INFINERA

PACKET-OPTICAL
THE INFINERA WAY
OPTICAL FIBER PROVIDES almost lossless transmission of signals at an ultra-wide range of frequencies. Packet switching, implemented using the Ethernet family of protocols and interfaces, offers one of the most efficient ways to sort and direct streams of digital data. Packet-optical networking combines these two outstanding technologies, positioning them to dominate the next generation of transport networks.

Packet-Optical the Infinera Way was written to help Infinera’s customers, prospects and partners, and anyone else who needs to have a better understanding of the packet-optical world. This book focuses on the integration of higher Open Systems Interconnection (OSI) layer functionality into optical systems to create packet-optical transport systems (P-OTS), i.e. packet-optical networks. The term P-OTS is widely used within the industry and has been recycled from an earlier definition (plain old telephone service) to cover a wide range of solutions and networks with varying degrees of capabilities and functionality.

Packet-optical integration has some great advantages in terms of cost and service differentiation. Infinera’s technologies take this one step further, with benefits including reduced equipment, lower operational costs and key capabilities such as low latency and excellent synchronization, outlined in Chapter 2. Chapter 3 describes how packet-optical networks are best managed and how to take advantage of current and future software-defined networking (SDN) developments. Chapter 4 takes the reader further into how the described technologies are leveraged by various applications, such as business Ethernet, mobile fronthaul/backhaul and cable TV backhaul.

For those looking for a better understanding of Layer 2 Ethernet technologies, Chapter 5 includes a more detailed description of how these technologies work and how they are leveraged in wide area networks.

We hope you find Packet-Optical the Infinera Way informative and useful, whether you use it to research a particular subject or read the complete volume from beginning to end.

The descriptions are kept independent of product releases as much as possible. Current details of the Infinera product portfolio are available at www.infinera.com.

Features of Infinera’s packet-optical solutions that we believe to be unique are highlighted with this marker throughout the text.

The information included is subject to change without further notice. All statements, information and recommendations are believed to be accurate but are presented without warranty of any kind.
2.2.3 The Infinera Intelligent Packet-Optical Networking of the Network

Chapter Summary

The Cloud-driven Transformation

The Multi-layer Service Architecture and Terminology

Advantages of Packet-Optical Transport

Benefits of the Packet-Optical Approach

Advantages when Using Infinera’s Portfolio for Packet-Optical Transport

2.2.4 The DTN-X Packet-Switching Module (PXM)

2.2.5 One Common Infrastructure for Ethernet and Legacy TDM Services

2.2.1 The Main Elements of an Infinera Packet-Optical Network

2.2.2 Ethernet Demarcation Units (EDU) and Network Interface Devices (NIDs)

2.2.3 Optical Add-Drop Multiplexers (OADM, ROADM) and Other Optical Elements

2.2.4 Optical Transport Switches (ETMX) and the PT-Fabric

2.2.5 Packet-Optical Transport with the XTM Series

2.2.6 Leveraging the XTM Series and PXM in the Same Network

2.3 MPLS-TP for Traffic Engineering and Service Scalability

2.4 Traffic Management

2.4.1 Traffic Shaping and Policing

2.4.2 Implementing Traffic Shaping

2.5 Managing Legacy TDM Services to Ethernet

2.5.1 One Common Infrastructure for Ethernet and Legacy TDM Services

2.5.2 Using the SFP to Convert TDM Services for Ethernet Transport

2.5.3 The Multi-layer Service Management System

2.6.1 Using the SFP to Convert TDM Services for Ethernet Transport

2.6.2 The Main Elements of an Infinera Packet-Optical Network

2.6.3 Ethernet Demarcation Units (EDU) and Network Interface Devices (NIDs)

2.6.4 Optical Add-Drop Multiplexers (OADM, ROADM) and Other Optical Elements

2.6.5 The DTN-X Packet-Switching Module (PXM)

2.6.6 The Multi-layer Service Management System

2.6.7 Advantages of Packet-Optical Transport

3 OPERATING THE NETWORK

3.1 Chapter Summary

3.2 Multi-layer Network Management

3.2.1 Management Framework

3.2.2 Infinera’s Management Software Suite

3.2.3 Infinera Digital Network Platform

3.2.4 A Unified Information Model for Multi-layer Management

3.2.5 Layer 2 Service Fulfillment

3.2.6 Layer 2 Service Assurance

3.2.7 Network Planning and Optimization

3.3 Software-defined Networking and Network Virtualization

3.3.1 Basic Concepts

3.3.2 Infinera’s Multi-layer SDN Vision

4 APPLICATIONS OF PACKET-OPTICAL NETWORKING

4.1 Chapter Summary

4.2 Ethernet Services for Enterprises – Business Ethernet

4.2.1 Serving Enterprise Customers

4.2.2 A Metro Network for Business Ethernet

4.2.3 A Long-haul Network for Business Ethernet

4.2.4 Aggregation of IPv Traffic – IP Backbone

4.3 IP-based Services over a Common Infrastructure

4.3.1 Layer 2 Service Fulfillment

4.3.2 Layer 2 Service Assurance

4.3.3 Network Planning and Optimization

4.4 Mobile Backhaul

4.4.1 4G/LTE and 5G Place New Requirements on Mobile Backhaul

4.4.2 A Backhaul Network Optimized for 4G/LTE and 5G

4.5 Switched Video Transport

4.5.1 Streaming 3D and HD Video to the Home

4.5.2 Infinera’s Solution for Switched Video Transport

5 ETHERNET AND LAYER 2 TECHNOLOGIES

5.1 Chapter Summary

5.2 Ethernet Basics

5.2.1 Ethernet Mode of Operation

5.2.2 Virtual LAN

5.2.3 Ethernet Physical Media (PHY)

5.3 Carrier Ethernet: Ethernet as a Transport Technology

5.3.1 Synchronization and Circuit Emulation Services over Ethernet

5.3.2 Synchronization and Asynchronous Transport

5.4 Ethernet Protection

5.4.1 Link Aggregation

5.4.2 Ethernet Ring Protection Switching

5.5 Carrier Ethernet Architecture and Services

INDEX

5.5.1 Carrier Ethernet: Ethernet as a Transport Service

5.5.2 The Carrier Ethernet Architecture and Terminology

5.5.3 Carrier Ethernet 2.0 Services

5.5.4 Carrier Ethernet Service Attributes

5.6 Class of Service and Service Level Agreements

5.7 Carrier Ethernet Operations, Administration and Maintenance (Ethernet OAM)

5.8 Carrier Ethernet OAM – Performance and Fault Management

5.9 Metro Ethernet Forum "Third Network" Vision

4.4.3 MPLS-TP for Traffic Engineering and Service Scalability

4.4.4 Traffic Management

4.4.5 Traffic Shaping and Policing

4.4.6 Implementing Traffic Shaping

4.4.7 Managing Legacy TDM Services to Ethernet

4.4.8 MPLS-TP (Ethernet OAM)

4.4.9 Time Stamp

4.4.10 Class of Service and Bandwidth Policy

4.4.11 Synchronization and Circuit Emulation Services over Ethernet

4.4.12 Synchronization and Asynchronous Transport

4.4.13 Ethernet Protection

4.4.14 Link Aggregation

4.4.15 Ethernet Ring Protection Switching

4.4.16 Carrier Ethernet Architecture and Services

4.4.17 Carrier Ethernet: Ethernet as a Transport Service

4.4.18 The Carrier Ethernet Architecture and Terminology

4.4.19 Carrier Ethernet 2.0 Services

4.4.20 Carrier Ethernet Service Attributes

4.4.21 Class of Service and Service Level Agreements

4.4.22 Carrier Ethernet Operations, Administration and Maintenance (Ethernet OAM)

4.4.23 The Carrier Ethernet Management Framework

4.4.24 Carrier Ethernet Operations, Administration and Management (Ethernet OAM)

4.4.25 Synchronization and Circuit Emulation Services over Ethernet

4.4.26 Synchronization and Asynchronous Transport

4.4.27 Ethernet Protection

4.4.28 Link Aggregation

4.4.29 Ethernet Ring Protection Switching

4.4.30 Carrier Ethernet Architecture and Services

4.4.31 Carrier Ethernet: Ethernet as a Transport Service

5.5.2 The Carrier Ethernet Architecture and Terminology

5.5.3 Carrier Ethernet 2.0 Services

5.5.4 Carrier Ethernet Service Attributes

5.6 Class of Service and Service Level Agreements

5.7 Carrier Ethernet Operations, Administration and Maintenance (Ethernet OAM)

5.8 Carrier Ethernet OAM – Performance and Fault Management

5.9 Metro Ethernet Forum "Third Network" Vision

INDEX
1 INTRODUCTION
over the past decade, IT infrastructure has undergone a profound transformation, as cloud services, consisting of Layer C, cloud services, and Layer T, intelligent transport (Figure 1).

The control plane of Layer T can use reconfigurable optical add-drop multiplexer (ROADM) functionality. Flexibility of reconfigurable optical add-drop multiplexing (WDM) and the optical path and multiplexing (MPLS) and Ethernet packet switching. They have varying degrees of burstiness and deterministic nature. As a consequence, flows can be handled by several technologies across the multi-layered Layer T network, including optical wavelengths, digital OTN circuits, MPLS label-switched paths (LSPs) and Ethernet virtual connections (Figure 2). To optimize the cost-to-performance ratio of Layer T, it is of the utmost importance to match the transport and switching technology to the traffic flow characteristics, and ultimately to the end-user services. Also, these technologies are not necessarily exclusive.

For example, Ethernet/MPLS packets may be carried in digital OTN circuits, which in turn are carried by coherent optical super-channels as Layer T services are aggregated. Meanwhile, switching capabilities are essential at each of the layers in order to maintain the efficient use of capacity and provide alternative routing for traffic engineering or protection events.

The choice of technologies to employ within Layer T also has a geographical and procedural aspect, splitting the industry into distinct sub-segments: metro/edge packet-optical systems and long-haul/core packet-optical systems.

TCP and OTN, but must also offer excellent support for Layer 2 Ethernet functionality. This functionality includes the advanced provisioning, management, verification and protection of Layer 2 Ethernet services using a defined group of standardized protocols and procedures.

Systems at the core of a network are dealing with traffic from many applications, and as such require less service awareness. However, they do require the capacity to handle higher-capacity links, as well as a
higher degree of OTN Layer 1 transport capabilities versus Layer 2 Ethernet. This geographical balance between Layer 1 and Layer 2 functionality is shown in Figure 3.

Long-haul/core packet-optical systems must therefore support not only high capacity but also switching across the whole chassis or node, from any port to any other port, rather than just within ports on a single plug-in unit as is common in metro/edge platforms.

In the long-haul/core market, the DTN-X Family provides the world’s only commercial multi-terabit super-channel system based on large-scale photonic integrated circuit (PIC) technology. It includes the Packet Switching Module (PXM), which enables traffic over virtual local area networks (VLANs) or MPLS LSPs with assured quality of service (QoS).

1.3 THE INFINERA INTELLIGENT TRANSPORT NETWORK PORTFOLIO

Infinera’s end-to-end portfolio for packet-optical networks consists of the platforms shown in Figure 4.

In the metro/edge space, Infinera is a pioneer of metro WDM through the XTM Series, which today includes leading packet-optical metro access, aggregation and core platforms. This platform delivers services designed for applications such as triple play broadband, cable broadband, Ethernet and mobile transport.

In long-haul/core packet-optical networks, the DTN-X family is a powerful companion to the XTM Series.
2 PACKET-OPTICAL NETWORKING
2.1 CHAPTER SUMMARY

Optical fiber provides almost lossless transmission of signals at an ultra-wide range of frequencies. Packet switching, implemented according to the Ethernet family of protocols and interfaces, offers one of the most efficient ways ever to sort and direct streams of digital data. Packet-optical networking fundamentally leverages the outstanding characteristics of these two technologies to implement a new generation of telecommunication networks.

The scalability and cost-effectiveness of Ethernet has made it the unifying service protocol for modern local and wide area networking. Increasingly, consolidation of the optical and Ethernet/Internet Protocol (IP) transport infrastructures within the same network elements has become the means to drive down both network investment costs and the associated operational costs. The additional support for OTN- and label-switching mechanisms (such as Multiprotocol Label Switching—Transport Profile, or MPLS-TP) provides two technologies, including how traffic is transported with minimal delay and without loss of synchronization.

2.2 THE PRINCIPLES OF PACKET-OPTICAL INTEGRATION

2.2.1 Why Aggregate Traffic at Layer 2?

The introduction of aggregation at Layer 2, i.e., the Ethernet layer, brings several benefits to network operators. Traditionally, metro aggregation networks were implemented using dedicated WDM equipment that provided wavelengths, for example, BRAS, radio base stations, and enterprise networks to more central locations. The traffic from the connected equipment was transported transparently to an IP core network at OSI Layer 1, via wavelengths on fibers in ring or star topologies. As the number of endpoints grew, the central IP core network had to be extended, requiring more IP routers at more sites and more ports, as indicated on the left side of Figure 5.

In this type of network, there are several reasons to introduce Layer 2 aggregation. The IP core network can be reduced in size to just a few central routers instead of being spread out throughout a full metro network area. Layer 2 aggregation equipment is generally less costly, consumes less power, has lower latency and requires less expertise to configure than IP routers. Thus, centralization of the IP core network reduces the necessary investment and operational costs.

Layer 2 aggregation can perform statistical multiplexing of data traffic, and the WDM channels of the underlying optical network can be used much more efficiently than if only Layer 1 aggregation is employed. Statistical multiplexing allows the bandwidth to be shared among multiple users of varying data rates, in contrast to Layer 1 aggregation (time or frequency multiplexing), where the number of users and their data rates are fixed. Statistical multiplexing makes use of the fact that the information rate from each source varies over time and that the optical path’s bandwidth only needs to be consumed when there is real information to send.

Since data traffic is concentrated at Layer 2 in the aggregation network, it can be handed over to IP core routers via a few high-speed interfaces rather than over many lower-speed interfaces. This simplifies administration and contributes to a lower cost per handled bit. As an additional benefit, the aggregation network itself can be used to offer services within the metro/regional area. For example, point-to-point Ethernet connections can be provided between offices in a city center without loading any central router nodes. Such direct connectivity provides more rational traffic handling and reduces forwarding delay compared to using IP routers.

2.2.2 Ethernet Transport at Layer 2 Versus at Layer 1

Given the benefits of a Layer 2 aggregation network, it is important to understand how this type of network differs from a traditional network performing Layer 1 aggregation of Ethernet traffic over WDM.
Transporting Ethernet traffic between two remote sites with WDM as the underlying bearer technology can be done in two fundamentally different ways:

- Transporting the Ethernet frames “as they are” (transparently) over a WDM channel, i.e. Layer 1 (optical) transport.
- Using an intermediate Carrier Ethernet network that in turn has its frames transported over one or more WDM channels, i.e. using Layer 2 (Carrier Ethernet) transport. This is the technology used in a Layer 2 aggregation network. Both alternatives have advantages and disadvantages.

A basic Layer 1 transport solution takes every incoming frame from the sending subscriber Ethernet network and puts it into a digital wrapper adapted for transmission over the WDM channel. At the receiving end, the wrapper is removed and the original frame is handed over to the receiving Ethernet network. In this way, every single frame is forwarded without modification between the two subscriber networks.

The Layer 1 transport solution provides a transparent path between the two subscriber networks, giving the highest possible QoS in terms of latency, latency variation and packet loss. A Layer 1 network is also fully deterministic and latency variation and packet loss are totally transparent to Ethernet traffic. However, since a Layer 1 network is used in a Layer 2 aggregation network, every single frame is forwarded without any need for demultiplexing or a beneficial impact on the cost of that equipment.

In a Layer 2 transport solution, the incoming subscriber Ethernet frames are analyzed and acted upon by the equipment located at the ingress point of the Carrier Ethernet network before being forwarded. It is possible to concentrate the incoming flow of Ethernet traffic to the same subscriber Ethernet frames are analyzed and acted upon by the equipment located at the ingress point of the Carrier Ethernet network before being forwarded. It is possible to concentrate the incoming flow of Ethernet traffic to the same subscriber. The frames of the Carrier Ethernet SVLAN/pseudowire are transported over channels of the WDM network, just as described previously.

A Layer 1 transport solution cannot concentrate the Ethernet traffic being transported, which may result in low utilization of WDM wavelengths. For example, a Layer 1 network collecting Gigabit Ethernet signals that is utilized to transport Gigabit Ethernet traffic may offer much more flexibility, such as 25 megabits per second (Mb/s), 200 Mb/s or 400 Mb/s transport services over a physical 1 Gb/s port. Due to statistical multiplexing, a Layer 2 transport network solution is intrinsically less deterministic than a Layer 1 solution. The throughput of a Layer 2 network may suddenly change because a new service has been introduced or because the traffic situation has changed. However, the Layer 2 network can be made to behave in a deterministic way by the use of pre-defined capacity reservations, i.e. by the use of traffic engineering.

The table on the following page summarizes some of the main differences between Layer 1 and Layer 2 wide area Ethernet transport.

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
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<tbody>
<tr>
<td>Transporting Ethernet frames transparently over a WDM channel (Figure 7)</td>
<td>Transporting Ethernet frames via a Service VLAN in a Carrier Ethernet Network extending between operator sites (Figure 8)</td>
</tr>
<tr>
<td>Provides 100% throughput regardless of what services are carried by the Ethernet network. A service VLAN (SVLAN) or an MPLS-TP pseudowire in the Carrier Ethernet network is used to keep traffic from different sets of subscriber Ethernet networks separated, i.e. the SVLAN/pseudowire establishes connectivity between the subscriber Ethernet networks belonging to the same subscriber. The frames of the Carrier Ethernet SVLAN/pseudowire are transported over channels of the WDM network, just as described previously.</td>
<td>Provides services at standard Ethernet line rates, such as 1 Gb/s or 10 Gb/s, a Layer 2 network may offer much more flexibility, such as 25 megabits per second (Mb/s), 200 Mb/s or 400 Mb/s transport services over a physical 1 Gb/s port. Due to statistical multiplexing, a Layer 2 transport network solution is intrinsically less deterministic than a Layer 1 solution. The throughput of a Layer 2 network may suddenly change because a new service has been introduced or because the traffic situation has changed. However, the Layer 2 network can be made to behave in a deterministic way by the use of pre-defined capacity reservations, i.e. by the use of traffic engineering.</td>
</tr>
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</table>
Layer 1: Ethernet Transport

Packet-Optical Networking

Layer 2: Ethernet Transport

Layer 1: Ethernet Transport

TDM multiplexing. Collects and delivers traffic without changing its format and data rate. Statistical multiplexing. Collects traffic at one data rate and can deliver input from many sources over one single physical interface at a higher rate.

Layer 2: Ethernet Transport

Layer 1 performance management based on bit errors (cyclic redundancy check or CRC).

Layer 1: Ethernet Transport

Layer 2 Ethernet Transport according to the Metro Ethernet Forum’s (MEF) Carrier Ethernet 2.0 (CE 2.0) specifications, i.e. protocols that provide aggregation and concentration of Ethernet and other traffic over a selected set of Layer 2 functions that support the transport task. Such functions include, for example, the Institute of Electrical and Electronics Engineers (IEEE) 802.3ad Ethernet Link Aggregation, traffic shaping, policing and bandwidth allocations with guaranteed bandwidth allocation. The XTM Series’ Layer 2 network elements – the EMXP packet-optical transport switches – are also Layer 1-aware, meaning that they can be connected directly to a WDM link and support features such as forward error correction (FEC) at the optical layer. All the traffic units mentioned above are part of the plug-in type and can be installed side by side with optical units such as ROADMs in the XTM Series platform’s different chassis options. As an example, Layer 2-capable EMXPs can be used at the edge of the network to collect and aggregate Ethernet traffic and hand it over to Layer 1 transponders or muxponders that provide continued transport with cost-efficiency and a high quality of service (Figure 10). The XTM Series provides the operator with three primary alternatives for transport of Ethernet traffic:

- **Plain Layer 1 transport**, i.e. transponders and muxponders that provide 100% transparent Ethernet transport at OSI Layer 1.
- **Layer 2 transport** using the PXM, a DTN-X network’s supports Ethernet aggregation, switching and CE 2.0 services over an OTN core, as described in section 2.2.5.
- **Full Layer 1 and Layer 2 Wide Area Ethernet Transport**

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Using the PXM, a DTN-X network’s supports Ethernet aggregation, switching and CE 2.0 services over an OTN core, as described in section 2.2.5.
optical channel data unit (ODU), which is carried within an optical channel transport unit (OTU), defining the line rate of the connection (Figure 11). OTN includes OTU standards for a fixed unit (OTU), defining the line rate of the connection (Figure 11). OTN includes OTU standards for a fixed number of line rates covering the range from 2.6 Gb/s up to 112 Gb/s. These number of line rates has been selected based on the overall requirements of the optical transport system, but are not necessarily multiples of the bitrates of the signals to transport, e.g. Gigabit Ethernet (GbE). The consequence is that optical channels may be underutilized if an efficient multiplexing scheme is not used at the ODU level. Three ODU multiplexing schemes important in a packet-optical transport can be realized. This becomes especially important at the edge of the network that optical channels are transported as is, i.e. sequence as on an ordinary LAN when using the same preamble and end-of-frame control information, i.e. to perform statistical multiplexing and differentiation of services at the Ethernet level. Optimal Ethernet means that no additional framing is applied to the data payload at the edge of the network. By treating the Ethernet packets natively, it is possible to inspect them within the intermediate network nodes and to act upon the Ethernet headers so that the combined benefits of Layer 2-intelligence and efficient Layer 1 transport can be realized. This becomes especially important at the edge of the network extends over longer distances, since it allows each intermediate node to inspect them within the intermediate network nodes and to act upon the Ethernet headers so that the combined benefits of Layer 2-intelligence and efficient Layer 1 transport can be realized. This becomes especially important at the edge of the network.

Network Ethernet: The frames of the Carrier Ethernet network are carried over a WDM wavelength by ODUs according to the OTN standard. This encapsulation is especially favorable when the Carrier Ethernet network extends over longer distances, or the data to be transported is via an intermediate core OTN network. Using ODU2 framing between EMXPs allows the use of OTN’s inherent FEC mechanisms and optical path monitoring bits, which are important for long-haul links. Since the encapsulation is in ODU format, these data units can also easily traverse any intermediate OTN switches transparently before reaching their final destination (Figure 13). Since the encapsulation is in ODU format, these data units can also easily traverse any intermediate OTN switches transparently before reaching their final destination (Figure 13).

2.2.4 Packet-Optical Transport with the XTM Series The XTM Series supports two types of encapsulation of Carrier Ethernet traffic for WDM transport:• Native Ethernet: The frames of the Carrier Ethernet network are transported as is, i.e. sequence as on an ordinary LAN when using the same preamble and end-of-frame control information, i.e. to perform statistical multiplexing and differentiation of services at the Ethernet level. • Framing according to the OTN standard: The frames of the Carrier Ethernet network are carried over a WDM wavelength by ODUs according to the OTN standard. This encapsulation is especially favorable when the Carrier Ethernet network extends over longer distances, or the data to be transported is via an intermediate core OTN network. Using ODU2 framing between EMXPs allows the use of OTN’s inherent FEC mechanisms and optical path monitoring bits, which are important for long-haul links. Since the encapsulation is in ODU format, these data units can also easily traverse any intermediate OTN switches transparently before reaching their final destination (Figure 13).
network where decisions about traffic prioritization are made and where traffic is aggregated to “fill the pipes.” The wrapping of traffic into full OTN can then be done at the handover to the core network, after aggregated pipes of traffic that are correctly shaped have been created, avoiding wasted bandwidth.

Native Ethernet uses the VLAN tag or MPLS label to switch the frames to ports associated with either IP services or transport services. It is very useful once the traffic has been aggregated as much as possible to ensure the best utilization of the 10 Gb/s circuit. Figure 15 contrasts the differing characteristics of native Ethernet and OTN framing.

Figure 15: Native Ethernet and OTN Framing

An OTN container not only provides a unified transport layer where core nodes combine traffic from OTN muxponder-based Layer 1 services with EMPP-based, ODU-framed Ethernet services. End-to-end performance monitoring is achievable even over multiple operator’s networks through OTN with tandem connection monitoring and Carrier Ethernet’s enhanced operations, administration and maintenance (OAM) capabilities.

For example, frames containing data for high-value and high-quality IP services such as IP/MPLS, Ethernet’s inherent operations, administration, and maintenance (OAM) capabilities. The 2.2.5 Packet-Optical Transport with the PXM

The DTN-X Family of platforms performs integrated WDM transport and OTN switching, grooming and service protection at Layer 1, based on large-scale PIC technology. Using the PXM, the DTN-X Family can map Ethernet VLANs to ODUflex subnetwork connections, which enables ODUflex-based traffic engineering in long-haul networks. With the introduction of the PXM, the DTN-X Family supports statistical multiplexing for Ethernet frames, and can range from 1.25 Gb/s to 100 Gb/s, allowing for right-sized transport and maximum bandwidth efficiency (Figure 16).

The PXM maps incoming streams of data packets, such as Ethernet VLANs, into flows that can be co-routed through the network with other flows that have the same destination. The packet flows with the same destination are grommed into a single ODUflex container for efficient routing. ODUflex containers are built as necessary for packet streams mapped to standard ODUflex containers allow for multiplexing with other types of ODU containers and for switching the flows as appropriate at the optical layer using the DTN-X OTN Switch Module (OXM). Hence, it becomes possible to apply standard Layer 1 traffic engineering and protection to flows of Ethernet packets as well.

For instance, the PXM can provide multiple services or flows on one physical port and fiber connection per service. The PXM supports port consolidation, which can range from 1.25 Gb/s to 100 Gb/s, allowing for right-sized transport and maximum bandwidth efficiency (Figure 16).
Mapping the Ethernet traffic to the ODU can be done in various ways, for example by carrying the Ethernet VLANs in MPLS-TP pseudowires (PWs), creating additional options for traffic engineering and protection (Figures 17 and 18).8

2.2.6 Leveraging the XTM Series and PXM in the Same Network

The XTM Series, with its advanced handling of Ethernet services, can seamlessly interwork with the PXM and its super-channel-based transport of Ethernet traffic mapped to ODU containers. Deploying a high-capacity OTN core based on the DTN-X Family with PXM allows for the interconnection of multiple metro networks into one intelligent packet transport infrastructure, as depicted in Figure 19. In this infrastructure, end-to-end Ethernet services, such as those defined by Metro Ethernet Forum for CE 2.0, can be offered to users in one or more geographical regions.

As shown by the dotted lines in Figure 19, packet services may span one or more metro networks, have their endpoints in an EMXP or be delivered directly to, for example, a service router from a node in the core network via the PXM in the DTN-X.

The flexible architecture of the packet transport network allows for cost-efficient aggregation of all types of packet-based traffic. Service routers can be consolidated to a few central sites and equipped with high-speed interfaces, thereby reducing overall network investment and operational costs. The packet services offered adhere to recognized Metro Ethernet Forum standards and can be managed according to well-established OAM procedures defined for Carrier Ethernet. Layer 1 protection schemes can be applied in the core network segment, while additional Layer 2 protection schemes, such as MPLS-TP switching and G.8032v2 Ethernet Ring Protection Switching (ERPS), can be applied when services are delivered via EMXPs.

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In summary: In the access and aggregation part of the transport network, where service granularity is required, a service-aware packet-optical mechanism is beneficial to support different QoS. Also, access to Ethernet OAM bytes and service tags enables end-to-end management of Ethernet services. Using native Ethernet framing offers benefits from revenue-generation, investment and operational perspectives in the access and aggregation parts of the network. On the other hand, OTN has all the benefits of a long-haul optical transport network once the traffic has been sufficiently aggregated and traverses the core part of the network. Combining these two framing schemes within one intelligent packet-optical transport architecture makes it possible to exploit the benefits of both technologies in a common infrastructure for service creation.

2.3 MPLS-TP FOR TRAFFIC ENGINEERING AND SERVICE SCALABILITY

While Carrier Ethernet networks and the use of service VLANs bring great advantages to the packet-optical network, there are some limitations in terms of protection options, traffic engineering and service scalability.

These can be addressed by the use of MPLS-TP, which is the transport profile of multi-protocol label switching. MPLS-TP is a way to simplify Carrier Ethernet services by pre-defining connection-oriented services over packet-based networking technologies in a way that gives support for traditional transport operational models. It takes the advantages of MPLS concepts by adding more flexibility and network manageability than the basic Ethernet VLAN architecture (Figure 20).

Principles of MPLS-TP

MPLS is a technique that forwards packets based on labels, as opposed to a standard Carrier Ethernet network where the frames are switched based on their SVLAN tags and media access control (MAC) addresses. A label-switched path is defined between nodes where traffic enters and leaves the MPLS-TP network. Using MPLS-TP terminology, the entry and exit nodes are referred to as MPLS-TP provider edge (PE) nodes, and any intermediate nodes being passed by the LSP are referred to as MPLS-TP provider (P) nodes. Often the physical node performing the PE function is called a label edge router (LER) and the intermediate core node is called a label switching router (LSR). The LSPs may carry one or more pseudowires, i.e. the pseudowires offer a mean for multiplexing of traffic (Figure 23).

Both the tunnel and the LSP can be envisaged as predefined circuits for information to follow through the network, and consequently tunnels and LSPs are configured in advance from the network management system. A key feature of MPLS-TP that distinguishes it from classic IP/MPLS is that management and protection are deeply integrated to operate without a dynamic control plane, i.e. similar to a traditional SDH/SONET network, where circuits are set up by the management system.

The actual data traffic is carried by a pseudowire inside the LSP/Tunnel. One MPLS-TP LSP may carry one or more pseudowires, i.e. the pseudowires offer a mean for multiplexing of traffic (Figure 23).
Both Ethernet SVLAN and MPLS-TP forwarding techniques have their own benefits, and it is often advantageous to be able to offer services based on both technologies. For example, multicast services can often be deployed directly over SVLANs on Ethernet, whereas point-to-point trunks requiring protection can benefit more from the MPLS-TP features. However, MPLS-TP pseudowires can also be used for multi-point communication using VPLS, which allows geographically dispersed sites to share an Ethernet broadcast domain by connecting sites through pseudowires.

MPLS-TP is fully supported by the EMXP. Any router port on an EMXP can support both native Ethernet and MPLS-TP, allowing operators to deploy MPLS-TP where and when it makes sense for them. It is possible to run MPLS selectively per port or to separate MPLS traffic based on MAC address and VLANs within the same port. This allows seamless migration and coexistence with the two protocols running independently side by side.

Services can be extended over OTN-X-based networks through the PMD, which supports MPLS-TP and VLAN over ODUflex in an OTN core network. In order to deploy MPLS-TP in a production network, it can be introduced either as an overlay to the existing Ethernet or incrementally as an evolutionary build-out in parallel on the same networking hardware. Infinitra believes in a smooth evolution, parallel on the same networking hardware, incrementally as an evolutionary build-out in parallel on the same networking hardware. Infinera’s MPLS-TP pseudowires allow network operators to design network resilience strategies that are closely aligned to the physical structure of the network, ensuring the best possible resilience and service uptime.

MPLS-TP—Easy Service Creation

Another advantage of MPLS-TP is that it breaks service creation into two steps. First, tunnels are created between endpoints within the network for service and protection paths for MPLS-TP-based services. Then, the network administrator simply creates new services by adding them to the tunnel endpoints as pseudowires, safe in the knowledge that all routing aspects of the service have already been handled. This brings two distinct advantages. First, it makes the solution more scalable, as it is simpler to add a large number of services to the network. Second, it brings a very familiar look and feel to service creation as it is similar to the processes involved in traditional transport networks. This helps operators migrate from traditional transport networks to packet-optical networks.

MPLS-TP Resolves the MAC Scalability Problem

In an SVLAN-based Carrier Ethernet network, all MAC addresses in the attached subscriber Ethernet networks are visible to every switch within the Carrier Ethernet network. Since each subscriber network may include an extensive number of devices and MAC addresses, this results in a need for large MAC address tables in each network node, creating various problems and extra equipment cost. Using MPLS-TP, the subscriber MAC addresses are encapsulated within the pseudowire payload and not seen by the intermediate switches of the Carrier Ethernet network.
These switches do not have to be designed with the number of subscriber Ethernet MAC addresses in mind.

MPLS-TP Allows for a Virtually Unlimited Number of Customers

The IEEE 802.1Q standard allows for a maximum of 4094 SVLANs in a Carrier Ethernet network, with one SVLAN typically required per subscribing customer. Since MPLS-TP uses tunnels and label-switched paths to define the connectivity within the network, there is no such upper limit for the number of subscribers that can be handled by a network using MPLS-TP.

Layer 2 networks rely on packet switching and statistical multiplexing when forwarding information. Statistical multiplexing implies that the ports of the network can be allocated more “bandwidth” than is totally available, so a Layer 2 packet-optical network must have an inherent mechanism to control the amount of information entering the network and passing over network links. These procedures are collectively referred to as traffic management, and the two most important such tools are traffic shaping and policing.

Traffic shaping is typically done per port, interface or other physical entity, while policing can be applied more granularly and per Ethernet service, VLAN, etc. As shown in Figure 27, policing plays an important role in traffic management of Carrier Ethernet services and their individual SLAs, as described in section 5.6. Traffic shaping is done by imposing an additional delay on some packets such that the traffic conforms to a given bandwidth profile. Traffic shaping provides a means to control the volume of traffic being sent out on an interface in a specified period (bandwidth throttling), and the maximum rate at which the traffic is sent (rate limiting).

A drawback with traffic shaping is increased latency and jitter for the Ethernet Virtual Connection (EVC), but the gain can be better throughout since the overall flow of frames may be improved: instead of dropping traffic in a policer, it may be better to shape the traffic to make sure no frames are lost (or at least as few as possible), avoiding retransmissions at higher protocol layers.

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When a network element is congested, it starts to drop frames if there is no buffer left to allocate. Weighted random early detection (WRED) is a way for a network element to ask clients to request fewer resources from the network. However, WRED only acts on traffic that is transported by the TCP/IP protocol that ensures correct detection of data re-sent. With WRED, different discard profiles can be set for different CoS. The queues are emptied by a scheduler that can operate in different modes, e.g. strict priority or round robin. While a frame is waiting to be scheduled or transmission out on the line, it is buffered in the element, and if there is no buffer left the frame is dropped (Figure 28).

### 2.4.1 Traffic Shaping and Policing

Traffic shaping is a traffic management technique that delays some frames in a packet-optical network node in order to bring them into compliance with a desired traffic profile. Traffic shaping is a form of rate limiting, as opposed to the policing of excess frames. Traffic shaping is typically done per port, interface or other physical entity, while policing can be applied more granularly and per Ethernet service, VLAN, etc. As shown in Figure 27, policing plays an important role in traffic management of Carrier Ethernet services and their individual SLAs, as described in section 5.6. Traffic shaping is done by imposing an additional delay on some packets such that the traffic conforms to a given bandwidth profile. Traffic shaping provides a means to control the volume of traffic being sent out on an interface in a specified period (bandwidth throttling), and the maximum rate at which the traffic is sent (rate limiting).

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2.5 MIGRATING LEGACY TDM SERVICES TO ETHERNET

2.5.1 One Common Infrastructure for Ethernet and Legacy TDM Services

Transmission systems based on Layer 1 TDM technology, such as SDH and SONET, have been the backbone for many telecommunication services offered during the last few decades. However, from a bandwidth perspective, Ethernet traffic has already surpassed the amount of legacy TDM traffic. Operators are faced with the challenging task of maintaining existing TDM services while upgrading network infrastructures for new Ethernet services, all in the most cost-efficient way. More capacity is required to cater to the growing amount of packet-mode traffic generated by Internet access, video on demand, and cloud computing, while the shrinking amount of TDM traffic must be taken care of to sustain revenues from existing services. Building a separate new infrastructure for Ethernet traffic while maintaining a large SDH/SONET network is one option, but an integrated approach where the new packet-mode infrastructure also provides legacy TDM services is an attractive alternative (Figure 29).

Many legacy TDM services can be replaced by Ethernet equivalents and are well-suited for the packet-optical infrastructure described in the previous sections. However, there is a significant portion of traffic that cannot simply be migrated to Ethernet. This fact creates a dilemma for network operators as SDH/SONET systems start to reach end of life, or if a large SDH/SONET or even E1 network must be supported for a small number of services or subscribers.

Infinera’s packet-optical platforms offer several alternatives for the handling of legacy TDM-based services in a cost-effective manner. Infinera’s platforms include powerful ROADM functionalities that provide circuit emulation over shared optical transmission networks. The adaptation of TDM services as well as E1 services or channelized STM-4/OC-12 or STM-16/OC-48 SDH/SONET services using different wavelengths, while still using the same WDM platform and optical transmission network, facilitates a gradual shift toward one common, packet-mode, Ethernet infrastructure for all services.

Existing Layer 1 services carried over SDH/SONET or E1 networks can be transported separately from Ethernet services using different wavelengths, while still using the same WDM platform and optical transmission network. Infinera’s packet-optical platforms include powerful ROADM functionalities that provide flexible handling of the optical paths and multiplexing of signals that adapt SDH/SONET traffic to optical transport.

Layer 1 Point-to-Point Services
- STM-1/OC-3
- STM-4/OC-12
- STM-16/OC-48

Layer 2 Services
- E-Access
- E-LAN
- E-Line
- E-VPN

Ethernet/MPLS-TP Transport
- CE 2.0
- SyncE Capable

Ethernet Network

SDH/SONET

FIGURE 29: Migration Toward a Single, Packet-oriented Transport Infrastructure for All Services

2.5.2 Using the iSFP to Convert TDM Services for Ethernet Transport

The iSFP is used to deliver TDM services over a network built for Carrier Ethernet services. It provides circuit emulation for STM-1/OC-3, STM-4/OC-12 or STM-16/OC-48 SDH/SONET services as well as E1 services or channelized STM-4/OC-12 or STM-16/OC-48 can easily be adapted for transport over Ethernet through the use of Infinera’s Intelligent SFP (iSFP) pluggable optic that provides circuit emulation over a SyncE-capable Ethernet. The iSFP modules fit into any EMPP Gigabit Ethernet port, allowing a very flexible and tactical service migration.

The iSFP solution, synchronization transport is provided by the differential in recovery (DCR) mechanism, transferring the SDH/SONET clock to the transparent emulated service with SyncE as a reference at both ends. DCR transfers the synchronization clock to the emulated service and extracts it again at the far end of the service. (See also section 5.3.2.)

The two directions of the service can operate as two independent timing domains or one direction can be frequency-locked to the other direction. In cooperation with an ecosystem partner, Infinera also supports synchronization

Synchronization

Network synchronization is the cornerstone of an SDH/SONET network. Here the quality of the underlying Ethernet network is critical. The Infinera iSFP Series provides excellent Synchronous Ethernet performance due to patented innovations in circuit design.
management and monitoring. Probes can be deployed in the network to monitor network quality, which is used as a reference for both ends of the transparent TDM service. The probes can also be used to monitor the SDH/SONET sync quality of the Ethernet network (Figure 31).

Protection
To maintain SDH/SONET protection, the existing Automatically Switched Optical Network (ASON) and subnetwork connection protection (SNCP) protection schemes are replaced by MPLS-TP and Ethernet protection options. Protection is supported by MPLS-TP for topologies such as ring, mesh, and partial mesh. In addition, protection of the employed Ethernet Virtual Private Network (EVPN) is enabled by the Ethernet Ring Protection Switching (ERPS) and Link Aggregation Group (LAG) options, as described in section 5.4.

2.6.2 Packet-Optical Transport Switches
Infinera's Range of Packet-Optical Transport Switches
FIGURE 33. Two Examples of Infinera's Infinera's Range of Packet-Optical Transport Switches (EMXP) in the XTM Series, a Chassis-based Unit and a 1U Access Unit

In the metro aggregation network, traffic enters via an EMXP in the first node. The same physical node may also include multiplexers/transponders using additional WDM channels for fully transparent Layer 1 transport, with Layer 2 transport used only where inspection and OAM information is required at intermediate points, and where traffic needs to be aggregated by statistical multiplexing. The EMXPs are available in various configurations and mounting options, such as one- or two-slot chassis-mount units and a temperature-hardened access unit for deployment in non-controlled environments – all with full wire-speed forwarding on all ports for all traffic types.
A further development of the EMXP concept is the Packet Transport Fabrics (PT-Fabrics), where a high-capacity EMXP is interconnected to external 10 Gb/s and 100 Gb/s input/output (I/O) client units via a separate frontplane bus. The optical frontplane takes vertical-cavity surface-emitting laser (VCSEL) technology used in supercomputing, and brings it to standard transport equipment for the first time.

The metro aggregation and metro core networks are interconnected via the XTM Series packet-optical platform, which can provide switching at OSI Layers 1 and 2. The XTM Series node may be interconnected to external 10 Gb/s and 100 Gb/s input/output (I/O) client units via a separate frontplane bus. The optical frontplane takes vertical-cavity surface-emitting laser (VCSEL) technology used in supercomputing, and brings it to standard transport equipment for the first time.

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### 2.6.3 Optical Add-Drop Multiplexers and Other Optical Elements

The Layer 2-specific elements of metro aggregation and metro core networks use Layer 1 optical WDM channels for the transport of Ethernet frames between network nodes, as described in section 2.2.3. All the above Layer 2-specific network elements interwork seamlessly with the optical networking elements at Layer 1 when present in a truly integrated packet-optical platform, such as Infinera’s XTM Series. An XTM Series node may include Layer 1 transponders and muxponders, EMXPs, ROADM and other optical network elements.

### 2.6.4 The DTN-X Packet-Switching Module (PXM)

The metro/regional packet-optical network described above can be further augmented, both in the metro core and regarding integration with long-haul optical networks, by Infinera’s DTN-X Family of converged digital photonic platforms. The DTN-X Family is a terabit capable super-channel system leveraging large-scale photonic integrated circuit technology, integrating OTN switching and WDM transport. With the inclusion of the PXM, the DTN-X Family is transformed into a fully packet-aware platform where packet flows can be aggregated and switched in an 800Gbps ODU4 NNI interface to facilitate traffic engineering (Figure 34).

The PXM maps the Ethernet VLANs and MPLS services of the packet-optical network to the Layer 1 OTN transport services. This mapping is especially cost-saving when an OTN system is already in place, e.g. for long-haul purposes or in a densely populated area, where the packet-optical transport traffic can be transported by individual flows fully managed according to OTN standards. Furthermore, the PXM is certified for and can terminate CE 2.0 services such as E-Line and E-LAN, making it possible to set up Ethernet services starting in an NID in the access network and terminating via a DTN-X PXM in the metro core or long-haul network. More about how the PXM maps Ethernet traffic to OTN can be found in section 2.2.5.
This multi-layer management approach brings further benefits in terms of lower cost for management hardware, less training, less integration and simpler administration and maintenance of the entire network. Especially for network operators that do not already have an extensive operations support system (OSS) in place, the unified packet-optical management system offers significant advantages over the integration of multiple separate management systems.

2.7 ADVANTAGES OF PACKET-OPTICAL TRANSPORT

Now that we have a better understanding of the fundamental principles of packet-optical networking, we can summarize the advantages, both in general terms and more specifically as they are implemented with the Infinera product portfolio.

2.7.1 Benefits of the Packet-Optical Approach

Packet-optical networking in general helps the operator attain several types of valuable advantages:

Potential for Additional Service Revenues

Service awareness is critical if the differentiated QoS requirements of new multimedia applications and cloud services are to be met end-to-end throughout the network. To do that, it is important to retain service transparency where necessary, i.e. to leverage all existing information present in Ethernet VLAN tags and MPLS labels, for example. This should be done only as far as such a point in the network where traffic with the same QoS requirements has been fully aggregated.

Full service awareness enables the operator to differentiate and market higher-value services with specific SLAs, increasing service revenues.

Better Customer Satisfaction and Thereby Reduced Churn

Massive scalability is easily achieved through the WDM functionality in an optical/ethernet platform, where multiple services can be assigned to the same wavelength or to their own specific wavelengths. New wavelengths can be added on an as-needed basis. Support for scaling Ethernet services is the most important requirement, since Ethernet traffic will constitute the great majority of future growth in bandwidth requirements. With an integrated packet-optical platform, it is easy to upgrade transport capacity as subscriber demand grows.

End-to-end OAM is important to ensure the reliability and resiliency of the transport underlying the services carried over the network. It is important to ensure that both the SLAs and service objectives that are internal to the service operator and those that might explicitly be offered to a subscriber are met. Efficient tools for operations and maintenance are vital to achieve customer satisfaction.
2.7.2 Advantages to Using Infinera’s Portfolio for Packet-Optical Transport

Packet-optical transport provides many general advantages, as described above. But other characteristics more related to the actual implementation of the packet-optical nodes used in the network are also of significant importance. Infinera’s portfolio for packet-optical networking combines Infinera’s long and recognized optical networking experience with outstanding Ethernet/Layer 2 capabilities, including MEF Carrier Ethernet 2.0 services, MPLS-TP and OTN-compatible transport. Furthermore, the elements in this portfolio are truly optimized for the simplest and most cost-efficient implementation of packet-optical transport networks.

A Lean and Transport-centric Implementation of Ethernet/Layer 2 Functions

The packet-mode functionality of a packet-optical node may include anything from a simple Ethernet bridge to a full-fledged IP router and more. When implementing a transport-focused packet-optical node, it is of the utmost importance to select an optimal level of functionality for the transport task. Including superfluous functions adds to both equipment cost and operational complexity, especially in the aggregation and metro/ regional segments of the network, which have the majority of the network nodes. On the other hand, the node must include sufficient features to make service differentiation, OAM and necessary resilience possible. The EMXPs and other Layer 2 equipment have all been designed with this in mind. Functionality of value in a metro aggregation or metro core network, such as the capability to handle MPLS-TP, is included, while most of the complex IP handling has been omitted.

Efficient Transport of Synchronization

Accurate synchronization is essential, especially in mobile networks. As an example, Long Term Evolution (LTE)/4G and 5G networks need an accurate time stamp as well as frequency synchronization. The EMXPs and PT-Fabric fully support ITU-T SyncE standards for the distribution of timing signals throughout the packet-optical network. IEEE 1588v2 is a common standard to deliver both phase and frequency information over a packet network, but it is sensitive to packet delay variation (jitter). IEEE 1588v2 can be deployed over any legacy Ethernet network, but it may rapidly lead to quality problems if jitter becomes too high. With Infinera’s transport-centric, almost zero-jitter implementation of network nodes, IEEE 1588v2 will converge fast and can deliver the required time stamps.

Low Latency

The EMXPs and the PT-Fabric are designed for transport and capacity; they have no central switching fabric, no input queues and no network processors limiting performance. This results in minimal delay and no jitter within the EMXPs and the network. The ultra-low latency has significant value overall, and is crucial in certain applications, e.g. between data centers and in algorithmic trading applications for the financial world. Additionally, the stability and low latency of the EMXPs’ minimal jitter and delay in mobile backhaul applications, enabling more and longer radio hops when a combined wireless and wired backhaul network is being deployed.

Low Power Consumption

Energy costs can be a significant item in the OpEx of any telecommunications network. The hardware elements of Infinera’s intelligent packet transport architecture have all been designed with this in mind, with typical power consumption as low as less than 7 watts (W) per 10 Gigabit Ethernet, for example. Not only does low power consumption save on direct energy costs, but for every kilowatt saved in equipment power, an additional 0.5 kilowatt in reduced need for air conditioning is saved too.

High-density Implementation

The EMXPs and PT-Fabric have all been designed to provide as high port density per unit as possible while still maintaining high capacity. This translates to smaller footprint and reduced volume requirements, leading to less costly installations than with legacy equipment.

Multi-layer Management

Infinera’s multi-layer DNA-M management system enables unified Layer 1 and Layer 2 OAM of the packet-optical network. The management system supports the full range of operations, administration and maintenance functions defined by MEF for Carrier Ethernet 2.0. Furthermore, the system fulfills the requirements of ITU-T Recommendation Y.1731, which also addresses performance management.
OPERATING THE NETWORK
3.3 CHAPTER SUMMARY
The cost-effectiveness of a real network is highly dependent on how easy it is to operate and how well it can adapt to shifting service demands. While a well-designed multi-layer network management system is critical to efficient operations, network operators are also increasingly looking to software-defined networking (SDN) to enable more agile, dynamic service delivery and multi-layer optimization. In Chapter 3, we therefore take a closer look at the network management principles applicable to packet-optical networks, and at how SDN complements network management for dynamic service delivery and network optimization.

The key point to emphasize is that multi-layer network management and multi-layer SDN are complementary. While SDN generally focuses on the automation and programmability of end user services, multi-layer network management continues to support the full range of infrastructure management, from configuration and element management to monitoring, fault isolation and service assurance. Traffic engineering and service provisioning can be shared between traditional network management and SDN platforms, with hybrid operation that protects existing services while introducing new SDN-driven services on the same physical network. With this approach, SDN can be introduced step by step, for example, in only one domain of the network or applied only to a particular OSI layer.

3.2 MULTI-LAYER NETWORK MANAGEMENT
Many of the advantages of packet-optical networking originate from the ability to manage both the Layer 1 optical channels and the Layer 2 Ethernet services of the network in a coordinated way (Figure 37). Layer 1 optical channels can be established at the same time as the Ethernet service attributes are assigned to the Ethernet Virtual Connections that are using the Layer 1 optical channels. This allows for an easy procedure for end to end service creation. Importantly, it is only then possible to efficiently monitor the performance of an Ethernet service and determine if a fault originated in the optical or packet switching elements of the network.

Coordinated handling of the optical and Ethernet layers of the network calls for a multi-layer management system and, when using SDN, a multi-layer SDN platform (Figure 38). These systems must be designed from the start to enable multi-layer visibility and management, while also keeping ease of use for network operators in mind. Infinera’s suite of management systems, including the Infinera Digital Network Administrator (DNA), provides network operators with full control of their integrated packet-optical network and supports planning, deployment, and operation of the network infrastructure in a cost-efficient and rational way.

3.2.1 Management Framework
A great deal of the standardization of management procedures has taken place among operators and their vendors in order to facilitate business and network operations. TM Forum (TMF, formerly TeleManagement Forum), an industry association for service providers and their suppliers in the telecommunications and entertainment industries, has played a central role in this work.

Framework, which was developed by TM Forum, is a suite of best practices and standards that enable a service-oriented, automated and efficient approach to business operations. Framework provides hundreds of standardized business metrics that allow for benchmarking, as well as a suite of interfaces and APIs that enable integration across systems and platforms. Framework also includes adoption best practices and examples.

The central business process model used in Framework is the Business Process Framework (eTOM).14 This also is maintained by TM Forum (Figure 39, next page). This model describes the required business processes, including network management and operations, of service providers, and defines their key elements and how they should interact. eTOM is a guidebook that defines the most widely used and accepted standard for business processes in the telecommunications industry today.
For the management of packet-optical networks, two areas (columns in the eTOM model) are of particular interest:

• Fulfillment, which involves supply chain activities for assembling and making services available to subscribers. These activities create an infrastructure that matches the supply of services with subscriber demand in an economical way, and with consistently high levels of quality and reliability.

• Service assurance, which is the application of policies and processes to ensure that services offered over the network meet a predefined service quality level for an optimal subscriber experience.

Infinera's network management philosophy fully adheres to the relevant TM Forum standards. For example, for integration with back-office support systems, DNA comprises Framework-compliant web-services interfaces based on the TMN96 model. These interfaces hide the complexity of the underlying optical network and are designed to reduce the time, risk and costs associated with systems integration.

Infinera's DNA multi-layer management functions (DNA-M) provide the following full suite of MTOSI 2.0-compliant interfaces:

- Inventory
- Alarms
- Activation/provisioning
- Performance statistics

Another method often used to classify the many diverse actions involved in the management of communications networks is the FCAPS suite:

- Fault management (F) encompasses functions for detecting failures and isolating the failed equipment, including the restoration of connectivity.
- Configuration management (C) refers to functions for making orderly and planned changes within the network. An important part of configuration management is keeping an inventory of equipment, software releases, etc.; in the nodes.
- Accounting (or administration) management (A) deals with functions that make it possible to charge users for the network resources they use.
- Performance management (P) comprises functions for monitoring and fine-tuning the various parameters that measure the performance of the network and forms the basis for service level agreements with network users.
- Security management (S) refers to administrative functions for authenticating users and setting access rights and other permissions on a per-user basis.

3.2.2 Infinera’s Management Software Suite

Infinera offers a full suite of tools for the management of its optical and packet-optical transport networks. These tools help operators with tasks throughout the entire service and network life cycle when planning, deploying and operating the packet-optical network and its services. The suite has been created based on the Frameworks standards and eTOM framework described above, but given the role of Infinera as an infrastructure vendor, Infinera’s management suite focuses on the subset of activities in eTOM shown in Figure 40.

The components included in Infinera’s suite of management software can broadly be grouped into five categories, as depicted in Figure 41 (see next page).

At the most fundamental level, each network element of an Infinera packet-optical network supports local configuration.
and control by an internal element manager accessible through a local I/O device. Centralized, multi-layer management of all the elements in a network is done from a network manager – Digital Network Administrator – that provides an end-to-end view of the connections and services. The network operator often has extensive other operations and support systems for administration, billing, etc. of the services provided. Hence, the network manager must interoperate smoothly with the operator’s OSS environment, a task accomplished by an OSS integration toolkit. The unified information model allows the entire network to be modeled, all the way from the optical fibers run in the ducts up to the Ethernet service created on top of them, including all the OSI layers in between. At the bottom of the multi-layer information model used by Infinera is the TMF608 model used for the Layer 1 network. The higher-order models for connection-oriented Ethernet (802.1Q tunneling, or Q-in-Q), MPLS-TP and multi-point Ethernet models are added onto the Layer 1 model, as indicated in Figure 43 (on the next page).
management processes from Layer 1 into Layer 2. The app is plug-and-play on top of the Layer 1 assurance web app, and not only editable in DNA-M extends the management system before configuring a Layer 2 service, effectively speeding up the entire provisioning process. Provisioning services via a multi-layer SDN control platform (as outlined in Section 3.3), such as the Infinera Xceed SDN controller, automates and simplifies this process further, because the platform includes multi-layer path computation and constraint-based provisioning logic to enable the provisioning of all layers based on Layer 2 service requirements.

3.2.6 Layer 2 Service Assurance A Carrier Ethernet network must provide service assurance so that a user interface to help in quickly finding the problem, and the underlying Layer 1 paths that support them. Fault information is indicated not only on the map but also graphically for individual paths, links and ports. If the origin of a networking problem resides in Layer 1, the user can turn to the features in the Layer 1 assurance app to quickly resolve the problem without having to change system or interface. The app also presents G.826 performance statistics for Layer 1 (Figure 44). The assurance web app provides a complement to established Ethernet standards for fault management, such as IEEE 802.1ag (Connectivity Fault Management or CFM) The goal of CFM is to monitor an Ethernet network and pinpoint where a problem occurs, while DNA-M provides a graphical multi-layer assurance web app that can be used in DNA-M to extend the Layer 1 assurance app, and not only editable in DNA-M. This enables a physical decoupling of the system that makes decisions about where traffic is sent (the control plane) from the underlying network and its functions. This network abstraction enables a physical decoupling of the system that makes decisions about where traffic is sent (the control plane) from the underlying material, circuit traces and more.

3.3 SOFTWARE-DEFINED NETWORKING AND NETWORK VIRTUALIZATION

3.3.1 Basic Concepts Software-defined networking is an approach to computer networking that allows the management of network services through an abstraction of the managed network and its functions. This network abstraction enables a physical decoupling of the system that makes decisions about where traffic is sent (the control plane) from the underlying material, circuit traces and more.
The Infinera Xceed Software Suite is a centralized tool to one or more SDN controllers.

The functions of the control plane can be restricted to a single OSI layer or interface and protocol. Path computation is often performed by the network management system, in an SDN controller or in one or more network elements. However, given the computational resources required for multi-layer path computations, the PCE to the SDN controller is generally the most cost-efficient solution. When using a multi-layer SDN controller, the PCE must also be multi-layer, meaning that it can correlate path computations between all the relevant layers.
from specialized devices to software run on common server platforms. Advances in technology have now made it possible to run applications that once required specialized central processing unit (CPU) and interface hardware on industry-standard server blades. Arguments in favor of the transition to NFV are both the lower cost of servers compared to specialized appliances and the rationalization of spares handling – instead of numerous specialized devices, only server blades need to be kept in stock, and the servers are given their functions by the installed software. In short, NFV allows for more dynamic administration of network resources, making it possible for the network operator to respond to new demands in a more agile way.

Software-defined networking increases the flexibility of how the physical network can be used, since network services are created dynamically by the controller and the image it has of the network, rather than by direct manipulation of the physical switches, routers, etc. The SDN controller thus enables network virtualization, i.e. it maps the status of the physical network resources and network functionality into a single, software-based administrative entity; a virtualized network.

Network virtualization brings a higher degree of abstraction to the transport network, which is favorable when it comes to mobility of resources, service creation and management, especially in the context of cloud computing. The flexibility of the virtual network matches the dynamic reconfiguration capabilities of computing and storage in cloud computing.

OpenFlow enables SDN controllers to determine and set the paths of traffic flows across a network of switches. As an open standard, OpenFlow also allows switches from different vendors to be controlled from the same SDN controller. Generally, the OpenFlow protocol is carried within ordinary Transmission Control Protocol (TCP)/IP packets sent between the controller and the network elements.

As SDN has matured and SDN principles have been applied more broadly to a wide range of networks, additional protocols for control plane-to-data plane communication have been developed to complement OpenFlow. Some examples of other “southbound” protocols from the control layer to the infrastructure are the Open vSwitch Database (OVSDB) management protocol, Representational State Transfer (REST) and NETCONF.

**FIGURE 47:** Network Virtualization Allows Two Enterprises to “See” Different Virtual Networks, Although They Use the Same Physical Infrastructure

**FIGURE 48:** OpenFlow Defines the Communication Interface and Protocol Between the Control Plane and the Data Plane. Source: Open Network Foundation
3.3.2 Infinera’s Multi-layer SDN Vision

Infinera envisions that future network architectures will be simplified into just two main layers: Layer C, cloud services, and Layer T, intelligent transport. Layer C consists of all virtualized network functions, services and applications that run as software within a cloud environment, including virtualized routing control. Layer T consists of integrated packet-optical networks. SDN plays a central role in this architecture as the bridge between Layer C and Layer T (Figure 49).

SDN principles are applicable to all OSI levels of an Infinera Intelligent Transport Network; hence, Infinera’s SDN vision for the Xceed solution is also a multi-layer SDN vision. This integrated, multi-layer approach to SDN offers several benefits:

- Simplified service provisioning across multiple network layers
- A high level of automation when setting up end-to-end paths in transport networks
- Improved network resource utilization as a result of better topology information
- The programmability of new functions
- Open standards and vendor neutrality

Multi-layer SDN enables several important characteristics of a modern, flexible and cost-effective transport network, such as:

- Multi-layer virtual networks including OSI Layers 0 to 2 (photonic/WDM, OTN, Ethernet and MPLS-TP)
- Virtual networks can be defined in a flexible way over physical network resources in one or more network domains. These virtual networks may span multiple network layers and multiple network types, and can be used by one or more customers with complete isolation as needed between customers, protocols employed and OSI layers.
- Automatic provisioning of MEF Carrier Ethernet 2.0 services
- All Carrier Ethernet services as defined by MEF CE 2.0 can be provisioned automatically with SDN. Bandwidth can be allocated to services dynamically, with restoration and protection functions centralized.
- Virtual routing – distributed routing functionality

As described in section 3.3.3, an Intelligent Transport Network can employ SDN to implement virtualized IP control plane operations. The Xceed multi-layer SDN architecture has standardized, open software interfaces, which make it possible for other higher-level management and orchestration systems, as well as other external SDN-compatible web apps, to interact with the multi-layer SDN control platform. The Xceed multi-layer SDN control platform is logically centralized, and may be physically located in a single central node or distributed to multiple sites in the network. Thus, Xceed enables seamless integration with other software-defined networks and is an excellent foundation for the virtualization of higher-order networks and services.

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3.3.3 Applications of Intelligent Packet Transport with SDN

With multi-layer SDN as an element of intelligent transport, new and attractive options for service differentiation and network operations become available to the network operator. The operator may, for example, adjust the bandwidth of a service dynamically based on customer requests (bandwidth on demand), or optimize the routing of an existing service as the network evolves without dropping a single packet (Figure 50).

Dynamic Layer 2 services with SDN provide a way for the network to reconfigure itself to meet bandwidth peaks and unpredictable traffic patterns. Dynamic services will also automatically detect changes in network topology and optimize services accordingly.

An SDN application of specific interest from a cost and efficiency standpoint is the introduction of virtual networking, which refers to distributed routing functionality (DRF),...
within the transport network. The objective of DRF is to let virtualized routing engines, implemented as software instances residing in the multi-layer SDN control platform, participate in Layer 3 routing decisions and control the physical network elements to make segments of the transport network behave as if they were IP routers when seen from the outside world of other IP routers. Note that a DRF solution is not intended as a direct replacement for conventional core routers, but can offer significant opportunities for capital expense (CapEx) reduction and a more seamless integration of Layer 3 out to the network edge, and can extend the operational life of existing routers in the metro environment.

Figure 51 shows how a DRF function might work. The DRF (shown in both logical and physical views in Figure 51) "listens" to Layer 3 control plane traffic (e.g. Open Shortest Path First [OSPF], Intermediate System to Intermediate System [IS-IS] and Border Gateway Protocol [BGP] packets) from its "real" router neighbors (peer routers) and passes the control packets to a routing engine in the SDN controller. The routing engine makes decisions and sends updated routing control packets back toward the external peer routers. The routing engine for the DRF also creates its own routing tables, which are turned into forwarding rules, controlling the packet flows in the physical transport network.

DRF enables significant simplification and cost reduction, especially in aggregation networks, which are common in metro areas. As shown in Figure 52, without a DRF, all IP traffic is forwarded to the central core router, even traffic that could be sent directly between the metro nodes. Adding more base stations with site routers typically also involves manual configuration changes to the transport network. If DRF is enabled, local IP traffic between sites is no longer routed via the central core router. Since the DRF updates its routing tables dynamically, configuration changes at the IP level are detected automatically, without any manual intervention needed in the transport network.
4 APPLICATIONS OF PACKET-OPTICAL NETWORKING
4.1 CHAPTER SUMMARY
Packet-optical networks that provide Carrier Ethernet services are rapidly becoming a primary infrastructure for telecommunications network operators. The versatility of packet-mode Ethernet services and the capacity and scalability of optical transport have proven to be a winning combination in a variety of applications. In this chapter, we take a brief look at some of the areas in which packet-optical technology has already proven its superiority.

4.2 ETHERNET SERVICES FOR ENTERPRISES – BUSINESS ETHERNET

4.2.1 Serving Enterprise Customers

As ICT managers look for solutions, Ethernet services such as MEF-defined Carrier Ethernet are gradually being phased out by many network operators. Wide area connectivity based on TDM leased lines does not provide the operational flexibility expected by the modern enterprise (Figure 53).

As ICT managers look for solutions, Ethernet services such as MEF-defined Carrier Ethernet services have emerged as an attractive alternative to provide businesses with a best-of-breed, cost-effective wide area networking solution for enterprise ICT applications. Ethernet standards from the MEF, ITU, and IEEE have now added features and functionalities that make Ethernet a WAN-capable technology. The potential of Ethernet services has already been discovered by industries such as finance, healthcare, education, government, IT, retail, real estate, legal, media and more.

An increasing number of network operators are offering MEF-compliant Carrier Ethernet services. In many cases, these services are replacing some of the operators’ legacy technologies such as FR and ATM, while in other cases they exist alongside other established wide area networking technologies, such as Layer 3 virtual private network services (also referred to as IP-VPN services).

For the network operators, Ethernet offers an additional business opportunity, especially if Carrier Ethernet can be implemented in a cost-efficient way on the same equipment already used to provide Layer 1 transport services. Infinera and other packet-optical equipment vendors are actively enabling this important transition.

4.2.2 A Metro Network for Business Ethernet

Infinera’s portfolio for metro Ethernet includes both demarcation units (EDUs and NIDs), and aggregation and metro core equipment. The integrated packet-optical network is ideally suited to support a multitude of enterprise subscribers, each with their own individual requirements for the characteristics of the wide area service they want to buy.

Infinera’s metro Ethernet portfolio includes both demarcation units (EDUs and NIDs), which can be placed at the customer site (customer premise equipment or CPE), and packet-optical transport switches (EMXPs) with integrated Layer 2 functions, which are located in the network nodes (AOUs) all units are fully MEF-certified for Carrier Ethernet 2.0 services and form an integral toolkit for the creation of a state-of-the-art packet-optical network. Furthermore, the EMXPs are seamlessly integrated with other traffic units and optical units in the Infinera XTM Series, forming a true packet-optical network.

The Ethernet Demarcation Unit is designed for today and the future, providing a low-cost, purpose-built, unaggregated QoS and SLA fulfillment. The EDU includes highly accurate and precise DAM and performance monitoring through microsecond resolution and per-service visibility for all key QoS and SLA parameters. It is capable of monitoring Ethernet transport technology and is enhanced with Ethernet switching functions to carry Ethernet traffic between the subscribers’ area networks (LANs) and other data networks as needed.

The integrated packet-optical network enables both transparent Layer 1 services and more advanced Layer 2 (Carrier Ethernet) services. Having the optical network as the base makes it possible to support a broad range of traditional Layer 1 transport services. Also, thanks to the integrated Layer 2 functions, it is possible to offer the enterprise a wide range of Ethernet services with different bit rates, QoS and SLAs, using bandwidth profiles and various protection and monitoring functions. The packet-optical network is ideally suited to support a multitude of enterprise subscribers, each with their own individual requirements for the characteristics of the wide area service they want to buy.

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4.2.3 A Long-haul Network for Business Ethernet

For operators wanting to offer integrated long-haul and high-capacity Carrier Ethernet services, the Infinera DTN-X Family of super-channel systems presents a very attractive solution. Infinera’s DTN-X platforms perform integrated WDM and OTN switching, grooming and service protection at Layer 1, based on large-scale photonic integrated circuit technology designed for long-haul data transmission. Using the PXM, the DTN-X Family can map Ethernet VLANs to ODUflex subnetwork connections, which enables ODUflex-based traffic engineering in the long-haul network (Figure 54).

Much of telecommunications operators’ efforts today are centered on creating seamless services working over both the fixed and mobile networks – fixed-mobile convergence (FMC). One important element of an operator’s FMC strategy is to use a common transport infrastructure of packet-optical equipment for all IP services, irrespective of whether access is fixed or mobile. This simplifies the implementation of common higher-layer service entities and reduces both CapEx and OpEx (Figure 55).

4.3 AGGREGATION OF IP TRAFFIC – IP BACKHAUL

4.3.1 IP-based Services over a Common Infrastructure

Fixed and mobile networks provide telecommunications services to end users – services that are generated by the operators themselves and by external entities. The services can be Internet access, telephony with access to the public switched telephone network and consumer access to TV and media streams. Increasingly, all these services are built on the IP suite of protocols, with service provisioning to an end user becoming equivalent to enabling the flow of IP traffic to and from the subscriber.

The infrastructure delivering the operator’s services is typically divided into an access network, an aggregation network and a core network. Much of telecommunications operators’ efforts today are centered on creating seamless services working over both the fixed and mobile networks – fixed-mobile convergence (FMC). One important element of an operator’s FMC strategy is to use a common transport infrastructure of packet-optical equipment for all IP services, irrespective of whether access is fixed or mobile. This simplifies the implementation of common higher-layer service entities and reduces both CapEx and OpEx (Figure 55).

4.3.2 A Lean and Transport-centric Aggregation Network

The role of the aggregation network is to transport IP traffic from a large number of access nodes to many fewer core nodes. Traditionally, this task has been performed by SDH/SONET links and WDM wavelengths, but a more capacity-efficient aggregation network is accomplished when Ethernet services are used to aggregate multiple traffic streams. Ethernet leverages the inherent possibilities for the statistical multiplexing of much of the data traffic and fits the available bandwidth pipes more efficiently. That is why Infinera recommends the use of native Ethernet and MPLS-TP in the aggregation network.
There is no need for advanced routing and filtering functions in the aggregation network (Figure 56). Instead, a carefully chosen combination of Ethernet switching and optical functions should make the aggregation network act as a bundle of wires carrying the traffic. The handling of the IP protocol, including IP/MPLS, should be restricted to as few nodes as possible, i.e. to the core nodes and as needed in the access nodes. Such a consolidation of IP/MPLS reduces both cost and operational complexity. Furthermore, the simpler processing of Ethernet frames compared to IP packets in the nodes of the aggregation network reduces delay and jitter, while making all traffic flows more predictable than in an IP network.

An aggregation network implemented with the Infinera XTM Series is optimized for transport and does not introduce unnecessary complexity or extra IP functions. It is designed, in particular, for Ethernet transport (Layer 2) according to the MEF CE 2.0 specification, providing:

- High bandwidth utilization
- The low latency necessary for IPTV, IP telephony, video on demand and mobile backhaul
- Support for both point-to-point and multicast applications
- Layer 2 performance management (utilization, latency, jitter, packet loss)
- Efficient synchronization (Full SyncE support)
- Excellent protection and resilience LAG, Ethernet Ring Protection Switching Version 2 (ERPSv2), MPLS-TP linear protection
- Predictable performance, in order to be easy to maintain and troubleshoot
- Low power consumption

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- Predictable performance, in order to be easy to maintain and troubleshoot
- Low power consumption

4.3.3 The Flexible Optical Network Brings Scalability

Given the rapid demand for more bandwidth from consumers and enterprises, the aggregation network requires flexibility to accommodate future growth. Infinera’s solution seamlessly integrates the capacity of an optical WDM network with the Layer 2 switching functions of a Carrier Ethernet network. It is easy to upgrade the capacity of the transmission links between the nodes and the switching capacity as needed according to a pay-as-you-grow model. For example, assume that the demand for bandwidth has been growing especially fast at one particular remote node in the aggregation network. Thanks to the packet-optical integration of the XTM Series, an additional express wavelength can easily be opened up for the high-traffic node, leading its Ethernet traffic directly to the core node (Figure 57). This has several benefits:

- Only the high-traffic node and the core node need to be upgraded. There is no requirement for a forklift upgrade of the whole aggregation network—pay as you grow.
- A dedicated wavelength for the additional traffic means minimal latency.
- The express wavelength can be equipped with error correction (OTN-FEC) to cater to the longer distance.
- Protection schemes can be implemented in the optical layer to improve resilience.
- Thanks to the integrated packet-optical functionality of the XTM Series, it is also possible to complement the EMXP with other types of muxponders, should there be a need to transport legacy TDM traffic over yet another wavelength toward the core node, for example.

4.4 MOBILE BACKHAUL

4.4.1 4G/LTE and 5G Place New Requirements on Mobile Backhaul

Mobile networks have been undergoing a rapid evolution over the last few decades that shows no sign of abating anytime soon. Modern LTE/4G and LTE-Advanced mobile networks are required to support a wide range of services, including voice, video, and data communications. These networks are expected to handle increasing traffic demands and provide better quality of service (QoS) to users. Infinera’s solutions enable mobile operators to meet these challenges by providing high-performance, scalable, and cost-effective solutions. Infinera’s XTM Series is optimized for mobile backhaul applications, offering a cost-effective solution for transporting legacy TDM traffic over yet another wavelength toward the core node, for example.

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- The express wavelength can be equipped with error correction (OTN-FEC) to cater to the longer distance.
- Protection schemes can be implemented in the optical layer to improve resilience.
- Thanks to the integrated packet-optical functionality of the XTM Series, it is also possible to complement the EMXP with other types of muxponders, should there be a need to transport legacy TDM traffic over yet another wavelength toward the core node, for example.

For example, assume that the demand for bandwidth has been growing especially fast at one particular remote node in the aggregation network. Thanks to the packet-optical integration of the XTM Series, an additional express wavelength can easily be opened up for the high-traffic node, leading its Ethernet traffic directly to the core node (Figure 57). This has several benefits:

- Only the high-traffic node and the core node need to be upgraded. There is no requirement for a forklift upgrade of the whole aggregation network—pay as you grow.
- A dedicated wavelength for the additional traffic means minimal latency.
- The express wavelength can be equipped with error correction (OTN-FEC) to cater to the longer distance.
- Protection schemes can be implemented in the optical layer to improve resilience.
- Thanks to the integrated packet-optical functionality of the XTM Series, it is also possible to complement the EMXP with other types of muxponders, should there be a need to transport legacy TDM traffic over yet another wavelength toward the core node, for example.
networks place tough demands on their mobile transport networks, and the step change in network performance that 5G brings will add to the demands on the underlying transport network.

The growth in data rates and higher number of cells place an ever-increasing demand for more capacity and reach on mobile backhaul networks, whether they are implemented by microwave links, copper wires or fiber. A primary challenge for the mobile operator is to dimension the backhaul network to cope with upcoming traffic demand, avoiding a bottleneck for mobile services as well as end-user frustration over long response times and unpredictable performance.

4G/LTE introduced new requirements on synchronization and maintenance in the network, and mobile operators require transport services with more stringent service level agreements. For a regional utility carrier or local operator sitting on large fiber assets, this constitutes an important business opportunity if a network that allows the introduction of such services can be built in a cost-effective manner.

4.4.2 A Backhaul Network

Optimized for 4G/LTE and 5G

The most attractive offering for a mobile operator running 4G/LTE and ultimately 5G is an Ethernet-based backhaul network that allows the introduction of such services can be built in a cost-effective manner.

- Efficient mechanisms for synchronization.
- Latency must be low, predictable and stable, not varying with load, throughput or packet replication.
- Efficient services for synchronization. Synchronization is critical in mobile backhaul networks as users move from cell site to cell site and expect uninterrupted service.
- Resilience. The network must include protection mechanisms that guarantee carrier-class resilience against outages. An XTM Series network supports protection mechanisms such as link aggregation, ERPSv2 and MPLS-TP for the network to ensure a high degree of reliability.
- Efficient fronthaul integration. The flexible structure of the XTM Series allows for efficient integration with the Layer 1 WDM network as users move from cell site to cell site. The DNA-M Portal even allows mobile operators to monitor the performance of subscriber services in real time.
- Efficient tools to manage operational complexity. To be successful in the long run, it is also necessary to control and operate the network in an efficient way. Infinera’s DNA layer 3.0 layer multi-layer management suite has features that make the network easy to operate. Service creation can otherwise be difficult for complex networks, but with DNA, setting up integrated Layer 1 services, MPLS-based Layer 2 services and MPLS-TP services is easy. The DNA-M Portal even allows mobile operators to monitor the performance of subscriber services in real time.

backhaul offerings and make maximum use of installed fiber.

Implementing Ethernet services, rather than IP/MPLS-based services with similar characteristics, can make the necessary investments significantly lower, especially if the Ethernet services can be implemented on a previously deployed WDM platform, such as the XTM Series. The Ethernet services in Infinera’s XTM Series are fully MEF CE 2.0-certified and have functionality that makes it possible to implement all the CE 2.0 service types shown in Figure 58.

Further, a backhaul network implemented with Infinera’s XTM Series has the following characteristics of immediate importance for mobile operators:

- Very little latency and jitter. Latency and jitter have a cumulative effect as traffic passes through consecutive nodes in access rings, aggregation networks and the core.
- Efficient mechanisms for synchronization. Synchronization is critical in mobile backhaul networks as users move from cell site to cell site and expect uninterrupted service.
- Resilience. The network must include protection mechanisms that guarantee carrier-class resilience against outages. An XTM Series network supports protection mechanisms such as link aggregation, ERPSv2 and MPLS-TP for the network to ensure a high degree of reliability.
- Efficient fronthaul integration. The flexible structure of the XTM Series allows for efficient integration with the Layer 1 WDM network as users move from cell site to cell site. The DNA-M Portal even allows mobile operators to monitor the performance of subscriber services in real time.

To meet these demands, network providers need to lower the cost of their transport networks to enable them to be profitable in the future, and that requires reducing costs without compromising on scalability, efficiency, manageability or the ability to offer differentiated services.

4.5 SWITCHED VIDEO TRANSPORT

4.5.1 Streaming 3D and HD Video to the Home

Cable television (CATV) operators/multiple-service operators (MSO) offer a wide range of services over the transport infrastructure once built for TV distribution. These services encompass both entertainment and communications for residential users as well as connectivity and value-added services to enterprises. Some services, like LAN interconnect, may be created fully in-house by the CATV operator/MSO, while others rely on external networks, data centers and media hubs.

A major trend in CATV networks is the rapid growth of traffic per end user and in the overall network. The advent of streaming high-definition and 3D video services as well as the cloud computing has made IP traffic grow some 30 to 50% per year. Network operators also feel the need to radically lower the cost of their transport networks to enable them to be profitable in the future, and that requires reducing costs without compromising on scalability, efficiency, manageability or the ability to offer differentiated services.
analog to digital distribution technologies and packet-optical networks. The industry consensus is that packet-optical networks will meet future needs, with the convergence of legacy and next-generation services onto Ethernet (Figure 59).

Essential for the transformation of CATV networks today is the introduction of DOCSIS 3.0- compatible equipment and the development of a new, super-dense, power- and space-saving access node architecture. The new architecture, referred to as the Converged Cable Access Platform (CCAP), combines edge quadrature amplitude modulation (QAM) and cable modem termination system (CMTS) into one node. Such upcoming super nodes will require significant amounts of bandwidth in the aggregation/distribution network, whereas traditional CMTS and edge QAM (EQAM) nodes could be served with 1 Gb/s, capacities of 10 to 100 Gb/s per CCAP will be required.

4.5.2 Infinera's Solution for Switched Video Transport

Infinera's Switched Video Transport solution integrates selected Layer 2 functionality into the Layer 1 WDM network, which enables cost-efficient capacity increases and the service differentiation capabilities typically found in Ethernet networks. The EMXP range allows operators the use of unique features for the demarcation, aggregation and transport of Ethernet services. Enabling the cost-efficient increase of metro network capacity, the EMXPs use packet-optical technology for the best transport network economics.

Infinera’s Switched Video Transport solution implements Internet Group Management Protocol, Version 3 (IGMPv3) features in the EMXP to listen to the IGMP network traffic between edge QAMs and multicast routers. By participating in the IGMP conversation and switching the individual channels, the Infinera solution is designed to reduce the cost of the network significantly. The IGMPv3 features, IGMP snooping and source-specific multicast, allow network resources to be utilized in an efficient way, as a destination only receives the traffic intended for it as opposed to a broadcast approach where the traffic is distributed to everyone in the network (Figure 60).

FIGURE 59: New Access Nodes (CCAP) in CATV Networks Require Robust, High-capacity Aggregation Networks

FIGURE 60: An Overview of the Infinera Switched Video Transport Solution, Based on a Packet-Optical Aggregation Network

APPLICATIONS
5 Ethernet and Layer 2 Technologies
5.1 CHAPTER SUMMARY
Packet switching may come in many shapes, but in the context of packet-optical networks for access and metronodal applications, packet switching is almost synonymous with Ethernet switching and the use of the Ethernet frame format. This chapter focuses on the characteristics of Ethernet, and especially on how the original connectionless LAN protocols for Ethernet have been augmented to make Ethernet a connection-oriented technology suitable for use in wide area networks, i.e., to make it into a Carrier Ethernet network. Attention is also paid to how to handle synchronization and how to create resilience in Ethernet networks.

This chapter is primarily intended as a tutorial and source reference for those interested in the general Ethernet and Layer 2 technologies used for wide area networks.

5.2 Ethernet Basics
Ethernet is a family of protocols and networking technologies that was originally designed for local area networks in the 1980s but is now also widely used for other topologies and distances. Standardized by the IEEE in the IEEE 802.3 family of standards, Ethernet has largely replaced competing wired LAN technologies and is today the dominating link layer protocol in data networks. Ethernet can be used in bus, star and mesh topologies and over a variety of physical media, including coaxial cable, twisted-pair copper cable, wireless media, and optical fiber. Typical Ethernet data rates today range from 100 Mb/s (Fast Ethernet), 1 Gb/s (Gigabit Ethernet or GbE), 10 Gb/s (10 GbE) and up to 100 Gb/s, with standards for Terabit Ethernet being developed. The term Terabit Ethernet is used to collectively describe all rates above 100 Gb/s Ethernet. To this date, it includes 200 Gb/s and 400 Gb/s standardization, with future plans for a full 1 Tbs Ethernet capability.

5.2.1 Ethernet Mode of Operation
Systems communicating over Ethernet divide a stream of data into individual packets called Ethernet frames. Each frame contains a source and destination address and an error-checking code so that damaged data can be detected and retransmitted (Figure 61).

5.2.2 Switched Ethernet
In the 1990s, the IEEE 802.3x standards for Ethernet defined full-duplex operation between a pair of Ethernet stations, i.e., simultaneous transmission and reception of frames over a twisted-pair or fiber pair. At the same time, a flow control mechanism called the MAC control protocol was introduced. If traffic gets too heavy, the control protocol can pause the flow of frames for a brief time period.

Today practically all Ethernet LANs and every WAN are based on switched Ethernet. In switched Ethernet, all Ethernet stations have their own individual full-duplex connection to a central switch (sometimes called a multipoint bridge). The switch has a forwarding table that matches Ethernet stations’ MAC addresses with a corresponding switch port and sends the frame to the correct destination.

Switched Ethernet removes the media contention and capacity problem inherent to shared Ethernet and reduces it to a contention problem within the switch, which needs to buffer frames from multiple users trying to access the same destination simultaneously. Another advantage of switched Ethernet is that switches can be made non-blocking, allowing for simultaneous traffic between several ports. Furthermore, each switch port now provides the full bandwidth of the Ethernet medium to the connected station.

Basic Ethernet switches do not modify the Ethernet frames as they pass through and are generally much simpler than Layer 3 IP routers because they operate at the link layer and do not need complex routing protocols. Switches may also be both cheaper and faster than IP routers because
the switching function can be implemented entirely in hardware, rather than in software running on an expensive high-performance processor. Finally, switches are simpler to manage than IP routers, since configuration does not involve the same complexity as with routers.

In a meshed Ethernet, shown in Figure 62 on the previous page, there are several paths between nodes, and frames can be forwarded in infinite loops within the network if no countermeasures are taken. There must be one and only one open route between each node of the network, and all other interconnecting ports on the switches must be blocked. Such a “one-route” network topology is called a spanning tree. The Spanning Tree Protocol (STP) and the Rapid Spanning Tree Protocol (RSTP) in the Ethernet standards are distributed algorithms that can be run by the switches to form a spanning tree (Figure 63).

In wide area applications of Ethernet, e.g. Carrier Ethernet, other mechanisms, such as Ethernet Ring Protection Switching and manual configuration of virtual connections, are used to ensure that there is only one path between the ingress and egress nodes of the network. More information about this can be found in section 5.4.

5.2.2 Virtual LANs

The task of the Ethernet switch is to move the frame from one LAN segment to another based on the destination MAC address. If the address is unknown, the frame is flooded to all the switch ports except the incoming one. This creates one single broadcast domain per switched network, which is a potential problem in larger networks since broadcast frames are propagated and replicated throughout the entire network. The problem of large broadcast domains as well as the security problem of having all traffic available at every Ethernet station is overcome by the introduction of virtual LANs.

A VLAN is a logical group of Ethernet stations that appear to one another as if they were on the same physical LAN segment, even though they may be spread across a large network. Each Ethernet station on a particular VLAN will only hear broadcast traffic from the other members of the same VLAN. Using MAC address-based VLANs makes it possible to let the VLAN span multiple switches. Interconnection between VLANs may then be provided by Layer 3 devices such as IP routers. All Ethernet frames in a VLAN have a distinct identifier, called the VLAN identifier (VID), located in a designated VLAN tag field (Figure 64), specified by the IEEE 802.1Q/p standard and inserted in the frame by the Ethernet switch. The full VLAN tag field is 4 bytes long and contains a tag protocol identifier (TPID) and a priority code point (PCP), which indicate the frame priority level. 12 bits of the VLAN tag are available for VLAN identification, but two values are reserved, making a maximum of 4094 VLANs possible in a single switched network using the basic standard. VLANs can be used to implement virtual private networks, and VLAN frames include

FIGURE 62: Three Virtual LANs (Green, Blue and Red), Each with Its Own Individual Broadcast Domain, Interconnected by a Router

FIGURE 64: IEEE 802.1Q/p Encapsulation of the VLAN Tag

FIGURE 66: IEEE 802.1ad Encapsulation of the SVLAN Tag

FIGURE 65: Customers Running Their Own VLANs Inside the Service VLANs of a Service Provider

FIGURE 63: IEEE 802.1Q Tag Encapsulation of the SVLAN Tag
with other features like control protocol and provider control domains when used can also help in separating the customer technology is also known as stacked VLANs, LANs within the customer domain. This VLAN (CVLAN) tag is used to create virtual destination MAC address, and the customer can then be based on the SVLAN tag and the service provider domain, switching To allow for service VLANs, a 4-byte SVLAN page). of the service provider (Figure 65, previous page). To allow for service VLANs, a 4-byte SVLAN tag is added to the header of the Ethernet frame in the IEEE 802.1ad standard. In the service provider domain, addressing can then be based on the SVLAN tag and destination MAC address, and the customer VLAN is isolated from the service VLANs within the customer domain. This technology is also known as stacked VLANs. Q-in-Q2 in provider bridges (Figure 66, previous page). Q-in-Q is primarily a way to overcome the limitations on the VLAN identifier space. It can also help in separating the customer and provider control domains when used with other features like control protocol tunneling or Fan-VLAN Spanning Tree. A further refinement of the concept of service VLAN is standardized in IEEE 802.1ah specifying Provider Backbone Bridges (PBB). The PBB standard supports complete isolation of customer VLAN address fields and service VLAN addressing fields.

5.2.3 Ethernet Physical Media (PHY) The Ethernet standard comprises a data link layer and an Ethernet physical media (PHY) part, the latter being specific for the transmission technology and data rate employed. When Ethernet is transported over a WDM wide area network, the Gigabit Ethernet, and 10 Gigabit Ethernet PHY standards are of the most interest since these are the types of Ethernet deployed in metropolitan and other wide area networks. The Infinea product portfolio includes transponders and muxponders that can be equipped with transceivers supporting Fast Ethernet, Gigabit Ethernet, 10 Gigabit Ethernet and 100 Gigabit Ethernet.

5.2.3.1 Fast Ethernet Physical Layer (FE) Fast Ethernet, i.e. Ethernet at 100 Mbit/s, has two predominant physical formats: 100BASE-TX, which runs over two unshielded twisted pairs (UTP) of copper wire, and 100BASE-FX, which runs over optical fiber. 100BASE-FX uses 1300 nanometer (nm) light transmitted via two strands of optical fiber, one for receive and the other for transmit. The maximum length is 2 kilometers (km) over multimode optical fiber. The 100 in the media type designation refers to the transmission speed of 100 Mbit/s. The “BASE” refers to baseband signaling, which means that only Ethernet signals are carried on the medium. The TX and FX refer to the physical medium that carries the signal.

<table>
<thead>
<tr>
<th>Name</th>
<th>Medium</th>
<th>Specific Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>100BASE-CX</td>
<td>Twisted-pair cabling</td>
<td>25 meters</td>
</tr>
<tr>
<td>100BASE-BX</td>
<td>Multimode fiber</td>
<td>220 to 350 meters depending on fiber diameter and bandwidth</td>
</tr>
<tr>
<td>100BASE-LX</td>
<td>Multimode fiber</td>
<td>550 meters</td>
</tr>
<tr>
<td>100BASE-BX10</td>
<td>Single-mode fiber</td>
<td>5 km</td>
</tr>
<tr>
<td>100BASE-LX10</td>
<td>Single-mode fiber, 1310 nm wavelength</td>
<td>10 km</td>
</tr>
<tr>
<td>100BASE-BX29</td>
<td>Single-mode fiber, 1,550 nm wavelength</td>
<td>70 km</td>
</tr>
<tr>
<td>100BASE-BX510</td>
<td>Twin-axial fiber, 1.490 nm wavelength</td>
<td>25 km</td>
</tr>
<tr>
<td>100BASE-CX10</td>
<td>Twin-axial fiber, 1.310 nm uplink</td>
<td>40 km</td>
</tr>
<tr>
<td>100BASE-CX10</td>
<td>Twin-axial fiber, 1.310 nm downlink</td>
<td>40 km</td>
</tr>
</tbody>
</table>

The XTM Series traffic units support both the electrical (100BASE-TX) and optical (100BASE-BX) variants for single- and multi- mode fiber in the GbE physical layer when interfacing to client systems.

5.2.3.2 Gigabit Ethernet Physical Layer GbE can be transmitted over shielded fiber cables or shielded copper cables. It can also be transmitted over unshielded twisted pairs of copper. This transmission is set up to operate in full-duplex (most common) or half-duplex mode. The standard defines a physical media dependent (PMD) sublayer that specifies the transceiver for the physical medium in use. There are three types of PHY for optical fiber: TX, RX, and Copper. The short-range PMD uses 850 nm light with a reach of 220 to 250 meters (m) on multi-mode fiber. The long-range PMD uses 1310 nm light with a reach of 550 m on multimode fiber and 5 km on single-mode fiber. The PMD for shielded copper reaches only 25 m. For unshielded copper, which is common in many office installations, multiple twisted pairs are used to send multi-level signals in a way that extends the reach to 100 m. Ethernet Fast FiberMedia (FFM), a variant of Gigabit Ethernet, is deployed in broadband access networks, later added 100BASE-LX10 and -BX10 (Figure 67).

Both LAN PHY and WAN PHY operate over a short-range, long-range, extended-range or long-range extended-range PFD. Short-range PFD uses 850 nm light over multi-mode fiber up to 300 m, long range uses 1310 nm light and reaches 260 m on multimode and 10 km on single-mode fiber. The extended-range PFD uses 1550 nm light and has a maximum reach of 40 km on single-mode fiber. 10GGE is supported across the Infinea packet- optical (PON) portfolio.

5.2.3.4 40 and 100 Gigabit Ethernet Physical Layer The 40 and 100 Gigabit Ethernet standards encompass a number of different Ethernet physical layer specifications. A networking device may support different PHY types by means of pluggable optical modules. The 40 and 100 Gigabit Ethernet standards are also standardized by many official standards bodies but are defined by multi-source agreements (MSA). One such
agreement that supports 40 and 100GbE is the C form-factor pluggable (CFP) agreement, which was adopted for distances of 100 meters or more. Quad small form-factor pluggable (QSFP) and CXP connector modules support shorter distances. 100GbE is supported across the Infinera packet-optical portfolio. The 40/100GbE standard supports only full-duplex operation (Figure 68).

5.3 SYNCHRONIZATION AND CIRCUIT EMULATION SERVICES OVER ETHERNET

5.3.1 Synchronous and Asynchronous Transport

Packet switching technologies, including Ethernet, are inherently asynchronous, i.e. incoming frames are received at one data rate (one rate of bits per second), buffered and multiplexed with other frames over intermediate links with higher data rates, and delivered at yet another rate to the receiver. There is no fixed relationship between the timing, phase or frequency of the incoming bit stream and the outgoing bit stream from the network. This is quite different from the principles of time-division multiplexed transmission technologies, such as PDH, SDH and SONET, traditionally used in wide area transport networks. In TDM, each stream of information to be transferred over the network is allocated a specific timeslot in the transmission system, a procedure that requires careful frequency and phase synchronization of all intermediate network nodes handling the flow of passing bits. Today, services such as circuit-switched telephony and storage area networks in data centers are still based on TDM technologies, but increasingly this TDM traffic needs to be transported over packet-optical networks. It becomes necessary to emulate a traditional wireline circuit over an Ethernet network and to maintain synchronization between the ingress and egress points of the Ethernet wide area network.

FIGURE 68: 40 and 100 GbE Physical Media

Somehow in every TDM network there is an extremely accurate frequency source, a primary reference clock (PRC) from which all other TDM clocks in the network directly or indirectly derive their timing, i.e. frequency. Clocks derived in this manner are said to be traceable to a PRC. The primary clock signal is distributed “downstream” through the network in order to synchronize all other devices, which are normally grouped into separate stratum clock levels depending on how “far” from the original PRC the device is located (Figure 69). The migration from such a synchronous TDM network to Ethernet-based asynchronous transport introduces new challenges. When a packet network is to support TDM-based services, it must provide correct timing at the traffic interfaces. The transport of TDM signals through Ethernet requires that the signals at the output of the packet network comply with the TDM timing requirements in order for the attached TDM equipment to interwork correctly. Such an adaptation of TDM signals to be transported by a packet network is called a circuit emulation, and the entity performing the adaptation is referred to as an interworking function (IWF) (Figure 70, next page).

Circuit emulation is closely related to the concept of pseudowires. A pseudowire is an emulation of a point-to-point connection over a packet-switching network. The pseudowire emulates the operation of a "transparent wire" carrying the service, but it must be realized that this emulation rarely will be perfect. The service being carried by the pseudowire may be SDH, SONET, ATM or frame relay, while the underlying packet network may be a Layer 2 network such as Ethernet, an IP network or an MPLS network.

FIGURE 69: Stratum Clock Levels in a TDM Network for Circuit-switched Telephony. Clock Signals May Be Distributed over Several Paths to Ensure Redundancy

ETHERNET AND LAYER 2 TECHNOLOGIES
The indirection of frequency is the indirect generation of frequency (differential timing).

The most advanced requirements on synchronization in today’s metro networks are generated by mobile backhaul traffic, which is dependent on both frequency, and phase and time synchronization. For example, for 3GPP2 base stations, including those for LTE, the following requirements are typical:

- A frequency accuracy of 0.05 parts per million (ppm) at the air interface
- 2.5 microseconds (µs) time accuracy between neighboring base stations, i.e. ± 1.25 µs difference to coordinated universal time (UTC)

The EMXPs can do automatic selection of the synchronization source to improve synchronization resilience. Network-level selection logic, possible clock quality levels, noise tolerances, noise generation and transfer limits, holdover performance, etc.

The primary synchronization source. If this primary clock fails, the messages can identify a secondary clock that then becomes the primary. If the primary clock fails, the messages can identify a secondary clock that then becomes the primary. The SSM messages are sent over the Ethernet Synchronization Message Channel (ESMC), as described in ITU-T Recommendation G.8264. In an Infinera packet-optical network, the Synchronous Ethernet function is entirely based on the Ethernet PHY media and its connectivity in the EMXPs. Using either of the Layer 2 traffic forwarding mechanisms (see Chapter 2), MPLS-TP Label-Switched Paths or Ethernet Service VLANs, has no effect on timing or the ESMC. A physical Ethernet interface using MPLS-TP will forward Synchronous Ethernet in the same way as a physical Ethernet interface using an Ethernet user network interface (UNI) or network to network interface (NNI) (Figure 72).
5.3.2.2 Precision Time Protocol (PTP) - IEEE 1588v2

PTP is based on IP multicasting and can be used on any network that supports multicasting. Precision is typically in the range of 100 ns to 10 µs, depending on the real-time capabilities of the end systems. The PTP standard can distribute time precisely and estimate wander, jitter and delay within an EMXP-PTP protocol handling, the very low convergence time of the PTP protocol, i.e. the time it takes for the protocol to recover from a failed network node can be routed around the failure in the network to realign the clock and compensate for the wander that builds up in the network. The convergence time of the PTP protocol, i.e. the time it takes for the protocol to achieve the desired level of synchronization, is dependent on the quality of the underlying packet network. Although the EMXPs are not directly involved in PTP/1588v2 protocol handling, the very low wander, jitter and delay within an EMXP-based packet-optical network makes the PTP protocol converge extremely rapidly.

IEEE 1588 specifies two different mechanisms to maintain synchronization: boundary clock (BC) and transparent clock (TC). The BC mode of operation relies primarily on the master/slave relationship between network elements. In the TC mode of operation, the network elements add an arrival and departure time stamp to outgoing messages, indicating the delay that has been added by internal processing (Figure 73). The TC mode of operation, which EMXPs support, has several advantages since it does not require any preconfiguration, is easily interoperable between network elements and handles various types of asymmetries in the network. IEEE 1588 TC can be used for Ethernet VLANs, Ethernet service VLANs and MPLS-TP pseudowires. The BC mode of operation allows the network to reinitialize the clock and compensate for the wander that builds up in the network.

5.3.2.3 Differential Timing

Timing recovery for a TDM circuit emulation service requires that the timing of a signal is similar on both ends of the packet network, i.e. at the “outside” of the MPE. The clock of the TDM service must be preserved in such a way that the incoming service clock frequency is replicated as the outgoing service clock frequency. In network-synchronous operation, the packet network operates in a fully synchronized manner using a PRC-traceable clock, but this does not necessarily preserve the timing of the external TDM service. Using differential timing, the difference between the external TDM service clock and the network reference clock is encoded and transmitted across the packet network. Differential timing makes it possible to recover the external TDM service clock at the far end of the packet network. More information on timing recovery and transport of legacy TDM services such as SDH and SONET over an Infinera packet-optical network can be found in section 2.5 of this book.

5.4 ETHERNET PROTECTION

Wide area services, such as telephony, internet access and video on demand, require a high level of availability; unavailability is typically only tolerated for a few minutes per operating year. When failures occur in the network, they are not supposed to be noticed by the subscriber. The main purpose of an automatic protection switching (APS) mechanism is to guarantee the availability of backup resources and ensure that switchover is achieved within milliseconds. Protection switching can be implemented at various OSI network layers. An optical transmission network may include alternative fiber routes and protection switching at Layer 1. Ethernet/Layer 2 can perform protection switching as well, and there may also exist protection mechanisms at higher OSI layers. This section deals with the Ethernet/Layer 2 protection mechanisms.

Ethernet Spanning Tree Protocol and Rapid Spanning Tree Protocol can prevent loops and assure backup paths. However, both protocols are too slow to respond to network failures and are not used in packet-optical networks. Instead, other mechanisms, such as Link Aggregation Group (LAG) and Ethernet Ring Protection Switching, are more suitable. For Layer 2 networks employing MPLS-TP label-
MAC client can treat the group as if it were a single link. Link aggregation is capable of increasing both the capacity and the availability of the communication channel between devices interconnected by Ethernet. Link aggregation can also provide load balancing, in which traffic is spread across several physical links in order to avoid the overload of any single link (Figure 74, previous page).

5.4.1 Link Aggregation

5.4.1.1 Principles

Link aggregation, as defined by IEEE 802.3ad, is a method for aggregating two or more parallel transmission links to a LAG, such that a MAC client can treat the group as if it were a single link. Link aggregation is capable of increasing both the capacity and the availability of the communication channel between devices interconnected by Ethernet. Link aggregation can also provide load balancing, in which traffic is spread across several physical links in order to avoid the overload of any single link (Figure 74, previous page).

A dedicated protocol, the Link Aggregation Control Protocol (LACP), is used to authenticate and coordinate the network elements participating in the LAG (Figure 75). It is important to understand that a Layer 2 network may not change the order of frames sent between two endpoints (host). The LACP protocol will therefore assign each “conversation” between two hosts to one specific physical link and send all frames belonging to that conversation over this link. Dedicated hash algorithms, analyzing the fields of the frame header (VLAN ID, MAC address, MPLS-TP label, etc.), are used to spread the conversations evenly across the available physical links.

5.4.1.2 Multi-chassis LAG

Multi-chassis LAG (MC-LAG) refers to the ability to set up LAGs in which one or both endpoints have physical links that end in two or more different chassis, or in the case of the XTM Series, EMXPs. MC-LAG is supported by many vendors, but is not fully standardized, and its implementation varies by vendor. Multi-chassis LAG uses normal LACP signaling toward the connected peer and is “seen” by the connected peer as an ordinary LAG (Figure 75).

5.4.2 Ethernet Ring Protection Switching

Ring-based networks are often attractive since they can offer a simple form of redundancy in a network consisting of many nodes. A redundant path for each node is provided by just one additional link that closes two adjacent branches to form a loop. However, Ethernet as such does not allow for loops since frames would circulate forever, so the loop has to be blocked at some point in the network. This can be accomplished by the use of ERPS, as specified in ITU-T Recommendation G.8032 (Figure 77).

State and protection are coordinated between the EMXPs involved, using a special signaling protocol (Inter-Control Center Protocol or ICCP). Protection LAG 1+1 and N+N are supported by the Infinera packet-optical network. The XTM Series’ multi-chassis LAG brings a number of benefits, such as:

• Increased network availability
• Fast protection switching (< 50 ms) that allows for demanding customer SLAs (compare to IP-level protection < 5 s)
• Network redundancy without complex signaling between nodes
• Few interoperability issues, since each side can see the other just as in standard protection LAG
• Supported by almost all client equipment

5.4.2.1 Multi-chassis LAG

Multi-chassis LAG (MC-LAG) refers to the ability to set up LAGs in which one or both endpoints have physical links that end in two or more different chassis, or in the case of the XTM Series, EMXPs. MC-LAG is supported by many vendors, but is not fully standardized, and its implementation varies by vendor. Multi-chassis LAG uses normal LACP signaling toward the connected peer and is “seen” by the connected peer as an ordinary LAG (Figure 75).
Each node has two links connected to its adjacent nodes. To avoid loops, one of the links in the full ring is always blocked. This link, which is blocked under normal conditions, is called the Ring Protection Link (RPL). One of the nodes connected to the RPL is designated the RPL owner and is responsible for controlling the status of the link. In the example above, the link between node C and node D is the RPL and node C is the RPL owner.

When a failure is detected, the RPL owner is responsible for unblocking the RPL and opening it for traffic. A link failure can be detected by link-down events or OAM frames, for example, a loss of continuity.

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Ethernet Ring Protection Switching (ERPS) is a family of protection mechanisms that can be applied to Ethernet networks. It provides a simple and reliable method for protecting Ethernet traffic against link failures.

Ethernet Ring Protection Switching Version 2 adds some very useful features. Most important is that it introduces more advanced Ethernet ring interconnection architectures (multi-ring/ladder network), with the concept of sub-rings. This creates the ability to have different rings interconnected at two or more points, avoiding a single point of failure. ERPSv2 can support multiple ERPS instances on a single ring. In addition to the point-to-point service, security and high availability, must be guaranteed. ERPSv2 supports both revertive and non-revertive operation after the condition that caused the switch has been cleared to minimize unplanned traffic hits. ERPSv2 also includes “manual switch” and “force switch” operator administrative commands. The XTM Series includes support for both ERPSv1 and ERPSv2.

5.5 CARRIER ETHERNET
ARCHITECTURE AND SERVICES

5.5.1 Carrier Ethernet: Ethernet as a Transport Service

Ethernet is the all-dominant Layer 2 data networking protocol, which means that economies of scale have made Ethernet switching equipment very attractive from a cost perspective. Naturally, carriers want to take advantage of the continued performance and cost evolution of the Ethernet technology.

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To transport Ethernet traffic efficiently in metro and regional networks, the carrier network operator/service provider must establish an Ethernet of its own—a Carrier Ethernet network—that forwards traffic between the customer LANs “in the Ethernet way.” Using Ethernet as the transport mechanism requires the addition of functions that transform the connectionless and broadcast-oriented Ethernet for LAN use, into a more predictable and “circuit-like” channel suitable for wide area networking.

Packet-switched wide area networks, however, especially those based on Ethernet, offer other advantages to network operators than those typically found in legacy carrier networks.

- Most potential users of a WAN or metropolitan area network (MAN) service have an Ethernet-based LAN and want to extend it to multiple sites. It makes sense for a carrier to offer Ethernet-type transport services, since customers are familiar with the protocol, and their equipment already has Ethernet interfaces.

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services over metropolitan optical networks. The principal concept was to bring the simplicity and cost-model of Ethernet to wide area networks, while adding stability, predictability and manageability. Since then, MEF has issued a wide range of technical specifications for Carrier Ethernet equipment, specifications that are adhered to by Infinera (Figure 78, previous page). Metro Ethernet Forum defines a Carrier Ethernet network as a set of certified network elements that are interconnected and provide Carrier Ethernet services, locally and worldwide.

In this context, it is important to remember that the term “Ethernet” is ambiguous and world-wide.

Ethernet regarded as a “point-to-point” transmission link, i.e. the physical transmission technologies such as WDM, SDH/SONET, Ethernet PHY or any other physical transport layer, which can be included in an SLA for voice, video and data over converged business and residential networks.

Service management. Carrier Ethernet service providers are expected to manage large numbers of customers and their multiple services, spanning wide geographical areas. Carrier Ethernet includes advanced capabilities for provisioning, maintaining and upgrading Ethernet services (Figure 79).

5.5.2 Carrier Ethernet Architecture and Terminology

A service provided by a Carrier Ethernet network starts at one user network interface (UNI) and ends at another UNI. The UNI is the point where the service provider accepts and delivers Ethernet frames, i.e. a dedicated, physical demarcation point between the responsibility of the service provider and that of the subscriber. The attached customer equipment (CE) can be a router, switch or computer system, and the physical medium of the UNI can be copper, coax or fiber operating at 10 Mb/s, 100 Mb/s, 1 Gb/s or 10 Gb/s, according to the IEEE 802.3 Ethernet PHY/MAA protocol. The UNI functions are divided between the CE and provider edge equipment as the function sets UNI-C and UNI-N, respectively. Sometimes the CE does not support all the UNI-C functions; in such cases a network interface device of how the service provider to user various underlying transport technologies to achieve the best total economy.

Reliability. Carrier Ethernet is resilient and reliable. Protection mechanisms are available to provide end-to-end and individual link protection. The speed of recovery from failures is comparable to that of SDH/SONET networks or better.

Quality of service. Carrier Ethernet supports the delivery of critical applications that are expected to be treated with the best performance levels. The performance parameters of Carrier Ethernet are quantifiable and measurable so that they can be included in an SLA for voice, video and data over converged business and residential networks.

• Ethernet regarded as a service. This is the Metro Ethernet Forum’s scope and view. Carrier Ethernet services concern the user-to-user transmission of Ethernet frames over any available physical transport layer.

A Carrier Ethernet network is by definition a two-layer structure, consisting of a physical transport layer, which can be WDM, SDH/SONET, Ethernet PHY or any other physical transport technology, and a pure Ethernet frame handling layer, the Ethernet MAC (802.3) layer. The Ethernet services offered are created on “top” of transmission technologies such as WDM optical networking. The following discussion focuses on Carrier Ethernet services and the Ethernet MAC layer. Details of how the Ethernet MAC layer is carried by the optical WDM layer of the InfraFlex XTM Series are described in Chapter 2.2.4, “Packet-Optical Transport with the XTM Series.” Metro Ethernet Forum has defined five main attributes of Carrier Ethernet that distinguishes it from the familiar LAN-oriented Ethernet, and make it suitable as a transport service offered by carriers. The five attributes are:

- Standardized services. Carrier Ethernet provides five standardized service types (E-Line, E-LAN, E-Tree, E-Access and E-Transit) that enable transparent, private line, virtual private line and multipoint-to-multipoint connectivity over the wide area network. The services are provided independently of the underlying transport protocols and can be used with a high level of choice and granularity of bandwidth as well as quality of service. The services require no changes to customer LAN equipment or networks and accommodate existing network connectivity, such as time-sensitive TDM traffic and signaling, while being delivered over a single Ethernet connection between network and customer.

- Scalability. The scale of a customer LAN and that of a service used, with a transport network are fundamentally different in terms of geographical reach, number of users (endpoints) and speed. Carrier Ethernet is scalable in all those dimensions, while allowing the service provider to use various underlying transport technologies to achieve the best total economy.

- Reliability. Carrier Ethernet is resilient and reliable. Protection mechanisms are available to provide end-to-end and individual link protection. The speed of service management in Carrier Ethernet networks is a key element in Carrier Ethernet as it enables service provider to extend their control over the entire service path, starting and ending at the customer handoff points. The association between two or more UNIs via the Carrier Ethernet network is referred to as a virtual or Ethernet Virtual Connection. In the Carrier Ethernet world, this association is the equivalent of a “circuit,” and it is the Ethernet Virtual Connection that is assigned the various characteristics – attributes – to which a customer subscribes.

ETHERNET AND LAYER 2 TECHNOLOGIES

Scalability

Quality of Service

Service Management

Carrier Ethernet Attributes as Defined by Metro Ethernet Forum

FIGURE 79: Carrier Ethernet Attributes as Defined by Metro Ethernet Forum

91

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Footnotes start on page 111

90

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6.5.3 Carrier Ethernet 2.0 Services

In the Carrier Ethernet network, data is transported across point-to-point, point-to-multipoint and multipoint to-multipoint EVCs and OVCs according to the attributes and definitions of a set of well-defined Ethernet service types. Each service type provides transparent data transport between the UNIs and/or ENNIs of subscribers and operators. Three of the service types are based on EVCs (i.e. are for services between UNIs), and two are based on OVCs (i.e. at least one endpoint is an ENNI). EVC-based service types are E-Line, E-LAN and E-Tree, while E-Access and E-Transit are based on OVCs.

A complete MEP Carrier Ethernet service consists of an Ethernet service type associated with one or more bandwidth profiles and supporting one or more classes of service. A service also defines the transparency of Layer 2 control protocols and how they should be handled.

For Ethernet services based on EVCs, two variants are defined, differentiated by the method of service identification used at the UNIs. Services using port-based UNIs, i.e. where there is only one UNI and EVC per physical port of the provider edge device, are referred to as "private," while services using UNIs that are VLAN-based and multiplexed over the same physical interface are referred to as "virtual private." For example, an E-Line service that is port-based is referred to as Ethernet Private Line. E-Access and E-Transit services, which are based on Operator Virtual Connections and primarily defined for use within a service provider's network, have been restructured to eliminate the port/VLAN distinction where relevant, and has the functionality needed to implement all the service types above in a packet-optical network.

Implementing CE 2.0 services gives the network operator a whole new range of services to offer "on top" of the legacy Layer 1 transport service, thereby adding new revenue streams to an existing network investment. Furthermore, implementing Ethernet services, rather than IP/MPLS-based services with similar characteristics,
can make the necessary investments significantly lower, especially if the Ethernet services can be implemented on the previously deployed WDM platform.

5.5.4 Carrier Ethernet Service Attributes

A user of Carrier Ethernet subscribes to an Ethernet service type (E-Line, E-LAN, E-Tree, E-Access, E-Transit) with either a port-based or VLAN-aware service. The service attribute represents a service characteristic, which in turn is further defined by a set of Ethernet service attribute parameters. The attributes and parameters customize the overall performance and quality of service for each individual service and subscriber (Figure 83).

The Ethernet service attributes are of three main types:

1. Per-EVC service attributes defining the characteristics of the Ethernet Virtual Connection as such, such as:
   - EVC ID and type; point-to-point or multipoint
   - List of connected UNIs
   - Customer VLAN ID and class of service preservation
   - EVC performance: frame delay (latency), inter-frame delay variation, frame loss ratio and availability

2. EVC-per-UNI service attributes, such as:
   - UNI ID and physical interface capabilities: data rate, frame format
   - Ingress and egress bandwidth profiles
   - Service multiplexing capability
   - Layer 2 control protocol processing

3. Per-UNI service attributes, such as:
   - UNI/EVC ID
   - Customer VLAN ID/EVC mapping
   - Ingress/egress bandwidth profiles per class of service

5.6 Carrier Ethernet Traffic Management

The different applications, users and data flows in a Carrier Ethernet network require different priorities and performance guarantees. The process of differentiating traffic in this way is referred to as traffic management, and involves mechanisms such as queuing, scheduling and policing of Ethernet frames. With traffic management in place, it is possible to guarantee a certain quality of service for a given service with respect to, for example, data rate, delay, jitter and packet dropping probability. Quality of service guarantees are important if network capacity is insufficient, especially for real-time streaming applications such as voice over IP and IPTV, since these often require a fixed bit rate and are delay- and loss-sensitive. In the absence of network congestion, QoS mechanisms are in principle not required. However, temporary changes in traffic patterns and reconfigurations, for example when caused by protection switching, make QoS mechanisms necessary in virtually all networks.

Carrier Ethernet defines several traffic management mechanisms, which are described below.

5.6.1 Bandwidth Profiles

A bandwidth profile is a set of traffic parameters that defines the maximum average bandwidth available for the customer’s traffic. An ingress bandwidth profile limits traffic transmitted into the network and an egress bandwidth profile can be applied anywhere to control overload problems from multiple UNIs sending data to an egress UNI simultaneously. Frames that meet the profile are forwarded, but those that do not meet the profile are dropped.

Bandwidth profiles allow service providers to offer services to users in increments lower than what is set by the physical interface speed. Also, they provide the possibility to engineer the network and make sure that certain parts of the network are not overloaded.
MEF 10.2 specifies three levels of bandwidth profile compliance for each individual service frame:

- **Green**: the service frame is subject to service level agreement performance guarantees.
- **Yellow**: the service frame is not subject to SLA performance guarantees, but will be forwarded on a “best-effort” basis. These frames have lower priority and are discard-eligible in the event of network congestion.
- **Red**: the service frame is to be discarded at the UNI by the traffic policer.

Bandwidth profiles can be defined per Ethernet Virtual Connection and per class of service and are governed by a set of parameters, the most important being:

- **Committed information rate (CIR)**, which defines the assured bandwidth, expressed as bits per second.
- **Excess information rate (EIR)**, which defines “extra” bandwidth that may be temporarily used, expressed as bits per second.
- **Committed burst size (CBS)** and **excess burst size (EBS)**, which define temporary bursts of information that can be handled.

The EVPN also supports a simpler bandwidth profile that only uses the traffic parameters:

- **Rate**, expressed as bits per second.
- **Burst size**, expressed as bytes (Figure 84).

MEF 10.2 specifies three levels of bandwidth profile compliance for each individual service frame:

- **Green**: the service frame is subject to SLA performance guarantees, but will be forwarded on a “best-effort” basis. These frames have lower priority and are discard-eligible in the event of network congestion.
- **Red**: the service frame is to be discarded at the UNI by the traffic policer.

Ingress bandwidth profiles can be applied per UNI to all traffic regardless of VLAN tag or EVC ID, more granularly on an EVC basis, or even based on a class of service marking such as a customer-applied VLAN priority tag (Figure 85). Compliance to the bandwidth profile is determined through two “leaky-bucket” algorithms, using a principle referred to as two-rate three-color marker (TRTCM).

### 5.6.2 Class of Service and Service Level Agreements

The integration of real-time and non-real-time traffic over Ethernet requires differentiating packets from different applications and providing differentiated performance according to the needs of each application. When a network experiences congestion and delay, some packets must be dropped or delayed. This differentiation is referred to in Carrier Ethernet as class of service (CoS).

CoS can be applied at the EVC level (with the same CoS applied to all frames transmitted over the EVC), or applied within the EVC by customer-defined priority values (Figure 86).

### 5.7 Carrier Ethernet Operations, Administration and Maintenance (ETERNET OAM)

Using Ethernet as an end-to-end wide area network service rather than as a link layer protocol creates a need for a new set of operations, administration and maintenance mechanisms and protocols. Service providers must be able to provision and maintain large volumes of Ethernet services and subscribers in a rational and cost-efficient way.

Furthermore, an end-to-end wide area Ethernet service, i.e., an Ethernet Virtual Connection, often involves one or more carriers/network operators providing the underlying transmission capacity in addition to the Ethernet service provider. Carrier Ethernet OAM requires the coordination of OAM performed by a number of administrative entities and by different technical systems.

### 5.7.1 The Management Framework

Ethernet OAM builds on an established management framework and terminology.

---

**FIGURE 84**: Conceptual Example with Three EVCs Sharing the Same UNI. The Three EVCs Can Always Be Met, the Three EVCs Cannot Always Be Met Simultaneously

**FIGURE 85**: Three Types of Bandwidth Profiles Are Defined in MEF 10.1 in the data, such as customer VLAN IEEE 802.3 “q” or “p” tag markings.

The class of service settings, together with bandwidth profiles, are used to make service level agreements between the service provider and its customers. In addition to the various parameters of the bandwidth profiles (CIR, EIR, etc.), the SLA typically also specifies maximum values for various types of frame delay and frame delay variation (jitter), and values for the availability of the subscribed-to service (Figure 86, next page).
using the concept of a data model, a management information base (MIB), describing the status of the individual network elements in the managed network (Figure 87).

The Network Management System (NMS) uses an MIB to keep track of the status of the individual network elements. A management information base is a database representation of the managed objects in a telecommunications network. This database, normally located in the central network management system, keeps an updated view of network element status by sending queries to the elements, and is also used for configuration and provisioning activities. An MIB, together with an associated management protocol such as Simple Network Management Protocol Version 2 (SNMPv2), defines a standard network management interface for the administration and maintenance of a particular network element (Figure 88).

5.3.2 Standards for Ethernet OAM

From an OAM perspective, there are several standards that work together in a layered fashion to provide Carrier Ethernet OAM. The MEF 802.3ah defines OAM at the link-level. With more of an end-to-end focus, 802.1ag defines connectivity fault management for identifying network-level faults, while ITU-T Y.1731 adds performance management, which enables SLAs to be monitored. The functions of these OAM layers are implemented either in a standalone network demarcation device (i.e. the NID or EDU) or integrated into the node equipment (i.e. the EMXP in Infinera’s case) (Figure 89).

5.3.3 The Service Lifecycle

The life of an EVC starts with a service order initiated by a customer. The order contains various types of EVC information, such as UNI locations, bandwidth profiles, class of service, etc. After provisioning the EVC, the service provider and involved network operators conduct initial turn-up testing to verify that the EVC is operational and fulfills the subscribed-to characteristics. While the EVC is in use, all parties involved—the subscriber, the network operators/carriers, and the service provider—want to monitor the same EVC to ensure that it adheres to the specified SLA regarding delay, jitter, loss, throughputs, availability, etc. Finally, when the EVC is not needed any longer, the assigned network resources should be freed up and made available to other EVCs.

FIGURE 86: Examples of Service Level Agreements for Different Applications. Source: Metro Ethernet Forum

FIGURE 87: The Ethernet OAM Framework and Terminology

The described life cycle of an Ethernet service is depicted in Figure 90, next page. The involved processes fall into three main categories: provisioning, performance and fault management. The MEF, ITU-T and IETF OAM standards provide the means to monitor and execute the required actions on the Carrier Ethernet. Ethernet service provisioning comprises the processes of setting up the required EVCs for a customer and assigning them attributes such as bandwidth profiles and class of service. The provisioning process also includes procedures for testing the service once it is set up, but before it is turned over to the customer. The configuration of the service is checked for correctness and verified against its service acceptance criteria (SAC). The Carrier Ethernet provisioning process specified by MEF is based on the ITU-T Specification Y.1564.
5.7.4 Ethernet Service OAM – Performance and Fault Management

Performance management and fault management comprise the processes of monitoring EVCs for proper operations, discovering any problems and correcting faults that have occurred.

- Link level performance and fault management as defined by IEEE 802.3ah provides mechanisms to monitor link operation and health, and for elementary fault isolation.
- The more sophisticated end-to-end service level performance and fault management of the Ethernet Virtual Connection is often referred to as Ethernet service OAM (SOAM) and is addressed by MEF Specifications 17, 30 and 31, and the ITU-T Y.1731 and IEEE 802.1ag standards.

In a real wide area network, Ethernet Virtual Connections may span several networks, each with their own management needs. Since managing functionality "end-to-end" means different things to the end customer, the network operator and the Carrier Ethernet service provider, Ethernet SOAM must handle and interact with performance and fault management over several Ethernet OAM domains. An OAM domain is simply a network or sub-network of elements belonging to the same administrative entity (Figure 91).

Recognizing the fact that Ethernet networks often encompass multiple administrative domains, IEEE 802.1, ITU-T SG 13 and MEF have adopted a common, multi-domain SOAM reference model. The Carrier Ethernet is portioned into customer, service provider, and operator maintenance levels. Service providers have end-to-end service responsibility; operators provide service transport across a sub-network.

The concepts of the SOAM reference model are summarized by Figure 92 (on the next page), indicating the six default MEG levels considered by MEF.

Given the above SOAM reference model, MEF specifications 30.1 and 35 define a wide set of performance and fault management activities for the EVC and its sub-components, such as:

- Frame delay: Measurement of one-way and two-way (round-trip) delay from MEP to MEP.
• Continuity check.
• Availability.
• Frame loss ratio.
• Inter-frame delay variation.

Example of Ethernet SOAM Maintenance Entities. Source: Metro Ethernet Forum

FIGURE 92: Fault Management

Level
MEG are issued periodically by the MEPs and calculate the availability of the service. A period of time, e.g. a month.

The number of transmitted frames over a specified time, e.g. a month.

Downtime is measured over a period of time, e.g. a year, and used to calculate the availability of the service.

Fault Management

Continuity check is also used to detect unintended connectivity between MEGs, as well as to verify basic service connectivity and health.

Remote defect indication signal. When a downstream MEP detects a fault, it will signal the condition to its upstream MEPs. This behavior is similar to the remote defect indication function in SDH/SONET networks.

Alarm indication signal. An MEP can send “Heartbeat” messages to its peers.

Currently, three heartbeat messages are used periodically by the MEPs and

5.8 METRO ETHERNET FORUM “THIRD NETWORK” VISION

Current trends in data communications imply a scenario in which network operators can deliver self-service, on-demand communication services over multiple, interconnected networks. Metro Ethernet Forum refers to this evolution as the emergence of a “Third Network” (Figure 93). A central element of MEF’s Third Network vision is to enable a network to proactively detect the loss of connectivity between endpoints. Continuity check is also used to detect unintended connectivity between MEGs, as well as to verify basic service connectivity and health.

Remote defect indication signal. When a downstream MEP detects a fault, it will signal the condition to its upstream MEPs. This behavior is similar to the remote defect indication function in SDH/SONET networks.

Alarm indication signal. An MEP can send an alarm signal to its higher-level MEGs, which will inform the root of the disruption, immediately following the detection of a fault.

• Linktest is an on-demand QAM function initiated in an MEP to track the path to a destination MEP. It allows the transmitting node to discover connectivity data about the path.

• Loopback is an on-demand QAM function used to verify the connectivity of an MEP with its peers.

SUMMARY

Optical fiber provides almost lossless transmission of signals over a wide range of frequencies. Packet switching, implemented according to the Ethernet family of protocols, offers one of the most efficient ways ever to sort and direct streams of digital data. With packet optical networking, two outstanding technologies are positioned to dominate the next generation of transport networks. In addition, the continuing evolution driven by industry groups ensures dependable and open standards for future needs.

Infinera’s packet-optical technology, realized through its XTM Series platform, the DNA multi-operator network becomes more intelligent for the Emerging Layer C to thrive. The simplified Layer T network is best built using super-channels and intelligent capabilities designed to meet customer needs.

As the adoption of cloud services accelerates, it is imperative that the transport network becomes more intelligent for the Emerging Layer C to thrive. The simplified Layer T network is best built using packet-optical technologies combined with rich software management and control applications.
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<thead>
<tr>
<th>Layer</th>
<th>C</th>
<th>T</th>
<th>Layer 1</th>
<th>aggregation</th>
<th>15</th>
<th>Ethernet transport</th>
<th>16</th>
<th>Layer 2</th>
<th>aggregation</th>
<th>14</th>
<th>Ethernet transport</th>
<th>17</th>
<th>leased line</th>
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<tbody>
<tr>
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<td></td>
<td></td>
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<td>framework</td>
<td>45</td>
<td>native Ethernet</td>
<td>19, 20</td>
<td>network</td>
<td>functions virtualization (FV)</td>
<td>53</td>
<td>interface card (NIC)</td>
<td>74</td>
<td>interface device (ND)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>multiplexer</td>
<td>18, 36</td>
<td>OAM domain</td>
<td>100</td>
<td>multi-layer management</td>
<td></td>
<td>38</td>
<td>management system</td>
<td>45</td>
<td>network management</td>
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<tr>
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<td></td>
<td></td>
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<td></td>
<td>19</td>
<td>transport unit (OTU)</td>
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<td></td>
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<td>19</td>
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<td></td>
<td>Packet-Optical</td>
<td></td>
<td>Packet Transport Switch (EMXP)</td>
<td>35</td>
<td>transport system</td>
<td></td>
<td>3</td>
<td>networking, applications</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OSS integration toolkit</td>
<td>48</td>
<td>point-to-point EVC</td>
<td></td>
<td>92</td>
<td>optical data unit (ODU)</td>
<td></td>
<td>20</td>
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<td></td>
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<td></td>
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<td></td>
<td>69</td>
<td>power consumption</td>
<td></td>
<td>41</td>
<td>primary reference clock (PRC)</td>
<td></td>
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<td>Rapid Spanning Time Protocol (RSTP)</td>
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<td>Backbone Bridges</td>
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1 Optical Transport Network is a standard for multiplexing and switching signals at OSI Layer 1.
2 Multiprotocol Label Switching—Transport Profile is a mechanism to create virtual connections.
3 The Open Systems Interconnection (OSI) model is a conceptual model that characterizes and standardizes the communication functions of a telecommunication or computing system.
4 Analysts estimate that Layer 2 equipment is only 30 to 50% of the cost of Layer 3 equipment.
5 Service restoration times of 30 seconds or more are typical for STP.
6 A data communications network is used for the delivery of data from one device to another. The data can be transferred, and a stream of data is delivered in the same order as it was sent.
7 Known as e.g. 10G BASE-X.
8 See section 2.3 for more on MPLS-TP.
9 Note that the use of the term “router” is historic and neither requires nor precludes the ability to switch packets. A router is sometimes used instead of “node” in an MPLS context.
10 VPLS is defined in IETF RFC 4761 and RFC 4762.
11 E1 is a 2 Mb/s signal in the older Plesiochronous Digital Hierarchy (PDH) standard.
12 MPLS used in conjunction with IP and its routing protocols.
13 The IEEE 1588 standards describe a hierarchical master-slave architecture for clock distribution in computer networks, originally known as the Precision Time Protocol (PTP).
14 Enhanced Telecom Operations Map.
15 Multi-Technology Operation Systems Interface (MOTOSI) is a TM Forum standard for implementing interfaces between operations and support systems (OSS).
16 Connection-oriented service: A semi-permanent connection is established before any useful data can be transferred, and a stream of data is delivered in the same order as it was sent. Transport SDN is sometimes used to specifically designate integrated Layer 1/Layer 2 networks operating under the SDN scheme.
17 OSPF is a trade organization standardizing the OpenFlow protocol and related technologies.
18 "White box" is a generic term for minimalistic packet switches and commodity CPU and memory.
19 “Yellow box” is a generic term for minimalistic packet switches built from merchant silicon.
20 North American operators of cable and direct broadcast television systems are often referred to as MSOs. In other parts of the world, the abbreviation CATV operator is used.
21 Data Over Cable Service Interface Specification (DOCSIS) is an IEEE standard that defines the protocol used to talk to cable modems.
22 For Gigabit Ethernet, some vendors provide equipment that supports a jumbo frame option, where frames can have a data payload of up to 10,000 bytes.
23 The number 2 refers to the second layer in the standardized OSI reference model for data communications.
24 In CSMA/CD, the devices (called stations) can broadcast data over the medium whenever it is idle. If more than one station transmits at the same time and signals collide, the transmission is stopped by the involved stations, which will then wait for some random time and then restart transmission.
25 The “Q” refers to the name of the IEEE 802.1Q standard for VLANs.
26 Service restoration times of 30 seconds or more are typical for STP.
27 In many Metro Ethernet Forum technical specifications and some other literature, the abbreviation is used, while in carrier Ethernet terms, the abbreviation CATV-ET is used.
28 The ETH layer is sometimes referred to as the layer path.
29 A service frame is a subscriber Ethernet frame to be forwarded by a service in a Carrier Ethernet.
30 TDM is a mechanism to create virtual connections.
31 Weighted random early detection (WRED) is a mechanism to control the rate at which packets are dropped.
32 TM Forum is a trade organization standardizing the OpenFlow protocol and related technologies.
33 VLAN (VLAN) is a mechanism to create virtual connections.
34 SyncE is a mechanism to create virtual connections.
35 Technical multiplexing and switching signals at OSI Layer 1.