Ethernet switch running IOS. Configurations for other access node devices can be easily derived from this configuration example, given that it shows a simple Ethernet trunk configuration for each interface.

NNI Interfaces

```
interface GigabitEthernet0/13
 port-type nni
 switchport trunk allowed vlan 100-101
 switchport mode trunk
 load-interval 30
!
interface GigabitEthernet0/14
 port-type nni
 switchport trunk allowed vlan 100-101
 switchport mode trunk
 load-interval 30
 !
```

Ethernet Access Rings

In addition to hub-and-spoke access deployments, the Connected Roadways System design supports native Ethernet access rings off of the MPLS Transport domain. These Ethernet access rings are comprised of Cisco Industrial Ethernet switches, providing ruggedized and resilient connectivity to many trackside devices.

The Ethernet access switch provides transport of traffic from the roadside CE router and other roadside components. To provide segmentation between services over the Ethernet access network, the access switch implements 802.1q VLAN tags to transport each service. Ring topology management and resiliency for the Ethernet access network is enabled by implementing Cisco REP segments in the network.

The Ethernet access ring is connected to a pair of PANs at the edge of the MPLS Transport network. The PAN maps the service transport VLAN from the Ethernet access network to a transport MPLS L3VPN Virtual Routing and Forwarding (VRF) instance, which provides service backhaul across the Unified MPLS transport network. The REP segment from the access network is terminated on the pair of access nodes, providing closure to the Ethernet access ring.

If the endpoint equipment being connected at the roadside only supports a single default gateway IP address, Virtual Router Redundancy Protocol (VRRP) is implemented on the pair of PANs to provide a single virtual router IP address while maintaining resiliency functionality.

Pre-Aggregation Node Configuration

The following configurations are the same for both access nodes.

VRF Configuration

RT constrained filtering is used to minimize the number of prefixes learned by the PANs. In this example, RT 100:100 is the common transport RT which has all prefixes. While all nodes in the transport network export any connected prefixes to this RT, only the MTG nodes providing connectivity to the data center infrastructure and backend systems will import this RT. These nodes will also export the prefixes of the data center infrastructure with RT 1001:1001. The PAN nodes import this RT, as only connectivity with the data center infrastructure is required.

```
ip vrf DC
```

```
 rd 100:100
 !***Common RT for all nodes
 route-target export 100:100
 !***RT for DC-connected nodes only***
 route-target import 1001:1001
```

Ethernet Access Ring NNI Configuration

```
interface GigabitEthernet0/0
 description to Ethernet access ring
 no ip address
 negotiation auto
 !***REP segment configuration***
 rep segment 1 edge
 cdp enable
 !***Transport VLAN***
 service instance 100 ethernet
  encapsulation dot1q 100
  rewrite ingress tag pop 1 symmetric
  bridge-domain 100
! end
```

IP/MPLS Access Ring NNI Configuration

This interface has two service instances configured. The untagged service instance provides the L3 connectivity for the MPLS transport. The tagged service instance closes the Ethernet access ring and REP segment with the other access node.

```
interface GigabitEthernet0/11
 description to IP/MPLS Access Ring
 no ip address
 load-interval 30
 carrier-delay msec 0
 negotiation auto
 rep segment 1 edge
 synchronous mode
 cdp enable
 ethernet oam
 !***VLAN for IP/MPLS transport***
 service instance 11 ethernet
  encapsulation untagged
  bridge-domain 11
 !
 !***VLAN to close Ethenet access ring REP segment***
 service instance 100 ethernet
  encapsulation dot1q 100
  rewrite ingress tag pop 1 symmetric
  bridge-domain 100
! end
```

VRRP Configuration

The following configuration example shows how VRRP is implemented on each access node to enable a single gateway IP address for an endpoint device.

PAN-1

```
interface Vlan100
 ip vrf forwarding DC
 ip address 15.0.0.2 255.255.255.0
 vrrp 1 ip 15.0.0.1
 vrrp 1 timers advertise 2
```

```
 vrrp 1 preempt delay minimum 10
 vrrp 1 priority 110
 vrrp 1 track 1 decrement 20
```

PAN-2

```
interface Vlan100
 ip vrf forwarding DC
 ip address 15.0.0.3 255.255.255.0
 vrrp 1 ip 15.0.0.1
 vrrp 1 timers advertise 2
 vrrp 1 preempt delay minimum 10
 vrrp 1 priority 90
 vrrp 1 track 1 decrement 20
```

Ethernet Access Node Configuration

The identical configuration is used for each Ethernet access switch in the ring. Only one switch configuration is shown here.

Ethernet Ring NNI Configuration

```
interface GigabitEthernet1/1
 switchport mode trunk
 rep segment 1
!
interface GigabitEthernet1/2
 switchport mode trunk
 rep segment 1
!
```

UNI to Base Station Configuration

```
interface FastEthernet1/2
 switchport access vlan 100
 switchport mode access
!
```

L3VPN Service Implementation

L3 MPLS VPN Service Model

This section describes the implementation details and configurations for the core transport network required for the Layer 3 MPLS VPN service model. See Figure 7-6.

This section is organized into the following sections:

- MPLS VPN Core Transport, which gives the implementation details of the core transport network that serves all the different access models.
- L3VPN Hub-and-Spoke Access Topologies, which describes direct endpoint connectivity at the PAN.
- L3VPN Ring Access Topologies, which provides the implementation details for REP-enabled Ethernet access rings.

Note ASR903 RSP1 and RSP2 support L3VPN Services with Non-MPLS access.

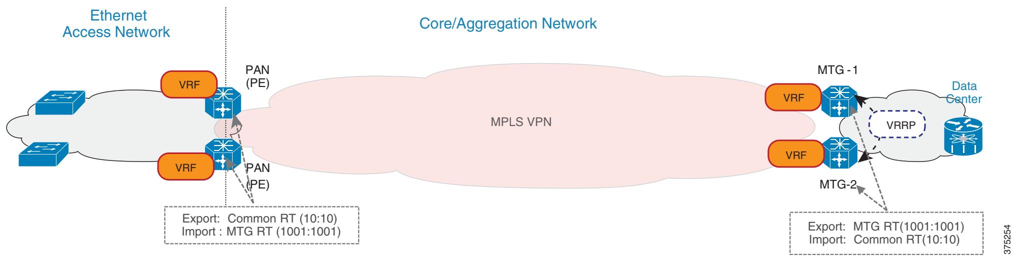


Figure 7-6 MPLS VPN Service Implementation

MPLS VPN Core Transport

This section describes the L3VPN PE configuration on the PANs connecting to the access network, the L3VPN PE configuration on the MTGs in the core network, and the RR required for implementing the L3VPN transport services.

This section also describes the BGP control plane aspects of the L3VPN service backhaul. See Figure 7-7.

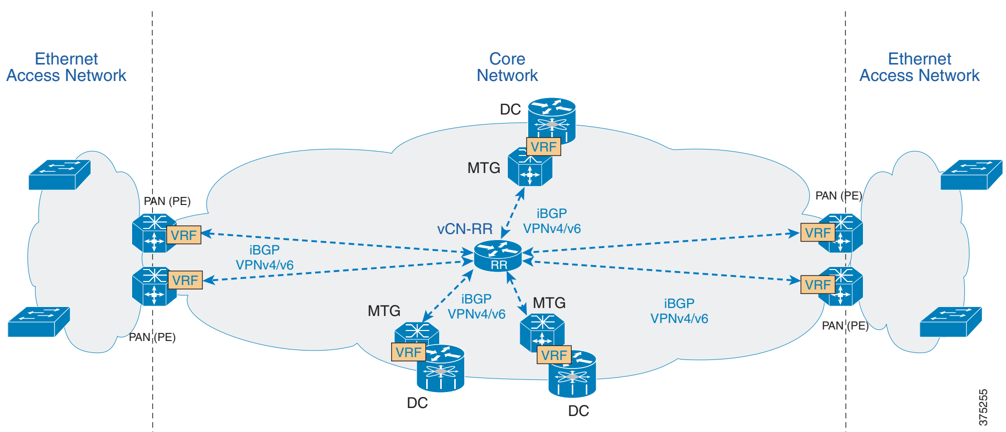


Figure 7-7 BGP Control Plane for MPLS VPN Service

MPLS Transport Gateway MPLS VPN Configuration

This is a one-time MPLS VPN configuration done on the MTGs. No modifications are made when additional access nodes or other MTGs are added to the network.

Data Center UNI

```
interface TenGigE0/0/0/2.1100
 description Connected to Data Center.
 vrf DC102
 ipv4 address 115.1.102.3 255.255.255.0
 ipv6 nd dad attempts 0
 ipv6 address 2001:115:1:102::3/64
 encapsulation dot1q 1100
!
```

VRF Definition

```
vrf DC102
 address-family ipv4 unicast
  !***Common Access RT imported by MTG***
  import route-target
   10:10
  !
  !***Export MSE RT.***
  !***Imported by every PAN in entire network.***
  export route-target
   1001:1001
  !
 !
 address-family ipv6 unicast
  import route-target
   10:10
  !
  export route-target
   1001:1001
  !
 !
!
```

MTG 1 VPNv4/v6 BGP Configuration

```
router bgp 1000
 bgp router-id 100.111.15.1
 bgp update-delay 360
!
 vrf DC102
  rd 1001:1001
  address-family ipv4 unicast
   redistribute connected
  !
  address-family ipv6 unicast
   redistribute connected
  !
 !
```

MTG 2 VPNv4/v6 BGP Configuration

```
router bgp 1000
 bgp router-id 100.111.15.2

 !
 vrf DC102
  rd 1001:1002
  address-family ipv4 unicast
   redistribute connected
  !
  address-family ipv6 unicast
   redistribute connected
  !
 !
```

Note Each MTG has a unique RD for the MPLS VPN VRF to properly enable BGP FRR Edge functionality.

A more detailed explanation is given in High Availability Implementation, page 7-38.

PAN VPNv4 PE Configuration

```
router bgp 1000
 bgp router-id 100.111.14.1

 !***CN-RR***
 neighbor 100.111.15.50 peer-group cn-rr
 !
 address-family vpnv4
  bgp nexthop trigger delay 3
  !***CN-RR***
  neighbor cn-rr send-community both
  neighbor 100.111.15.50 activate
  exit-address-family
 !
 address-family vpnv6
  bgp nexthop trigger delay 3
  !***CN-RR***
  neighbor cn-rr send-community both
  neighbor 100.111.15.50 activate
  exit-address-family
 !
 !***RT Constrained Route Distribution towards CN-RR***
 address-family rtfilter unicast
  neighbor cn-rr send-community extended
  neighbor 100.111.15.50 activate
  exit-address-family
 !
```

Centralized CN-RR Configuration

The BGP configuration requires the small change of activating the neighborship when a new PAN is added to the core/aggregation network.

Centralized vCN-RR Configuration

```
router bgp 1000
 bgp router-id 100.111.15.50
!
 address-family vpnv4 unicast
  nexthop trigger-delay critical 2000
 !
 address-family vpnv6 unicast
  nexthop trigger-delay critical 2000
 !
 !***Peer group for all nodes***
 session-group intra-as
  remote-as 1000
!
 !***Neighbor Group for MTGs***
 neighbor-group mtg
  use session-group intra-as
  !
  !***MTGs are Route-Reflector Clients***
  address-family vpnv4 unicast
   route-reflector-client
  !
  address-family vpnv6 unicast
   route-reflector-client
  !
 !
 !***Neighbor Group for PANs
```

```
 neighbor-group pan
  use session-group intra-as
  !
  !***PANs are Route-Reflector Clients***
  address-family vpnv4 unicast
   route-reflector-client
  !
  address-family vpnv6 unicast
   route-reflector-client
  !
 !
exit-address-family
!
!***MTGs***
 neighbor 100.111.15.1
  use neighbor-group mtg
 !
 neighbor 100.111.15.2
  use neighbor-group mtg
!
!***PANs***
 neighbor 100.111.14.1
  use neighbor-group pan
 !
neighbor 100.111.14.2
  use neighbor-group pan
!

end-policy
```

MTG VPNv4/v6 PE Configuration

```
router bgp 1000
 nsr
 bgp router-id 100.111.15.1
!
 session-group intra-as
!
 neighbor-group cn-rr
  use session-group intra-as
  !
  address-family vpnv4 unicast
  !
  address-family vpnv6 unicast
  !
 !
 !***CN-RR***
 neighbor 100.111.15.50
  use neighbor-group cn-rr
 !
```

L3VPN over Hub-and-Spoke Access Topologies

This section describes the implementation details of direct endpoint connectivity at the PAN over hub-and-spoke access topologies.

Direct Endpoint Connectivity to PAN Node

This section shows the configuration of PAN K1401 to which the endpoint is directly connected.

MPLS VPN PE Configuration on PAN K1401

Directly-attached endpoint UNI

```
interface GigabitEthernet0/3/6
 vrf forwarding VPN224
 ip address 114.1.224.1 255.255.255.0
 load-interval 30
 negotiation auto
 ipv6 address 2001:114:1:224::1/64
```

VRF Definition

```
vrf definition VPN224
 rd 10:104
 !
 address-family ipv4
  export map ADDITIVE
  route-target export 10:104
  route-target import 10:104
  route-target import 1001:1001
  route-target import 236:236
  route-target import 235:235
 exit-address-family
 !
 address-family ipv6
  export map ADDITIVE
  route-target export 10:104
  route-target import 10:104
  route-target import 1001:1001
  route-target import 235:235
 exit-address-family
!

!***Route map to export Global RT 10:10 in addition to Local RT 10:203***
route-map ADDITIVE permit 10
 set extcommunity rt 10:10 additive

!***VPN BGP Configuration***
router bgp 1000
 neighbor pan peer-group
 neighbor pan remote-as 1000
 neighbor pan password lab
 neighbor pan update-source Loopback0
 !
 address-family vpnv4
  bgp nexthop trigger delay 2
  neighbor pan send-community extended
 !
 address-family vpnv6
  bgp nexthop trigger delay 2
  neighbor pan send-community extended
 !
 address-family ipv4 vrf VPN224
  !***For Directly Connected endpoint***
  redistribute connected
 exit-address-family
 !
 address-family ipv6 vrf VPN224
  !***For Directly Connected endpoint***
  redistribute connected
 exit-address-family
```

L3VPN over Ring Access Topologies

L3VPN transport over ring access topologies are implemented for REP-enabled Ethernet access rings. This section shows the configuration for the pre-aggregation nodes terminating the service from the Ethernet access ring running IOS-XR and a sample router access node. Configuration of the access ring itself with Ethernet switches, as well as PANs running IOS-XE, has been covered in Transport Network Implementation, page 7-1.

PAN dual homing is achieved by a combination of VRRP, routed PW, and REP providing resiliency and load balancing in the access network. In this example, the PANs, AGN-K0301 and AGN-K0302, implement the SE for the Layer 3 MPLS VPN transporting traffic to the data center behind the MTG. A routed BVI interface acts as the service endpoint. The Ethernet access network is implemented as a REP access ring and carries a dedicated VLAN to Layer 3 MPLS VPN-based service. A PW running between the SE nodes closes the service VLAN providing full redundancy on the ring.

VRRP is configured on the Routed BVI interface to ensure the endpoints have a common default gateway regardless of the node forwarding the traffic.

AGN K0302 Configuration

```
interface TenGigE0/2/1/3.302 l2transport
 encapsulation dot1q 302
 rewrite ingress tag pop 1 symmetric
!
l2vpn
 bridge group L2VPN
  bridge-domain L3VPN-302
   interface TenGigE0/2/1/3.302
   !
!*** Routed PW configured to other SE Node 100.111.3.1***
   neighbor 100.111.3.1 pw-id 302
   !
   routed interface BVI302
  !
 !
!***VRF Definition***
vrf VPN224
 address-family ipv4 unicast
  import route-target
!***Local RT***
   10:104
   235:235
   236:236
   1001:1001
  !
  export route-policy ADDITIVE
  export route-target
   10:104
  !
 !
address-family ipv6 unicast
  import route-target
   10:104
   235:235
   236:236
   1001:1001
  !
  export route-policy ADDITIVE
  export route-target
   10:104
  !
```

```
 !
!
!***BVI  Interface Configuration***
interface BVI302
 vrf VPN224
 ipv4 address 30.2.1.2 255.255.255.0
 ipv6 nd dad attempts 0
 ipv6 address 2001:13:2:102::2/64
!
!***VRRP Configuration***
router vrrp
interface BVI302
  address-family ipv4
   vrrp 2
!***Highest Priority value to be active***
    priority 253
    preempt delay 600
    address 30.2.1.1
    bfd fast-detect peer ipv4 30.2.1.3
   !
  !
```

AGN K0301 Configuration

```
interface TenGigE0/2/1/3.302 l2transport
 encapsulation dot1q 302
 rewrite ingress tag pop 1 symmetric
!
l2vpn
 bridge group L2VPN
  bridge-domain L3VPN-302
   interface TenGigE0/2/1/3.302
   !
!*** Routed PW configured to other SE Node 100.111.3.2***
   neighbor 100.111.3.2 pw-id 302
   !
   routed interface BVI302
  !
 !
!
!***VRF Definition***
vrf VPN224
 address-family ipv4 unicast
  import route-target
!***Local RT ***
   10:104
   235:235
   236:236
   1001:1001
  !
  export route-policy ADDITIVE
  export route-target
   10:104
  !
 !
address-family ipv6 unicast
  import route-target
   10:104
   235:235
   236:236
   1001:1001
  !
  export route-policy ADDITIVE
```

```
  export route-target
   10:104
  !
 !
!
!***BVI  Interface Configuration***
interface BVI302
 vrf VPN224
 ipv4 address 30.2.1.3 255.255.255.0
 ipv6 nd dad attempts 0
 ipv6 address 2001:13:2:102::3/64
 !
!***VRRP Configuration***
router vrrp
 interface BVI302
  address-family ipv4
   vrrp 2
!***Highest Priority value to be active***
    priority 252
    address 30.2.1.1
    bfd fast-detect peer ipv4 30.2.1.2
   !
  !
```

Sample Access Node Configuration

```
interface GigabitEthernet0/5
!***connection to endpoint***
 service instance 302 ethernet
  encapsulation dot1q 302
  rewrite ingress tag pop 1 symmetric
  bridge-domain 302
!
interface TenGigabitEthernet0/1
!*** NNI port***
 service instance 302 ethernet
  encapsulation dot1q 302
  rewrite ingress tag pop 1 symmetric
  bridge-domain 302
interface TenGigabitEthernet0/0
!*** NNI port****
 service instance 302 ethernet
  encapsulation dot1q 302
  rewrite ingress tag pop 1 symmetric
  bridge-domain 302
```

Circuit Emulation Services Implementation

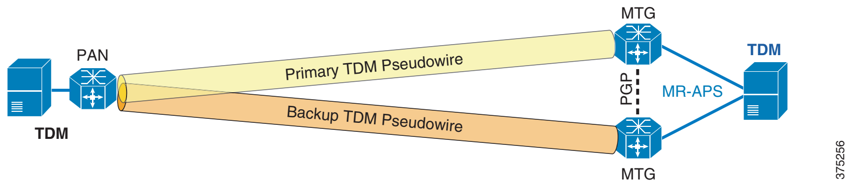
Layer 2 MPLS VPN service models provide TDM CES for legacy TDM circuit transport. The following models are shown in this section:

- TDM backhaul from the PAN to the MTG, utilizing the structured CESoPSN mechanism
- TDM backhaul from the PAN to the MTG, utilizing the unstructured SAToP mechanism

CESoPSN VPWS from PAN to MTG

Circuit Emulation Service over Packet Switched Network (CESoPSN) provides structured transport of TDM circuits down to the DS0 level across an MPLS-based backhaul architecture. The configurations for the PAN and MTGs are outlined in this section, including an illustration of basic backup pseudowire configuration on the PAN in order to enable transport to redundant MTGs. See Figure 7-8.

Figure 7-8 CESoPSN Service Implementation



Regarding CESoPSN Service Implementation:

- The Cisco ASR 903 Series router uses a 16-port T1/E1 Interface Module (A900-IMA16D) for TDM interfaces.
- Both Cisco ASR 9000 Series MTGs use 1-port channelized OC3/STM-1 ATM and circuit emulation SPA (SPA-1CHOC3-CE-ATM) in a SIP-700 card for the TDM interfaces.
- CESoPSN encapsulates T1/E1 structured (channelized) services. Structured mode (CESoPSN) identifies framing and sends only payload, which can be channelized T1s within DS3 and DS0s within T1. DS0s can be bundled to the same packet. This mode is based on IETF RFC 5086.
- mpls ldp discovery targeted-hello accept is required because the LDP session is tunneled via PW between the PEs, since they are not directly connected. Since targeted-hello response is not configured, both sessions will show as passive.

Cisco ASR 903 Series Pre-Aggregation Node Configuration

```
card type t1 0 5
!
controller T1 0/5/1
 framing esf
 clock source internal
 linecode b8zs
 cablelength short 110
 forward-alarm ais
 forward-alarm rai
 cem-group 0 timeslots 1-24
!
pseudowire-class CESoPSN
 encapsulation mpls
 control-word
!
!
interface CEM0/5/1
 no ip address
 load-interval 30
 cem 0
  xconnect 100.111.15.1 1401150113 encapsulation mpls pw-class CESoPSN
   backup peer 100.111.15.2 1401150213 pw-class CESoPSN
 !
 hold-queue 4096 in
 hold-queue 4096 out
```

```
!
interface Loopback0
 ip address 100.111.14.1 255.255.255.255
!
!
router isis agg-acc
 passive-interface Loopback0
!
!
!*** ISIS and BGP related configuration needed to ensure MPLS LDP binding with remote
PE so as to establish AToM PW***
mpls ldp discovery targeted-hello accept
```

Cisco ASR 9000 Series MPLS Transport Gateway Configuration

The other MTG configuration is identical, except with a Loopback 0 IP address of 100.111.15.2 and pw-ids ending in 1502 instead of 1501.

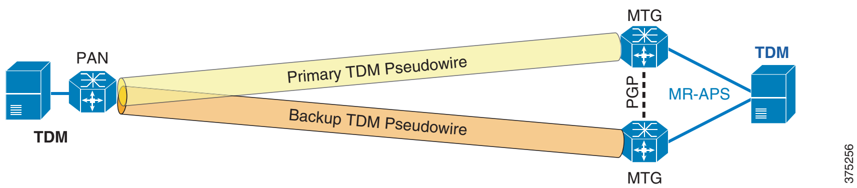
```
hw-module subslot 0/2/1 cardtype sonet
!
controller SONET0/2/1/0
 description To ONS15454-K1410 OC3 port 4/1
 ais-shut
 report lais
 report lrdi
 sts 1
  mode vt15-t1
  delay trigger 250
 !
!
controller T1 0/2/1/0/1/1/3
 cem-group framed 0 timeslots 1-24
 forward-alarm AIS
 forward-alarm RAI
 clock source internal
!
interface CEM0/2/1/0/1/1/3:0
 load-interval 30
 l2transport
 !
!
!
interface Loopback0
 description Global Loopback
 ipv4 address 100.111.15.1 255.255.255.255
!
l2vpn
 pw-class CESoPSN
  encapsulation mpls
   control-word
  !
 !
 xconnect group TDM-K1401
  p2p T1-CESoPSN-01
   interface CEM0/2/1/0/1/1/3:0
   neighbor ipv4 100.111.14.1 pw-id 1401150113
    pw-class CESoPSN
   !
  !
 !
router isis core
 interface Loopback0
  passive
```

```
  point-to-point
  address-family ipv4 unicast
  !
 !
!
router bgp 1000
 bgp router-id 100.111.15.1
 address-family ipv4 unicast
  network 100.111.15.1/32 route-policy MTG_Community
!
mpls ldp
 router-id 100.111.15.1
 discovery targeted-hello accept
!
!*** ISIS and BGP related configuration needed to ensure MPLS LDP binding with remote
PE so as to establish AToM PW***
!
```

SAToP VPWS from PAN to MTG

Structure-Agnostic Transport over Packet (SAToP) provides unstructured transport of TDM circuits across an MPLS-based backhaul architecture. The configurations for the PAN and MTGs are outlined in this section, including an illustration of backup pseudowire configuration on the PAN in order to enable transport to redundant MTGs. See Figure 7-9.

Figure 7-9 SAToP VPWS Implementation



Regarding SAToP VPWS implementation:

- The Cisco ASR 903 Series router uses a 16-port T1/E1 Interface Module (A900-IMA16D) for TDM interfaces.
- Both Cisco ASR 9000 Series MTGs use 1-port channelized OC3/STM-1 ATM and circuit emulation SPA (SPA-1CHOC3-CE-ATM) in a SIP-700 card for the TDM interfaces.
- SAToP encapsulates T1/E1 services, disregarding any structure that may be imposed on these streams, in particular the structure imposed by the standard TDM framing. This mode is based on IETF RFC 4553.
- mpls ldp discovery targeted-hello accept is required because the LDP session is tunneled via PW between the PEs, since they are not directly connected. Since targeted-hello response is not configured, both sessions will show as passive.

Cisco ASR 903 Series Pre-Aggregation Node Configuration

```
card type t1 0 5
!
controller T1 0/5/0
 framing unframed
 clock source internal
 linecode b8zs
```

```
 cablelength short 110
 cem-group 0 unframed
!
pseudowire-class SAToP
 encapsulation mpls
 control-word
!
!
interface CEM0/5/0
 no ip address
 load-interval 30
 cem 0
  xconnect 100.111.15.1 14011501 encapsulation mpls pw-class SAToP
   backup peer 100.111.15.2 14011502 pw-class SAToP
  !
 hold-queue 4096 in
 hold-queue 4096 out
!
interface Loopback0
 ip address 100.111.14.1 255.255.255.255
!
!
router isis agg-acc
 passive-interface Loopback0
!
!
mpls ldp discovery targeted-hello accept
```

Cisco ASR 9000 Series Mobile Transport Gateway Configuration

The other MTG configuration is identical, except with a Loopback 0 IP address of 100.111.15.2 and pw-ids ending in 1502 instead of 1501.

```
hw-module subslot 0/2/1 cardtype sonet
!
controller SONET0/2/1/0
 description To ONS15454-K1410 OC3 port 4/1
 ais-shut
 report lais
 report lrdi
 sts 1
  mode vt15-t1
  delay trigger 250
  !
!
controller T1 0/2/1/0/1/1/2
 cem-group unframed
 forward-alarm AIS
 forward-alarm RAI
 clock source line
!
interface CEM0/2/1/0/1/1/2
 load-interval 30
 l2transport
  !
!
!
interface Loopback0
 description Global Loopback
 ipv4 address 100.111.15.1 255.255.255.255
!
l2vpn
```

```
 pw-class SAToP
  encapsulation mpls
   control-word
  !
 !
 xconnect group TDM-K1401
  p2p T1-SAToP-01
   interface CEM0/2/1/0/1/1/2
   neighbor 100.111.14.1 pw-id 14011501
    pw-class SAToP
   !
  !
 !
router isis core
 interface Loopback0
  passive
  point-to-point
  address-family ipv4 unicast
  !
 !
!
router bgp 1000
 bgp router-id 100.111.15.1
 address-family ipv4 unicast
  network 100.111.15.1/32 route-policy MTG_Community
!
mpls ldp
 router-id 100.111.15.1
 discovery targeted-hello accept
```

Quality of Service Implementation

The Connected Roadways System design uses a DiffServ QoS model across all network layers of the transport network in order to guarantee proper treatment of all services being transported. This QoS model guarantees the SLA requirements of all services across the transport network. QoS policy enforcement is accomplished with flat QoS policies with DiffServ queuing on all network-to-network interfaces (NNI), and H-QoS policies with parent shaping and child queuing on the user-network interfaces (UNIs) and interfaces connecting to microwave access links.

This section covers the aggregate QoS policies implemented on the NNI interfaces in the transport network, illustrating the treatment of all services traversing the transport network. It also covers QoS policies for UNI interfaces on both the access network as well as MTG for proper service treatment.

The classification criteria used to implement the DiffServ PHBs is covered in Figure 7-10.

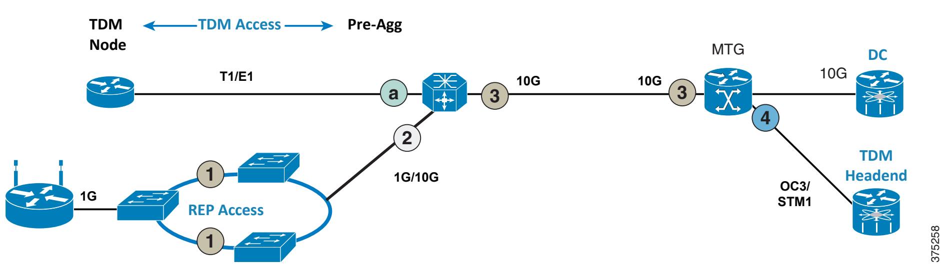
Figure 7-10 Differentiated Service QoS Domain

Traffic Class	PHB	Unified MPLS Transport		Ethernet/TDM/ATM UNI		
		DSCP	EXP	DSCP	802.1P	ATM
Network Management	AF	56	7	56	(7)	VBR-nrt
Network Control Protocols	AF	48	6	48	(6)	VBR-nrt
Real-Time Traffic Voice over IP Network Sync (1588 PTP) Mobility & Signaling traffic	EF	46	5	46	5	CBR
Video Distribution	AF	32	4	32	4	NA
Video Surveillance Control	AF	24	3	24	3	NA
Business Critical Committed Information Rate (CIR) Permitted Information Rate (PIR)	AF	16 8	2 1	16 8	2 1	NA
Best Effort	BE	0	0	0	0	UBR

In Figure 7-11, the following elements are called out:

- (a) H-QoS policy map on CE UNIs
- (1) (2) Flat QoS policy map on CSG and pre-aggregation NNIs in fiber access network
- (3) Flat QoS policy map on aggregation and core network NNIs
- (4) Flat QoS policy map on ingress for Circuit Emulation UNIs

Figure 7-11 QoS Enforcement Points



CE QoS Configuration

Class maps used for UNI classification are included here for reference. As stated above, the service-specific policies utilizing these class maps are covered in the service-specific design and implementation guides.

Class Maps

- QoS classification at the UNI in the ingress direction for upstream traffic is based on IP differentiated services code point (DSCP), with the marking done by the connected device for Layer 3 services.

```
!***Network management traffic***
class-map match-any CMAP-NMgmt-DSCP
```

```
  match dscp cs7
!
!***Voice/Real-Time traffic***
class-map match-all CMAP-RT-DSCP
  match dscp ef
!
!*** Video traffic***
class-map match-any CMAP-Video-DSCP
  match dscp cs4
```

- QoS classification at the UNI in the ingress direction for upstream traffic is based on 802.1p class of service (CoS) markings, with the marking done by the connected device for Layer 2 services.

```
!***Voice/Real-Time traffic***
class-map match-any CMAP-RT-COS
  match cos  5
!
!***Video conferencing and TelePresence traffic***
class-map match-any CMAP-BC-Tele-COS
  match cos  3
!
!***Business critical traffic***
class-map match-any CMAP-BC-COS
  match cos  1  2
```

- QoS classification at the UNI in the egress direction for downstream traffic is based on QoS groups with the QoS group mapping being done at the ingress NNI.
- QoS classification at the NNI in the egress direction is based on QoS groups, with:
  - QoS group mapping for upstream traffic being done at the ingress UNI.
  - QoS group mapping for traffic transiting the access ring being done at the ingress NNI.

```
!***Network management traffic***
class-map match-any CMAP-NMgmt-GRP
  match qos-group 7
!
!***Network control traffic***
class-map match-any CMAP-CTRL-GRP
  match qos-group 6
!
!***Voice/Real-Time traffic***
class-map match-all CMAP-RT-GRP
  match qos-group 5
!
!***Broadcast Video traffic***
class-map match-any CMAP-Video-GRP
  match qos-group 4
```

- QoS classification at the NNI in the ingress direction is based on MPLS EXP for MPLS access and based on CoS for G.8032 access.

NNI Classification for REP Ring Access

```
!***Network management traffic***
class-map match-any CMAP-NMgmt-COS
  match cos 7
!
!***Network control traffic***
class-map match-any CMAP-CTRL-COS
  match cos 6
!
```

```
!***Voice/Real-Time traffic***
class-map match-all CMAP-RT-COS
  match cos  5
!
!***Broadcast Video traffic***
class-map match-any CMAP-Video-COS
  match cos 4
!
!***Video conferencing and TelePresence traffic***
class-map match-any CMAP-BC-Tele-EXP
  match cos 3
!
!***Business critical traffic***
class-map match-any CMAP-BC-COS
  match cos 1 2
```

REP Fiber Ring NNI QoS Policy Maps

- For downstream and transit traffic, a flat QoS policy map with group mapping applied in the ingress direction is used.
- For upstream and transit traffic, a flat QoS policy map with DiffServ queuing applied in the egress direction is used.

```
!*** QoS enforcement point (E)***
!***Interface connecting to REP Fiber Access Ring.***
interface TenGigabitEthernet0/0
 service-policy input PMAP-NNI-I
 service-policy output PMAP-NNI-E
!
policy-map PMAP-NNI-E
!*** Egress policy on NNI PORT ***
 class CMAP-RT-GRP
  priority percent 20
 class CMAP-BC-GRP
  bandwidth percent 5
 class CMAP-BC-Tele-GRP
  bandwidth percent 10
 class class-default
!
policy-map PMAP-NNI-I
!*** Ingress Policy on NNI Port ***
 class CMAP-BC-COS
  set qos-group 2
 class CMAP-RT-COS
  set qos-group 5
  police rate 1000000
 class CMAP-BC-Tele-COS
  set qos-group 3
!
```

Pre-Aggregation Node QoS Configuration (Cisco ASR 903)

Class Maps

- QoS classification for any local UNI connections in the ingress direction for upstream traffic is based on IP DSCP with the marking done by the connected device for residential and mobile services.

```
!***Network management traffic***
class-map match-any CMAP-NMgmt-DSCP
  match dscp cs7
!
!***Voice/Real-Time traffic***
class-map match-all CMAP-RT-DSCP
  match dscp ef
!
!***Broadcast Video traffic***
class-map match-any CMAP-Video-DSCP
  match dscp cs4
```

- QoS classification for any local UNI connections in the ingress direction for upstream traffic is based on 802.1p CoS markings, with the marking done by the connected device for business services.

```
!***Voice/Real-Time traffic***
class-map match-any CMAP-RT-COS
  match cos  5
!
!***Video conferencing and TelePresence traffic***
class-map match-any CMAP-BC-Tele-COS
  match cos  3
!
!***Business critical traffic***
class-map match-any CMAP-BC-COS
  match cos  1  2
```

- QoS classification at the NNI in the ingress and egress directions is based on MPLS EXP.

```
!***Network management traffic***
class-map match-any CMAP-NMgmt-EXP
  match mpls experimental topmost 7
!
!***Network control traffic***
class-map match-any CMAP-CTRL-EXP
  match mpls experimental topmost 6
!
!***Voice/Real-Time traffic***
class-map match-all CMAP-RT-EXP
  match mpls experimental topmost 5
!
!***Broadcast Video traffic***
class-map match-any CMAP-Video-EXP
  match mpls experimental topmost 4
!
!***Video conferencing and TelePresence traffic***
class-map match-any CMAP-BC-Tele-EXP
  match mpls experimental topmost 3
!
!***Business critical traffic***
class-map match-any CMAP-BC-EXP
  match mpls experimental topmost 1 2
```

Fiber Ring UNI QoS Policy Maps

The ingress and egress QoS service policies on the UNI are service-specific and thus are covered in Chapter 4, "Service Infrastructure."

Fiber Access NNI QoS Policy Maps

- For downstream traffic, a flat QoS policy map with DiffServ queuing is applied in the egress direction on the pre-aggregation NNI that is facing the 1-G fiber access network.

```
!***QoS enforcement point (2).***
!***Interface connecting Fiber Access Network.***
interface GigabitEthernet0/2
  service-policy output PMAP-NNI-Access-E
!
policy-map PMAP-NNI-Access-E
  class CMAP-RT-EXP
    priority
    police cir 200000000
  class CMAP-CTRL-EXP
    bandwidth 15000
  class CMAP-NMgmt-EXP
    bandwidth 50000
  class CMAP-Video-EXP
    bandwidth 200000
  class CMAP-BC-EXP
    bandwidth 100000
  class CMAP-BC-Tele-EXP
    bandwidth 100000
```

Aggregation NNI QoS Policy Map

- For upstream and transit traffic, a flat QoS policy map with DiffServ queuing is applied in the egress direction on the pre-aggregation NNI facing the 10-G aggregation network.

```
!***QoS enforcement point (3).***
!***Interface connecting Aggregation Network.***
interface TenGigabitEthernet0/1
  service-policy output PMAP-NNI-E
!
policy-map PMAP-NNI-E
  class CMAP-RT-EXP
    priority
    police cir 1000000000
  class CMAP-CTRL-EXP
    bandwidth 150000
  class CMAP-NMgmt-EXP
    bandwidth 500000
  class CMAP-Video-EXP
    bandwidth 2000000
  class CMAP-BC-EXP
    bandwidth 1000000
  class CMAP-BC-Tele-EXP
    bandwidth 1000000
```

Aggregation and Core Network QoS Configuration

Class Maps

- QoS classification at the NNIs is based on MPLS EXP.

```
class-map match-any CMAP-BC-EXP
  match mpls experimental topmost 1 2
  end-class-map
```

```
!
class-map match-any CMAP-BUS-Tele-EXP
  match mpls experimental topmost 3
  end-class-map
!
class-map match-any CMAP-Video-EXP
  match mpls experimental topmost 4
  end-class-map
!
class-map match-any CMAP-RT-EXP
  match mpls experimental topmost 5
  end-class-map
!
class-map match-any CMAP-CTRL-EXP
  match mpls experimental topmost 6
  end-class-map
!
class-map match-any CMAP-NMgmt-EXP
  match mpls experimental topmost 7
  end-class-map
```

NNI QoS Policy Maps

- Flat QoS policy map with DiffServ queuing is applied at all NNIs.

```
!***10Gbps NNI***
policy-map PMAP-NNI-E
  class CMAP-RT-EXP
    priority level 1
    police rate 1 gbps
    !
  !
  class CMAP-CTRL-EXP
    bandwidth 200 mbps
  !
  class CMAP-NMgmt-EXP
    bandwidth 500 mbps
  !
  class CMAP-Video-EXP
    bandwidth 2 gbps
  !
  class CMAP-BC-EXP
    bandwidth 1 gbps
    !***Random Detect preserves CIR over PIR traffic***
    random-detect exp 2 80 ms 100 ms
    random-detect exp 1 40 ms 50 ms
  !
  class CMAP-BUS-Tele-EXP
    bandwidth 2 gbps
  !
  class class-default
  !
  end-policy-map

!***100Gbps NNI***
policy-map PMAP-NNI-100GE-E
  class CMAP-RT-EXP
    priority level 1
    police rate 10 gbps
    !
  !
  class CMAP-CTRL-EXP
    bandwidth 2 gbps
```

```
  !
  class CMAP-NMgmt-EXP
    bandwidth 5 gbps
  !
  class CMAP-Video-EXP
    bandwidth 20 gbps
  !
  class CMAP-BC-EXP
    bandwidth 10 gbps
    !***Random Detect preserves CIR over PIR traffic***
    random-detect exp 2 80 ms 100 ms
    random-detect exp 1 40 ms 50 ms
  !
  class CMAP-BUS-Tele-EXP
    bandwidth 20 gbps
  !
  class class-default
  !
  end-policy-map
!
```

MTG QoS Configuration

This section includes the UNI configuration for Ethernet, ATM, and TDM services on the MPLS Transport Gateway.

Ethernet UNI QoS Policy Maps

The following configurations show the simple class maps and policy maps for interconnecting service transport to and from the MPLS transport network at the MTG.

```
class-map match-all CMAP-RT-DSCP
 match dscp ef
 end-class-map
!
class-map match-any CMAP-NMgmt-DSCP
 match dscp cs7
 end-class-map
!
class-map match-any CMAP-Video-DSCP
 match dscp cs3
 end-class-map

policy-map PMAP-UNI-E
 class CMAP-RT-DSCP
  priority level 1
  police rate 10000 kbps
  !
 !
 class CMAP-NMgmt-DSCP
  bandwidth 50000 kbps
 !
 class CMAP-HVideo-DSCP
  bandwidth 200000 kbps
 !
 class class-default
 !
 end-policy-map
!
policy-map PMAP-UNI-I
```

```
 class CMAP-RT-DSCP
  priority level 1
  police rate 10000 kbps
  !
  set mpls experimental imposition 5
 !
 class CMAP-NMgmt-DSCP
  bandwidth 50000 kbps
 !
  set mpls experimental imposition 7
 !
 class CMAP-HVideo-DSCP
  bandwidth 200000 kbps
 !
  set mpls experimental imposition 3
 !
 class class-default
 !
 end-policy-map
!
```

ATM UNI QoS Policy Maps

The only ingress marking to match is the ATM Cell Loss Priority (CLP) bit on ATM UNIs, which indicates a discard preference for marked cells within a particular ATM CoS. This can be utilized to offer a bursting capability in a particular ATM CoS.

```
class-map match-any CMAP-ATM-CLP0-UNI-I
 match atm clp 0
 end-class-map
!
class-map match-any CMAP-ATM-CLP1-UNI-I
 match atm clp 1
 end-class-map
```

Two ATM policy maps are shown. The first corresponds to an ATM Variable Bit Rate-Real Time (VBR-rt) service where cells are marked with a CLP of 1 above a certain cell rate. The second corresponds to an ATM Unspecified Bit Rate (UBR) service, again where cells are marked with a CLP of 1 above a certain cell rate. The proper map is applied to an ATM PVC which corresponds to the ATM CoS carried on that PVC.

```
policy-map PMAP-ATM-UNI-I
 class CMAP-ATM-CLP0-UNI-I
  set mpls experimental imposition 5
 !
 class CMAP-ATM-CLP1-UNI-I
  set mpls experimental imposition 4
 !
 class class-default
 !
 end-policy-map
!
policy-map PMAP-ATM-UNI-DATA-I
 class CMAP-ATM-CLP0-UNI-I
  set mpls experimental imposition 4
 !
 class CMAP-ATM-CLP1-UNI-I
  set mpls experimental imposition 0
 !
 class class-default
 !
 end-policy-map
```

```
!
interface ATM0/2/3/0
 load-interval 30
!
interface ATM0/2/3/0.100 l2transport
 pvc 100/4011
  service-policy input PMAP-ATM-UNI-I
  encapsulation aal0
  shape vbr-rt 20000 14000 7000
 !
!
interface ATM0/2/3/0.101 l2transport
 pvc 100/4012
  service-policy input PMAP-ATM-UNI-DATA-I
  shape ubr 40000
 !
!
```

TDM UNI QoS Policy Map

The TDM UNI policy map simply marks all traffic on a CEM interface with an MPLS EXP of 5 to ensure that all traffic associated with the CEM interface is given EF treatment. This ensures that the emulated TDM circuit is transported with minimum packet delay variation (PDV) in order to guarantee the quality of the TDM circuit.

```
policy-map PMAP-TDM-UNI-I
 class class-default
  set mpls experimental imposition 5
 !
 end-policy-map
!
interface CEM0/2/1/0/1/4/4
 service-policy input PMAP-TDM-UNI-I
 load-interval 30
 l2transport
 !
!
```

Multicast Services in Global Routing

This section describes the implementation of multicast in global routing using Label-Switched Multicast (LSM) with Multicast Label Distribution Protocol (MLDP) Global in-band signaling to support Multicast service transport over the MPLS transport network. The MPLS Multicast domain is based on LSM, which is a solution that enables forwarding of IP multicast traffic over MPLS, thus allowing the MPLS infrastructure to provide a common data plane (based on label switching) for both unicast and multicast traffic.

In the configuration examples in this section, multicast sources are attached to each of the MPLS Transport Gateways, MTG-1501 and MTG-1502, respectively, and AGN K1101 and AGN K1102 mark the end of aggregation/core to where the mLDP domain extends.

MTG-9006-K1501 (Root-node/Ingress-PE)

```
!***Advertise the network prefix where the Multicast source is located***
router bgp 1000
 bgp router-id 100.111.15.1
```

```
!***Advertising the IPv4 multicast source prefixes***
 address-family ipv4 unicast
  network 200.15.12.0/24 route-policy MSE_IGW_Community
  network 200.15.1.0/24 route-policy MSE_IGW_Community
!***Advertising the IPv6 multicast source prefixes***
  address-family ipv6 unicast
  network 2001:100:111:15::1/128
  network 2001:100:192:10::/64
  allocate-label all
!***Enable MLDP***
mpls ldp
 mldp
  logging notifications
!
 interface TenGigE0/0/0/0
 interface TenGigE0/0/0/1
 interface TenGigE0/0/0/2
 !***Disable mLDP on interfaces that don't need mLDP***
  mldp disable
!***Configure route-policy to set the type of MLDP core tree***
route-policy MLDP-Inband
  !***Set mLDP-Inband signaling***
  set core-tree mldp-inband
end-policy
!***Assign the configured MLDP route-policy under router PIM***
router pim
 address-family ipv4
  rpf topology route-policy MLDP-Inband
 !
 address-family ipv6
  rpf topology route-policy MLDP-Inband
 !
!
!***Configure Multicast-routing to enable Multicast interfaces, MDT source, and MLDP
in-band signaling ***
multicast-routing
 address-family ipv4
  mdt source Loopback0
  mdt mldp in-band-signaling ipv4
  rate-per-route
  !***Enable multicast on all interfaces***
  interface all enable
  accounting per-prefix
 !
 address-family ipv6
  mdt source Loopback0
  mdt mldp in-band-signaling ipv4
  rate-per-route
  !***Enable multicast on all interfaces***
  interface all enable
  accounting per-prefix
 !
!
```

Branch Node Configuration

The branch node configuration is illustrated here for larger deployments that may require multiple nodes between the edges of the MPLS transport network. It essentially shows that the only configuration needed is to enable MLDP on the node.

```
!*** In the BRANCH-node/P-routers, the only configuration needed is MLDP***
```

```
!***Enable MLDP***
mpls ldp
!***Enables mLDP***
 mldp
  logging notifications
  !***Needed for faster LSM convergence***
  make-before-break delay 0 0
 !
 interface TenGigE0/0/0/0
 interface TenGigE0/0/0/1
 interface TenGigE0/0/0/2
 interface TenGigE0/0/0/3
 interface GigabitEthernet0/2/0/0
 !***Disable mLDP on CN-RR interface***
  mldp disable
```

AGN-9006-K1102(Leaf-node/Egress-PE)

This node is a Cisco ASR 9000 Series router acting as the service edge (SE) node and used as the Leaf-node/Egress-PE of the Multicast distribution tree. The native IP Multicast (v4 & v6) coming from the access network terminates here, and then LSM MLDP-Global starts from this node towards the ROOT-node/Ingress-PE passing through the MPLS transport network.

```
 mpls ldp
 !***Enables mLDP***
 mldp
  logging notifications
 !
 interface TenGigE0/0/0/0
 interface TenGigE0/0/0/2
 interface TenGigE0/0/0/1
   mldp disable
 interface TenGigE0/0/0/3
 !***mLDP uses the LDP interfaces by default.***
 !***Disable mLDP on interfaces facing the Access Network***
   mldp disable
!***Configure route-policy to set the type of MLDP core tree***!
route-policy MLDP-Inband
!***Set mLDP-Inband signaling***
  set core-tree mldp-inband
!***Assign the configured MLDP route-policy under router PIM***
router pim
 address-family ipv4
  rpf topology route-policy MLDP-Inband
 !
 address-family ipv6
  rpf topology route-policy MLDP-Inband
 !
!***Configure Multicast-routing to enable Multicast interfaces, MDT source, and MLDP
in-band signaling***
multicast-routing
 address-family ipv4
  mdt source Loopback0
  mdt mldp in-band-signaling ipv4
  rate-per-route
  accounting per-prefix
  !***Enable multicast on all IPv4 interfaces***
  interface all enable
  accounting per-prefix
 !
 address-family ipv6
```

```
  mdt source Loopback0
  mdt mldp in-band-signaling ipv4
  rate-per-route
  accounting per-prefix
  !***Enable multicast on all IPv6 interfaces***
  interface all enable
  accounting per-prefix
 !
!***Enable IPv6 for ISIS at the SE node on access interface***
router isis core
!***Enables ISIS for IPv6 ***
    address-family ipv6 unicast
    metric-style wide
    ispf
    spf-interval maximum-wait 5000 initial-wait 50 secondary-wait 200
    !
    interface Loopback0
    passive
    point-to-point
    address-family ipv4 unicast
    !
     address-family ipv6 unicast
    !
    interface TenGigE0/0/0/1
    address-family ipv4 unicast
    metric 10
    mpls ldp sync
    !
!***Enables IPv6 for ISIS on the interface going towards access***
     address-family ipv6 unicast
        metric 10
!***Redistribute BGP IPv6 multicast source prefixes into ISISv6 Level 2***
 router isis core
    address-family ipv6 unicast
    metric-style wide
    ispf
    spf-interval maximum-wait 5000 initial-wait 50 secondary-wait 200
    !***redistributing BGP IPv6 multicast source address into ISIS level 2***
   redistribute bgp 1000 level-2
```

High Availability Implementation

This section focuses on the implementation details of high availability functionality at the service level. Transport level resiliency has been previously covered in Transport Network Implementation, page 7-1.

- For MPLS VPN services, BGP Edge protection and BGP FRR Edge protection mechanisms are supported, and VRRP is enabled on the MTGs for redundant connectivity to the data center infrastructure.
- For TDM pseudowire-based services, pseudowire redundancy is supported, and MR-APS is enabled for redundant connectivity to the TDM-connected headend equipment.

MPLS VPN-BGP FRR Edge Protection and VRRP

BGP FRR provides deterministic network reconvergence in the Connected Roadways System design. BGP FRR edge functionality is supported at the MPLS VPN service level. The following example illustrates how to configure BGP FRR edge from the MTG to the PAN across the MPLS Transport infrastructure.

Note The VRF configuration under the BGP process uses a unique route distinguisher (RD) per MTG. This unique RD configuration in each MTG, combined with the BGP and VRRP timer adjustments in MTG 1, enables the ability for the rest of the transport infrastructure to optimize MPLS VPN protection via BGP FRR. This RD does not have to match the route target defined for the MPLS VPN VRF. The need for this unique RD will be eliminated once support for BGP additional-paths received is implemented for BGP VPNv4 address-family configuration in IOS, thus allowing for multiple MTG information to be propagated for the MPLS VPN.

Mobile Transport Gateway 1

VRF Configuration

```
vrf VPN102
 address-family ipv4 unicast
  import route-target
   10:10
  !
  export route-target
   1001:1001
  !
 !
 address-family ipv6 unicast
  import route-target
   10:10
  !
  export route-target
   1001:1001
  !
 !
!
interface TenGigE0/0/0/2.1100
 vrf VPN102
 ipv4 address 115.1.102.3 255.255.255.0
 ipv6 address 2001:115:1:102::3/64
 encapsulation dot1q 1100
!
```

VRRP Configuration

```
router vrrp
 interface TenGigE0/0/0/2.1100
  delay minimum 1 reload 240
  address-family ipv4
   vrrp 110
    priority 254
    timer msec 100 force
    address 115.1.102.1
   !
  !
  address-family ipv6
   vrrp 110
    priority 254
    timer msec 100 force
    address global 2001:115:1:102::1
    address linklocal autoconfig
   !
  !
```

BGP FRR Edge Configuration

```
router bgp 1000
 address-family vpnv4 unicast
  additional-paths receive
  additional-paths send
  additional-paths selection route-policy add-path-to-ibgp
  !
 !
 vrf VPN102
  rd 1001:1001
  address-family ipv4 unicast
   redistribute connected
  !
  address-family ipv6 unicast
   redistribute connected
  !
 !
route-policy add-path-to-ibgp
 set path-selection backup 1 install
end-policy
```

Mobile Transport Gateway 2

VRF Configuration

```
vrf VPN102
 address-family ipv4 unicast
  import route-target
   10:10
  !
  export route-target
   1001:1001
  !
 !
 address-family ipv6 unicast
  import route-target
   10:10
  !
  export route-target
   1001:1001
  !
 !
!
interface TenGigE0/0/0/2.1100
 vrf VPN102
 ipv4 address 115.1.102.4 255.255.255.0
 ipv6 address 2001:115:1:102::4/64
 encapsulation dot1q 1100
!
```

VRRP Configuration

```
router vrrp
 interface TenGigE0/0/0/2.1100
  delay minimum 1 reload 240
  address-family ipv4
   vrrp 110
    priority 253
    timer msec 100 force
    address 115.1.102.1
```

```
    !
   !
   address-family ipv6
    vrrp 110
     priority 253
     timer msec 100 force
     address global 2001:115:1:102::1
     address linklocal autoconfig
    !
   !
  !
 !
```

BGP FRR Edge Configuration

```
router bgp 1000
 address-family vpnv4 unicast
  additional-paths receive
  additional-paths send
  additional-paths selection route-policy add-path-to-ibgp
  !
 !
 vrf VPN102
  rd 1001:1002
  address-family ipv4 unicast
   redistribute connected
  !
  address-family ipv6 unicast
   redistribute connected
  !
 !
route-policy add-path-to-ibgp
 set path-selection backup 1 install
end-policy
```

Core Route Reflector

```
router bgp 1000
 address-family vpnv4 unicast
  additional-paths receive
  additional-paths send
  additional-paths selection route-policy add-path-to-ibgp
 !
 address-family vpnv6 unicast
 !
!
route-policy add-path-to-ibgp
 set path-selection backup 1 advertise install
end-policy
```

Pre-Aggregation Node

```
router bgp 1000
 address-family vpnv4
  bgp additional-paths install
  !***Enable CEF recursion for BGP host routes***
  bgp recursion host
 !
 address-family vpnv6
  !***Enable CEF recursion for BGP host routes***
  bgp recursion host
```

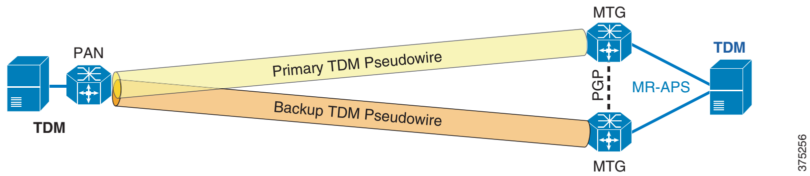
Pseudowire Redundancy for TDM Services

High availability for TDM services transported via CEoP PWs is achieved through PW redundancy over the transport network, where a backup PW pointing to an alternate MTG is configured for each primary PW. Corresponding to these redundant PWs is MR-APS functionality on the TDM side of the MTGs, which provides redundant TDM connectivity to the headend equipment.

TDM Services

Figure 7-12 and the example that follows illustrate TDM services.

Figure 7-12 CESoPSN/SAToP Service Implementation for TDM Backhaul



Pre-Aggregation Node Configuration

Note The only difference between CESoPSN and SAToP configuration is the lack of "control-word" in the pseudowire-class for SAToP configs.

```
pseudowire-class CESoPSN
 encapsulation mpls
 control-word
!
!
interface CEM0/0
 cem 0
  xconnect 100.111.15.1 13261501 encapsulation mpls pw-class CESoPSN
   backup peer 100.111.15.2 13261502 pw-class CESoPSN
!
interface Loopback0
 ip address 100.111.13.26 255.255.255.255
!
```

MPLS Transport Gateway 1 Configuration

```
aps group 1
 timers 10 15
 channel 0 remote 100.111.15.2
 channel 1 local SONET0/2/1/0
!
!
controller SONET0/2/1/0
 description To BSC
 ais-shut
 report lais
 report lrdi
 sts 1
  mode vt15-t1
  delay trigger 250
 !
```

```
 clock source line
!
controller T1 0/2/1/0/1/2/2
 cem-group framed 0 timeslots 1-24
 forward-alarm AIS
 forward-alarm RAI
!
interface Loopback0
 description Global Loopback
 ipv4 address 100.111.15.1 255.255.255.255
!
l2vpn
!
 pw-class CESoPSN
  encapsulation mpls
   control-word
  !
 !
 xconnect group TDM-K1326
  p2p T1-CESoPSN-01
   interface CEM0/2/1/0/1/2/2:0
   neighbor ipv4 100.111.13.26 pw-id 13261501
    pw-class CESoPSN
   !
  !
 !
!
```

MPLS Transport Gateway 2 Configuration

```
aps group 1
 revert 8
 timers 10 15
 channel 0 local SONET0/2/1/0
 channel 1 remote 100.111.15.1
 signaling sonet
!
!
controller SONET0/2/1/0
 description To ONS15454-K1410 OC3 port 4/1
 ais-shut
 report lais
 report lrdi
 sts 1
  mode vt15-t1
  delay trigger 250
 !
 clock source line
!
controller T1 0/2/1/0/1/1/3
 cem-group framed 0 timeslots 1-24
 forward-alarm AIS
 forward-alarm RAI
!
interface Loopback0
 description Global Loopback
 ipv4 address 100.111.15.2 255.255.255.255
!
l2vpn
!
 pw-class CESoPSN
  encapsulation mpls
   control-word
```

```
  !
 !
 xconnect group TDM-K1326
  p2p T1-CESoPSN-01
   interface CEM0/2/1/0/1/2/2:0
   neighbor ipv4 100.111.13.26 pw-id 13261502
    pw-class CESoPSN
   !
  !
 !
!
```

OAM Implementation

This section describes the implementation of Operations, Administration, and Maintenance (OAM) protocols and Performance Management (PM) protocols in the Connected Roadways System design. These mechanisms enable the system to monitor the health of the transport infrastructure and the services transported over that infrastructure, and to alert the network administrator to any issues that arise.

Service OAM Implementation for L3VPN

The OAM and PM functions are configured between the PAN and MTG to monitor the end-to-end network performance of L3VPN services across the MPLS transport network.

The following OAM and PM functions are enabled on the initiator and responder in each case:

- IP ping and traceroute operations for MPLS Transport monitoring
- VRF-aware IP ping operations for connectivity check for traffic within MPLS VPNs
- IP SLA responder enabled on responder only for both native IP/MPLS and MPLS VPN deployments
- IP SLA User Datagram Protocol (UDP) echo probes configured on initiator for round-trip time (RTT) measurement
- IP SLA UDP jitter probe configured on initiator for one-way latency, packet loss, and packet delay variation measurement

Service OAM Implementation for TDM Circuit Emulation

The OAM and PM functions are configured between the PAN and MTG to monitor the end-to-end network performance of TDM CES across the MPLS transport network.

The following OAM and PM functions are enabled on the initiator and responder in each case:

- MPLS pseudowire ping and traceroute operations for connectivity check for TDM PWs
- IP SLA responder enabled on responder for TDM PW deployments. Loopback address of node is used for IP SLA measurements.
- IP SLA UDP echo probes configured on initiator for round-trip time (RTT) measurement
- IP SLA UDP jitter probe configured on initiator for one-way latency, packet loss, and packet delay variation measurement

Transport OAM

The following OAM and PM functions between the PAN and MTG allow for monitoring the transport network health and performance.

- IP ping and traceroute operations for verifying the data plane against control plane and for isolating faults within the MPLS transport network between the PANs and the MTG
- MPLS LSP ping and traceroute operations for verifying the data plane against control plane and for isolating faults within the core/aggregation domain

IP SLA Configuration

IP SLA Responder Configuration on PAN

The PAN act as IP SLA responders for different measurement scenarios. Minimal configuration is required for enabling the responder function.

```
ip sla responder
```

MPLS Transport Gateway Initiator Configuration for IP SLA

The MTG is configured with IP SLA probes for initiating measurement of packet loss, packet delay, and packet delay variation (for example, jitter) towards the PAN.

Note The ToS values in IOS-XR are equal to four times the desired DSCP value.

VPN: Jitter Probes

```
ipsla
 operation 6
  type udp jitter
   vrf VPN102
   destination address 114.1.224.1
   packet count 100
   !***tos 184 = DSCP 46 (EF)***
   tos 184
   destination port 918
   frequency 30
  !
 !
 schedule operation 6
  start-time now
  life forever
 !
 !***Enabled IP SLA Responder***
 responder
 !
!
```

Reaction Configuration

The reaction configuration defines the thresholds for the previously configured probes, and it defines the corresponding actions to be taken when those thresholds are exceeded. The following configuration shows a single example of a jitter probe reaction and an echo probe reaction.

```
ipsla
 reaction operation 6
  react connection-loss
   action logging
   action trigger
   threshold type immediate
  !
  react jitter-average dest-to-source
   action logging
   action trigger
   threshold type immediate
   threshold lower-limit 10 upper-limit 15
  !
  react jitter-average source-to-dest
   action logging
   action trigger
   threshold type immediate
   threshold lower-limit 10 upper-limit 15
  !
  react packet-loss dest-to-source
   action logging
   action trigger
   threshold type immediate
   threshold lower-limit 3 upper-limit 5
  !
 !
!
```

CHAPTER 8

Summary

This CVD has defined and described in detail a system architecture for Connected Roadways as part of the Cisco Connected Transportation System (CTS) portfolio. It includes design and best practice recommendations for a scalable and resilient multiservice transport infrastructure for any size and scale of deployment.

The Connected Roadways System design is based on a proven architecture deployed by dozens of major service providers around the world: Unified MPLS Transport. This design addresses the requirements of both legacy and next-generation services in a converged, scalable, and operationally simplified design. It provides transport of any service to any location over any type of access, providing maximum flexibility. It eliminates the need for service-specific networks or protocols, optimizing both capital and operating expenditures for the network infrastructure.

Acronyms and Initialisms

Table A-1 lists the acronyms and initialisms used in this document.

Table A-1 Acronyms and Initialisms

Term	Definition
AF	Assured Forwarding
APTA	American Public Transportation Association
ATM	Asynchronous Transfer Mode
BE	Best Effort
BFD	Bidirectional Forwarding Detection
BGP	Border Gateway Protocol
CE	customer edge
CEoP	circuit emulation over packet
CES	Circuit Emulation Services
CESoPSN	Circuit Emulation Services over Packet Switched Networks
CN	Core Node
CoS	Class of Service
CoW	carbon dioxide
CTS	Connected Transportation System
DSCP	Differentiated Services Code Point
EAN	Ethernet access node
EF	Expedited Forwarding
EPN	Evolved Programmable Network
EXP	Experimental
FAN	Fixed Asset Node
FRR	Fast Reroute
GPS	Global Positioning System
H-QoS	Hierarchical Quality of Service
ICCP	Inter-Chassis Control Protocol
IGP	Interior Gateway Protocol

Table A-1 Acronyms and Initialisms (continued)

Term	Definition
IS-IS	Intermediate System to Intermediate System
L2VPN	Layer 2 Virtual Private Network
L3VPN	Layer 3 Virtual Private Network
LACP	Link Aggregation Control Protocol
LAN	Local Area Network
LDP	Label Distribution Protocol
LFA	Loop Free Alternate
LFIB	Label Forwarding Information Base
LSA	link-state advertisement
LSM	Label Switched Multicast
LSP	Label Switched Path
MC-LAG	Multi-Chassis Link Aggregation Group
MEF	Metro Ethernet Forum
mGRE	multicast Generic Route Encapsulation
mLACP	multi-chassis Link Aggregation Control Protocol
mLDP	multicast Label Distribution Protocol
MPLS	Multiprotocol Label Switching
MR-APS	Multirouter Automatic Protection Switching
MTG	MPLS Transport Gateway
NAT	Network Address Translation
NGN	Next Generation Network
NMS	Network Management System
NNI	network-to-network interface
OAM	Operations, Administration, and Maintenance
OSPF	Open Shortest Path First
PAN	Pre-Aggregation Node
PE	Provider Edge
PHB	Per Hop Behavior
PIC	Prefix-Independent Convergence
PIM	Protocol Independent Multicast
PoA	Point-of-Attachment
PTC	Positive Train Control
PWE3	Pseudowire Emulation Edge to Edge
QoS	Quality of Service
REP	Resilient Ethernet Protocol
rLFA	Remote Loop Free Alternate

Table A-1 Acronyms and Initialisms (continued)

Term	Definition
RR	Route Reflector
RT	Route Target
RTT	round-trip time
SAToP	Structure Agnostic Transport over Packet
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SONET	Synchronous Optical Networking
SPF	shortest-path first
STP	Spanning Tree Protocol
TCN	Topology Change Notification
TDM	time-division multiplexing
TE	Traffic Engineering
TLV	time-length-value
UDP	User Datagram Protocol
UNI	user network interface
VLAN	Virtual Local Area Network
VoIP	Voice over IP
VRF	Virtual Routing and Forwarding
vRR	virtual route reflector
VRRP	Virtual Router Redundancy Protocol