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WHITE PAPER

OPTICAL TRANSPORT NETWORK (OTN) AND/OR MULTI-PROTOCOL LABEL SWITCHING (MPLS)? THAT IS THE QUESTION

Franck Chevalier, John Krzywicki and Mike Pearson

Inside

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White paper audience

This white paper has been written and designed for operators' executives to be able to take an informed decision regarding their technical strategy for their core network.

White paper objectives

The objectives of this white paper are to provide operators' executives with:

- a simple analogy with the highway and railway network to illustrate the concepts of utilisation of resources, routing flexibility, reliability and impact of traffic change in circuit-switched and packet-switched networks, to better understand the key issues associated with the exponential growth of packet-switched traffic and the rapid decline of legacy circuit-switched traffic in their networks
- an explanation of multi-protocol label switching (MPLS) and optical transport network (OTN) technology and standards
- a business-case comparison for different network architectures to enable operators' executives to take an informed decision regarding their technical strategy for their core networks
- an insight into how their technical strategy for their core networks impacts the flexibility of the business model they can adopt to remain profitable.

CONTENTS

1 EXECUTIVE SUMMARY

This white paper explores the different technical options that are available to operators to cope with the explosion of packet-switched traffic on their core networks.

It shows that the choice of technology dramatically influences the business model that operators can adopt for their core networks to remain profitable, and provides a business-case comparison for different network architectures to enable operators' executives to take an informed decision regarding the optimum technical strategy for their core networks.

This white paper was developed in collaboration with a number of operators and equipment vendors. All the assumptions used within this white paper were validated with them over the period between May 2011 and October 2011.

If you would like to discuss further please contact Franck Chevalier
franck.chevalier@analysysmason.com

1.1 Key issues in the telecoms industry

"One of the main challenges for operators today is the increasing unpredictability of traffic in terms of the amount being carried on their networks, where it is coming from, and where it needs to go."

Today, it is widely accepted that the volume of packet-switched traffic is increasing at an exponential rate in operators' networks, and that in the next 10 to 20 years the vast majority of traffic will be packet-based.

This fast-changing paradigm in the telecoms industry has meant that operators must be more flexible than ever to adapt their business model to address the following issues:

- How to bridge the gap between stagnating revenues and increasing network costs?
- How to cope with the increasing unpredictability of traffic patterns?
- How to optimise the use of network resources to minimise capital and operational expenditure (capex and opex)?
- How to maximise revenue opportunities?
- How to guarantee appropriate levels of quality of service (QoS) for various kinds of packet-switched traffic (in particular, guaranteeing high-quality voice services)?

Bridging the gap between stagnating revenues and increasing network costs

Many operators are experiencing eroding profit margins because their costs and revenues are increasing at different rates. Revenues are stagnating, mainly due to a decrease in voice revenues and increasing competition in other, if not all, services. Costs, on the other hand, have continued to rise as a result of the infrastructure expansion required to support new data services. Most importantly, the traditional service provider business model is being challenged, primarily because of the de-integration of the traditional vertical model, forcing network service providers to carry an ever-increasing amount of traffic over the top (OTT). OTT services are services that are created outside of the operator's network. Yet, service providers have to carry this traffic without extracting any additional income, as all the service revenue goes to the owner of the content. Service provider revenues are restricted to the network access, which is sold as flat-rate bandwidth plans. As a result, the core of the network has become a cost-centre commodity, and the goal becomes to relentlessly pursue a strategy and architecture that takes every single bit of cost out of that network, yet making sure that it remains flexible enough to handle all the varying traffic it has to carry, while meeting or exceeding the service level agreements (SLAs) in place with customers.

Coping with the increasing unpredictability of traffic patterns

One of the main challenges for operators today is the increasing unpredictability of traffic in terms of the amount being carried on their networks, where it is coming from, and where it needs to go. The causes for this unpredictability are multiple:

- The consolidation of data centres and the advent of cloud computing allow content and service providers to 'migrate' content and computing resources from one location to another, based on where they need to be consumed. This creates substantial shifts in traffic patterns as sources and sinks of information can change instantaneously.
- The increased mobility of content users presents additional challenges. Until recently, there was a clear relationship between the user and the user's location when accessing the network, as everybody was physically 'tethered' to the network. Today's radio access networks are increasingly capable of supporting high-bandwidth applications, including streaming video, and a plethora of mobile devices allow people to consume content no matter where they are. As a result, consumers have detached themselves from the network; they are mobile and they can do things on the move that they used to only be able to do sitting in front of their 'attached' computers.
- Exceptional events such as sports events (e.g. football finals, Olympics, etc.) and other events such as political elections, can generate large short term demands between particular network nodes (i.e. telecommunication nodes serving the different venues of that event).

The net effect of mobility and cloud computing is that aggregation networks become less efficient. Aggregation networks are static and are built based on knowing where the users are, where the content is stored, and where the applications are running. All of this is now fluid and dynamic, and hence the core transport network needs to provide flexible, ad hoc aggregation, and packet-switched networks provide the optimum technology to achieve this. In marked contrast, circuit-based technology is more suitable for static traffic and is not well adapted for ever-changing traffic patterns.

"Operators are seeing rapid growth in demand for carrier Ethernet services, for both business and wholesale services. Industry analysts, including Infonetics Research and Ovum, continue to forecast strong growth in worldwide carrier Ethernet services – the market is currently worth USD20 billion and is set to grow to USD50 billion by 2014.[1]"

Nowadays, packet networks routinely carry voice traffic, as illustrated by the adoption of next generation networks (NGNs) by operators throughout the world.

Optimising the use of network resources to minimise capex and opex

Operating in such a difficult landscape requires more dynamic intelligence in the network and optical layers. More immediately, maximising the use of existing assets is of paramount importance for profitability. However, circuit-switched infrastructure is inefficient at carrying packet-based traffic. A typical packet-based traffic flow will only peak at its maximum bandwidth in short, infrequent intervals, and most of the time, will have a throughput significantly lower than the maximum bandwidth. Therefore, dedicating for example 1Gbit/s of capacity at all times for a GbE service traffic flow would result in a significant under-utilisation of network resources. Operators using circuit-switched technology (such as optical transport network or OTN) need to allocate fixed-capacity circuits to transport packet-switched traffic, which results in 'stranded' capacity on those circuits that no other services can use.

In marked contrast, the ability of packet-switched networks to aggregate traffic and use a pool of shared capacity means that trunk links on packet-switched networks typically require much less capacity than would be needed from an equivalent circuit-switched network. This effect is known as statistical multiplexing gain, where some traffic flows will peak and others will trough, compensating for one another, and therefore requiring much less capacity overall than if the networks were dimensioned for the peak traffic requirements.

Put another way, with a circuit-switched network, an operator can only sell the provisioned bandwidth only once, while packet-based capacity can be sold multiple times limited only by the amount of statistical gain that can be achieved.

Maximising revenue opportunities

Operators are seeing rapid growth in demand for carrier Ethernet services, for both business and wholesale services. . The challenging economic climate that currently exists is further driving the need for intelligent and efficient networks. Industry analysts, including Infonetics Research and Ovum, continue to forecast strong growth in worldwide carrier Ethernet services – the market is currently worth USD20 billion and is set to grow to USD50 billion by 2014.[1]

The most dramatic growth in carrier Ethernet services is coming from mobile backhaul. Infonetics Research forecasts that Ethernet microwave revenues will grow at a compound annual growth rate (CAGR) of 41% over the period 2011–2015. The problem facing mobile carriers – on top of downward price pressures – has been the surge in mobile data traffic since the iPhone was launched in 2007, plus the fact that the smaller footprint of 3G cell sites requires more cell sites with scalable backhaul capabilities. Another key driver for carrier-grade Ethernet services has been video applications. For example, Netflix is now dominating North America bandwidth demand and smartphones are pushing up the use of mobile video.

Operators are rapidly responding to this increase in demand by deploying packet-based infrastructure in their networks to support the delivery of carrier-grade Ethernet metro services. In marked contrast, circuit-switched technology can only provide a subset of carrier Ethernet services, therefore reducing the opportunity for revenue.

Guaranteeing appropriate levels of QoS for various kinds of packet-switched traffic

Packet-switched networks have evolved dramatically over time. In the early days of packet switching, all networks were 'best effort', which meant that different types of traffic were all carried with the same priority and were all subject to the same degradation in performance when a network congestion occurred. Consequently, there was a justified scepticism as to whether packet networks were good enough to carry voice. Nowadays, packet networks routinely carry voice traffic, as illustrated by the adoption of next generation networks (NGNs) by operators throughout the world. The focus has shifted entirely away from whether packet networks are capable of carrying high-priority traffic demanding high QoS; instead, the main interest is in using the technology to carry both high-priority and low-priority traffic over the same network at the lowest possible cost.

[1] Total Telecom (August 2011), Carrier Ethernet key to telecoms growth. Available at http://www.totaltele.com/view.aspx?ID=467030.

1.2 Technology scenarios

"In order to estimate the revenue associated with each network architecture, we conducted market research on what operators charge for Ethernet services when provided on an MPLS versus OTNs."

In response to these challenges, operators can implement different technical strategies based on different core network architectures. In this white paper, we consider three possible strategies to handle growth in packet-switched traffic and maintain service quality, namely the following:

- **Scenario 1 (MPLS) –** Implement a packet-switched network based on the multi-protocol label switching (MPLS) technology, where all switching in the core network occurs on a packet basis at every node.
- **Scenario 2 (OTN) –** Implement a circuit-switched infrastructure based on an OTN, where all switching in the core network occurs on a circuit basis and the switching of packets only occurs at the edge of the network.
- **Scenario 3 (MPLS + OTN) –** Implement an MPLS network as in scenario 1, but with additional OTN multiplexers in each node to implement traffic bypass.

In order to help operators make an informed decision regarding the optimum architecture for their own particular business model, we compare these three technology scenarios in terms of capex, revenues and opex for a reference core network linking London, Paris, Barcelona and Madrid. The average traffic flows assumed on the links in this reference network are shown in Figure 1.1.

In addition to the average traffic flows, we also modelled the impact of peak bandwidth demand on capex, revenue and opex. To do this, we considered the peak-to-average ratio (P/A ratio) for the traffic across all of the links of the network. We varied this ratio between 1.5 and 3 to investigate the impact of the burstiness of the traffic in each of the scenarios.

Note that our results for the OTN network serve as the base reference case (scenario 2) as we deliberately do not provide any absolute capex or opex, nor any absolute revenues due to the commercially sensitive nature of the data provided by the equipment vendors for the purpose of this study.

Capex and revenue results

The following figures illustrate the following for the different architecture scenarios[2]:

- provisioned capacity (Figure 1.2)
- total capex (Figure 1.3)
- revenue (Figure 1.4)
- revenue per unit capex - main result of study (Figure 1.5)

First, looking at the provisioned capacity, it can be noted that in order to carry the same traffic flows, an operator with an MPLS network only needs to provision 37% of the capacity compared to an OTN operator for a P/A of 2 as shown in Figure 1.2. The capacity provisioned in an MPLS network decreases to 35% of that required in an OTN network for the same traffic matrix when the P/A ratio increases to of 3. This is mainly due to the statistical multiplexing capability of the MPLS network.

Second, when comparing the total capex associated with the different architectures in Figure 1.3, it can be seen that, although we assume a unit cost for an MPLS port 33% higher than an OTN port, the lower

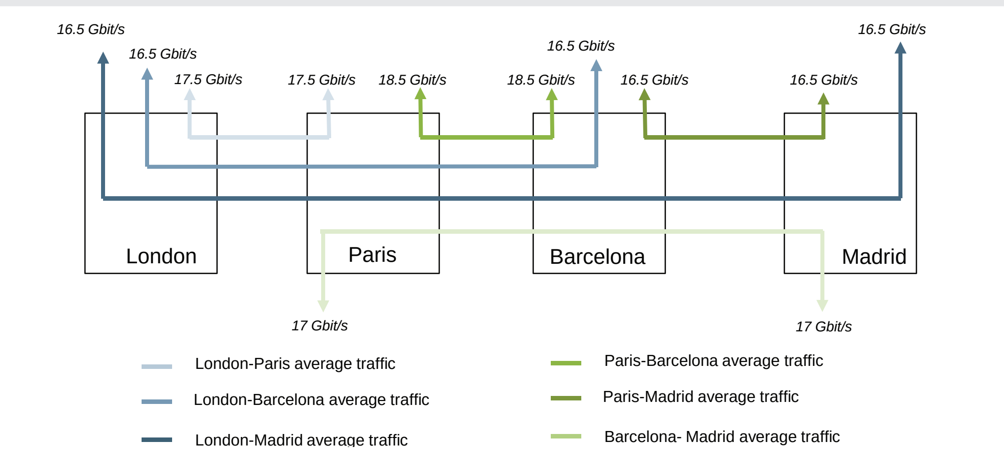

Figure 1.1: Reference network topology and traffic pattern
[Source: Analysys Mason, 2011]

[2] Relative to scenario 2- OTN network.

"We have seen that an MPLS operator does not need to provision as much additional capacity to cope with increasing demand for bandwidth. This leads to a much more sustainable business model, where capital costs are dissociated to a greater extent from bandwidth demand."

However, the business case for choosing the most efficient architecture is dictated by profitability. We found that, for every dollar of capex invested in the network, an MPLS network will provide 58% additional revenues for the operator compared to an OTN Network for a P/A ratio of 2, and 81% for a P/A ratio of 3.

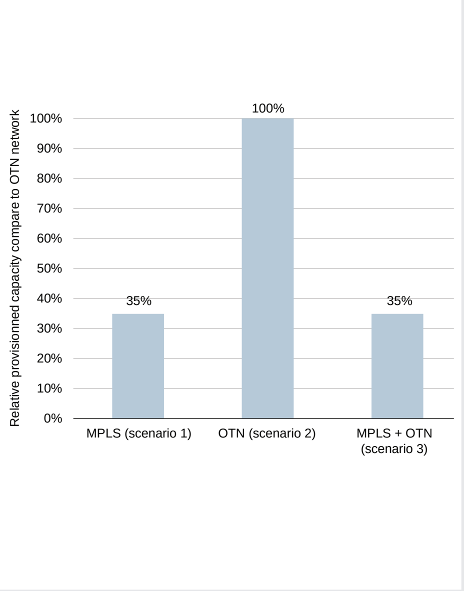

Figure 1.2: Provisioned capacity for different scenarios for P/A=2 [Source: Analysys Mason]

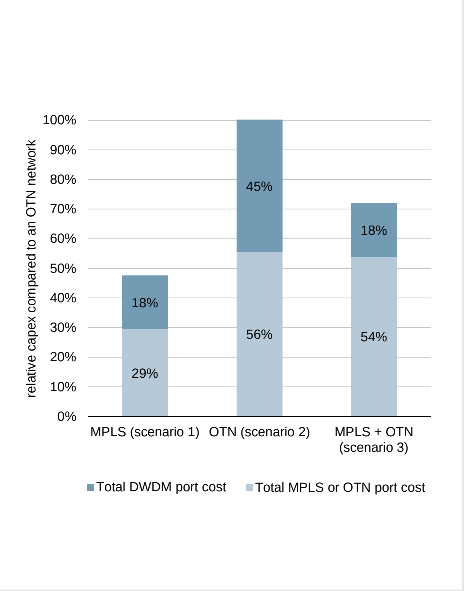

Figure 1.3: Total capex for different scenarios for P/A=2 [Source: Analysys Mason]

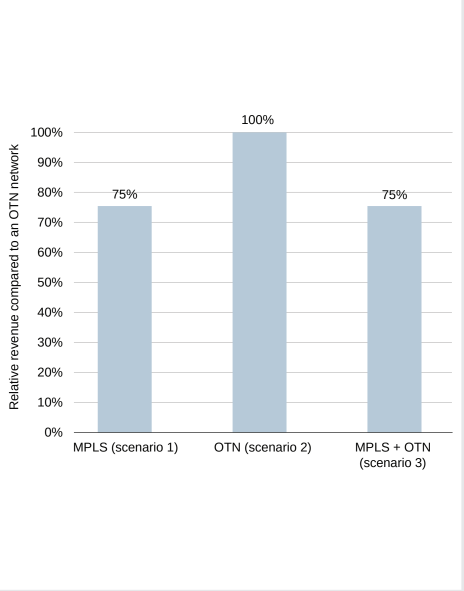

Figure 1.4: Revenue for different scenarios for P/A=2 [Source: Analysys Mason]

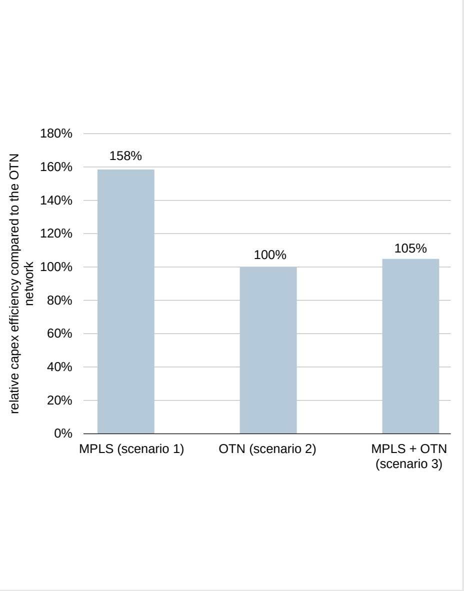

Figure 1.5: Main result of case study: revenue per invested unit capex for different scenarios for P/A=2 [Source: Analysys Mason]

1.2 Technology scenarios continued

"An MPLS network consumes 40% less energy compared to an OTN, which will help an MPLS operator reduce its energy bill and meet its green objectives."

capacity required in an MPLS network means that it has significantly fewer ports than an OTN (for the same traffic matrix). Overall, the capex for an MPLS network is only 47% of the capex for an OTN for a P/A of 2, and decreases to 42% for a P/A of 3.

In order to estimate the revenue associated with each network architecture, we conducted market research on what operators charge for Ethernet services when provided on an MPLS versus OTNs. We found that MPLS-based operators typically charge 25% less for a 1:3 contended service than OTN-based operators (as illustrated in Figure 1.4). The main difference between the two services is that the MPLS operator will typically provision capacity (and therefore guarantee) for just one third of the peak bandwidth, whereas the OTN operator will provision capacity for the full peak bandwidth.

However, the business case for choosing the most efficient architecture is dictated by profitability. We found that, for every dollar of capex invested in the network, an MPLS network will provide 58% additional revenues for the operator compared to an OTN for a P/A of 2 as illustrated in Figure 1.5, and 81% when the P/A ratio increases to 3.

It is interesting to note that in a real network it will not be possible to forecast the P/A ratio with any accuracy, mainly due to the increasingly unpredictable nature of traffic demand. The majority of operators interviewed expect the P/A ratio to increase over time, even for the highly aggregated trunk links in the core network, but no operator is able to predict by how much. In this dynamic scenario, MPLS networks provide an even better prospect than OTN because the higher the P/A ratio, the more profitable an MPLS operator will be compared to an OTN operator. In this context, it is clear that MPLS technology will be more suited to the unpredictable nature of future traffic.

We have seen that an MPLS operator does not need to provision as much additional capacity to cope with increasing demand for bandwidth. This leads to a much more sustainable business model, where capital costs are dissociated to a greater extent from bandwidth demand. This can be achieved by either:

- implementing different classes of service for revenue-generating compared to non-revenue-generating traffic such as OTT applications and peer-to-peer (e.g. best-efforts only for the non-revenue-generating traffic)
- increasing the contention ratio in the network, and thereby offering more and more services with the same provisioned capacity, but with a reduced SLA.

Opex results

In our modelling we have considered the following opex elements: maintenance, capacity planning and energy consumption. Figure 1.6 and Figure 1.7 represent the relative maintenance opex for the different scenarios with P/A ratios of 2 and 3. In Figure 1.6 and Figure 1.7, we differentiate between Level 1 and Level 2 maintenance which is usually performed by 'in-house' operational teams from the more complex Level 3 and Level 4 maintenance activities which are usually performed by the equipment vendor in the form of a contract with the service provider.

Figure 1.8 and Figure 1.9 show the relative energy consumption.

From the above analysis, it is clear that an MPLS network will require significantly less opex than an OTN for the following reasons:

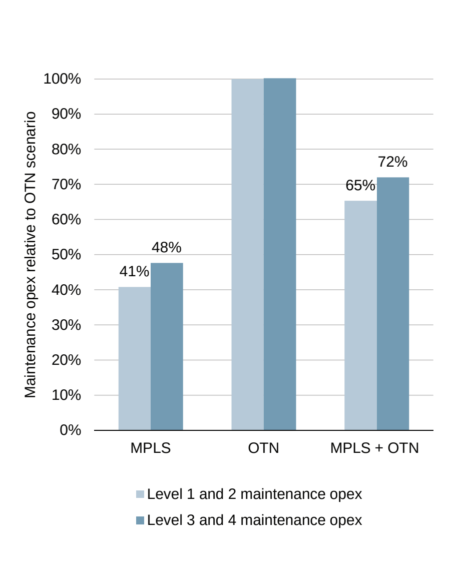

Figure 1.6: Maintenance opex comparison for P/A =2
[Source: Analysys Mason]

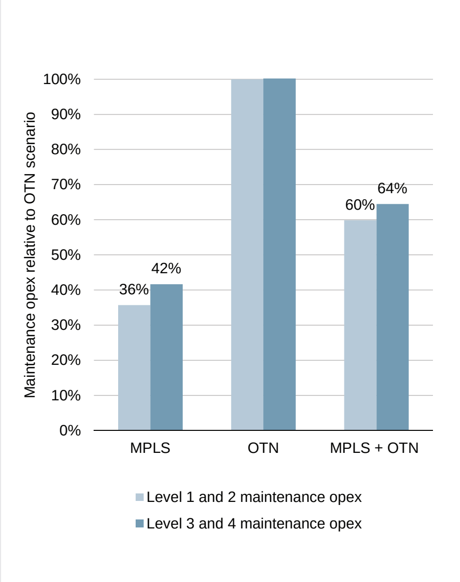

Figure 1.7: Maintenance opex comparison for P/A =3
[Source: Analysys Mason]

- An MPLS network incurs less than half of the maintenance opex of an OTN, mainly because the OTN requires a significantly higher number of OTN ports.
- An MPLS network consumes 40% less energy compared to an OTN, which will help an MPLS operator reduce its energy bill and meet its green objectives.

In addition, an MPLS network would require significantly less network reconfiguration in response to changing traffic patterns than an OTN, resulting in reduced opex for capacity planning and management.

Based on the above observations, it is clear that an MPLS operator will incur significantly less opex than an OTN operator.

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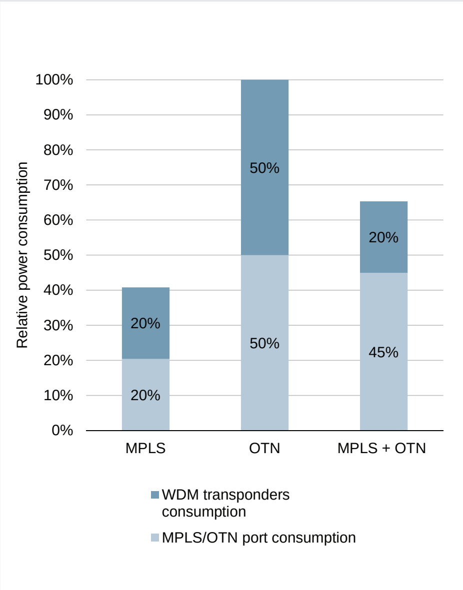


Figure 1.8: Power consumption for a P/A of 2
[Source: Analysys Mason]

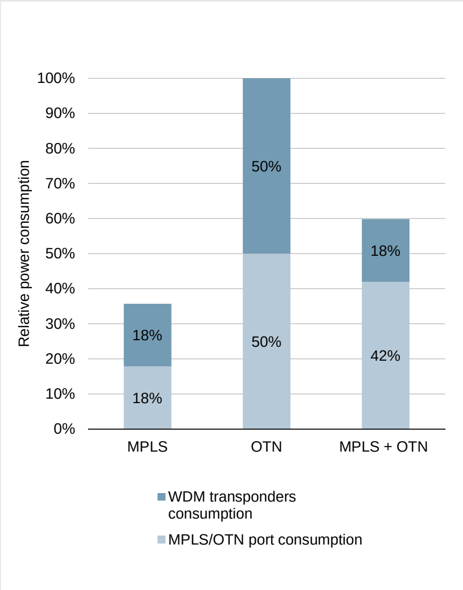


Figure 1.9: Power consumption for a P/A of 3
[Source: Analysys Mason]

1.3 Conclusions

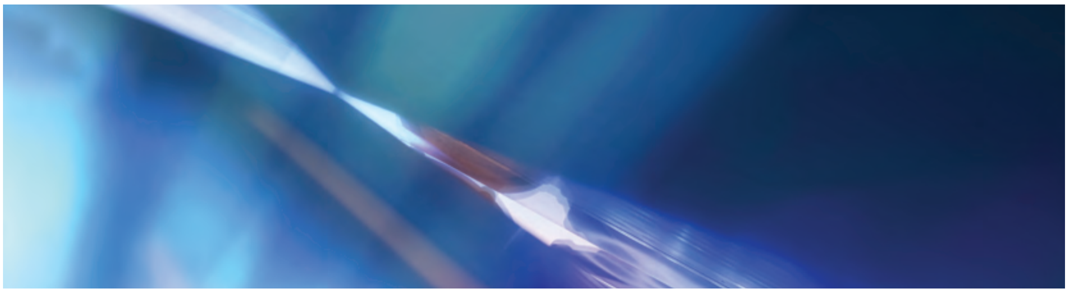
From our analysis, it is evident that MPLS technology is not only more cost-effective but also more flexible than OTN technology for providing packet-switched services. In this respect, an MPLS architecture will be the optimum investment for an operator, for the following reasons:

- MPLS enables an operator to dissociate traffic bandwidth and capacity provisioning, which is key in controlling costs and therefore breaking away from eroding margins.
- MPLS makes it possible to differentiate between different traffic types (e.g. revenue-generating versus non-revenue-generating) and to adjust their capex spending accordingly.
- MPLS provides the ability for the operator to offer the full range of carrier Ethernet services, which represent one of the fastest-growing markets.
- MPLS is more suited to accommodating changes in traffic patterns, which, with the advent of cloud computing and the increase in user mobility, is becoming an increasing issue.
- MPLS will enable the operator to generate between 58% and 81% more revenues than OTN, for the same capex investment.
- An MPLS-based operator will incur less opex compared to an OTN-based operator, which will have significantly more ports to operate and maintain.
- MPLS architecture and technology enable an operator to significantly reduce its power consumption, saving costs and helping it to meet its green agenda.

Therefore, a native MPLS architecture is the only one which offers the flexibility for operators to adapt their business model in line with the changes currently being experienced in the telecoms industry, by providing a way to differentiate revenue-generating and non-revenue-generating traffic, and to control capex and opex.

2 INTRODUCTION

"For most operators, the following question remains: how can they implement a network architecture that provides enough flexibility to accommodate the expected growth in packet-switched traffic, while addressing quality-of-service (QoS) issues by type of traffic and at the same time minimising costs to increase their profitability?"



Today, it is widely accepted that the volume of packet-switched traffic is increasing at an exponential rate in operators' networks, and that in the next 10 to 20 years the vast majority of traffic will be packet-based. The main factors driving the increase in packet-switched traffic are:

- market growth in both fixed and mobile broadband services
- availability and attractiveness of affordable smart phones and tablets (e.g. iPhone and iPad)
- growth in video applications, especially over-the top (OTT) applications such as Netflix, BitTorrent, YouTube, and catch-up TV applications such as the BBC iPlayer
- growth in the business segment
- migration of legacy circuit-switched services to packet-switched services (e.g. mobile backhaul, enterprise services and the public-switched telephone network or PSTN).

Yet, for most operators, the following question remains: how can they implement a network architecture that provides enough flexibility to accommodate the expected growth in packet-switched traffic, while addressing quality-of-service (QoS) issues by type of traffic and at the same time minimising costs to increase their profitability? The answer to this question is not straightforward: it depends, to a large extent, on the type of operator, the services provided and the legacy network of the said operator.

This white paper explores the different technical options that are available to operators to cope with the explosion of packet-switched traffic on their core network. There are three strategies available to operators to enable them to handle the expected growth in packet-switched traffic on their core networks whilst maintaining service quality:

- implement a circuit-switched network based on OTN technology, whereby switching in the core network occurs on a circuit basis and where the switching of packets only occurs at the edge of the network
- implement a packet-switched network based on MPLS technology, whereby switching in the core network occurs on a packet basis
- implement a mix of OTN and MPLS technology, whereby some core nodes can switch both packets and circuits and some other nodes switch either packets or circuits.

We assess the viability of the business case for each of these three strategies by comparing their costs and associated revenues.

"This white paper explores the different technical options that are available to operators to cope with the explosion of packet-switched traffic on their core network. There are three strategies available to operators to enable them to handle the expected growth in packet-switched traffic on their core networks whilst maintaining service quality."

We assess the viability of the business case for each of these three strategies by comparing their costs and associated revenues.

Structure of this white paper

The remainder of this white paper is laid out as follows:

- **Section 3** introduces the concepts of circuit switched and packet-switched networks, illustrating them by an analogy with the highway and railway network. This analogy is then used to explain how circuit- and packet-switched networks (such as MPLS networks) operate.
- **Section 4** covers the major challenges currently facing operators for their core networks and how these challenges may impact their technical strategy decisions in order to meet their business objectives. These challenges include:

— How to bridge the gap between stagnating revenues and increasing network costs?

— How to cope with the increasing unpredictability of traffic patterns?

— How to maximise revenue opportunities?

— How to optimise the use of network resources to minimise capital and operational expenditure (capex and opex)?

— How to guarantee QoS for packet-switched traffic (in particular, voice)?

- **Section 5** assesses the business case for the different technology strategy options available to operators by considering three reference scenarios:

— scenario 1: native MPLS network underpinned by a dense wavelength division multiplexing (DWDM) transport layer

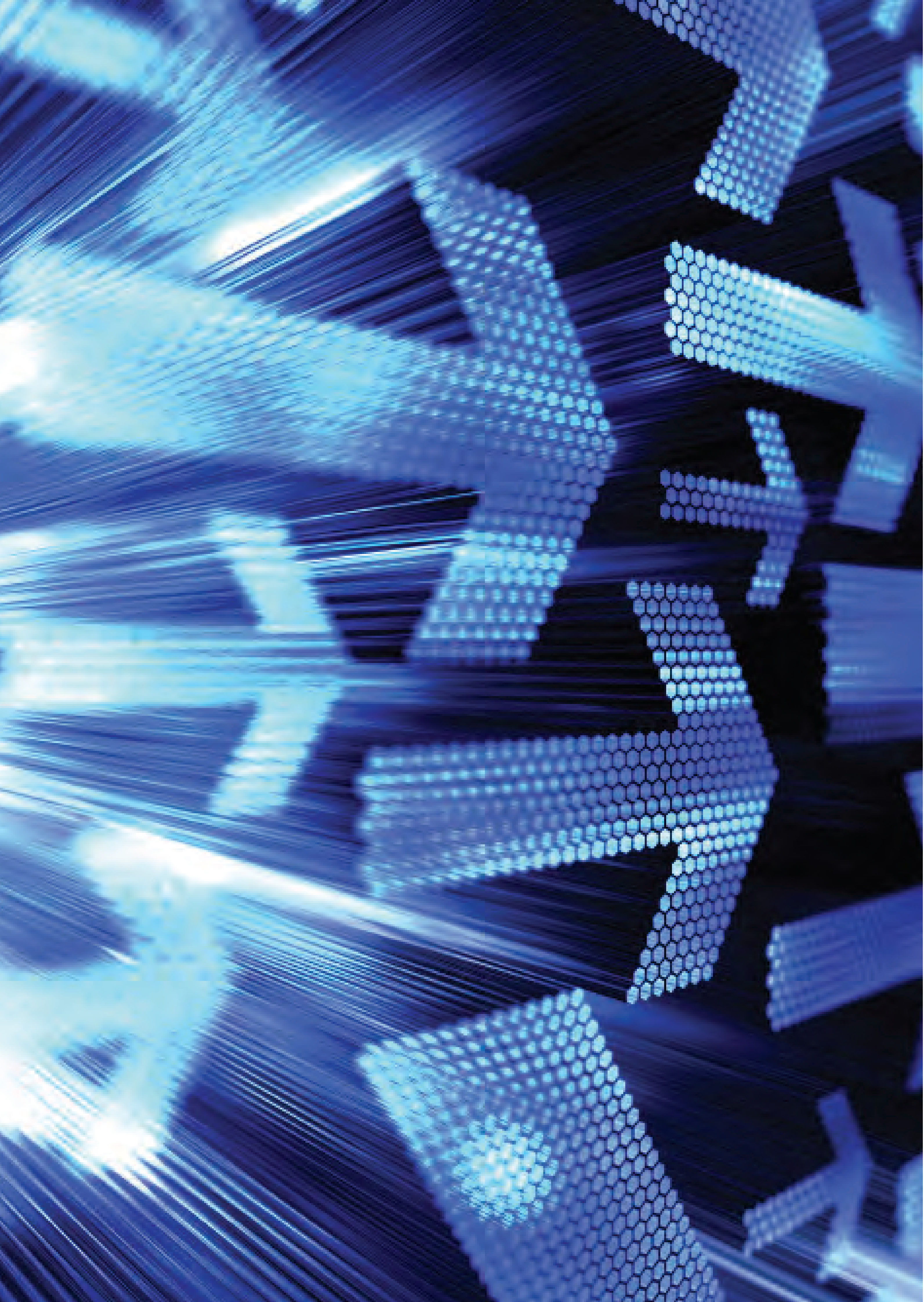
— scenario 2: native OTN underpinned by a DWDM transport layer

— scenario 3: MPLS network with OTN bypass and underpinned by a DWDM transport layer.

- **Section 6** presents our conclusions from the study.

This white paper also includes the following annexes containing supplementary documentation:

- **Annex A** includes the characteristics of all traffic flows considered for the different technology scenarios studied in this paper
- **Annex B** provides the detailed results of our assessment of the business case of the different technology scenarios
- **Annex C** includes a glossary of the terms used throughout this white paper.



3 CIRCUIT-SWITCHING AND PACKET-SWITCHING TECHNOLOGIES

This section introduces the concepts of circuit-switching and packet-switching. It is structured as follows:

- Section 3.1 illustrates these concepts by an analogy with the highway and railway network
- Section 3.2 explains the concept of circuit switching and packet switching technology in more detail in the context of a telecommunications network
- Section 3.3 provides an introduction to Optical Transport Network (OTN) and Multi-Protocol Label Switching (MPLS) technology
- Section 3.4 provides an introduction to carrier-grade metro Ethernet services

3.1 Transport analogy

"This is similar to a circuit-switched network, where circuits with dedicated and fixed capacity are set up between source and destination nodes in the network, in such a way that the network can accommodate traffic during peak time hours. Consequently, these circuits will be under utilised during non-peak time hours, which is usually the vast majority of the time."

Here we introduce the concepts of circuit-switching and packet-switching by using an analogy with the highway and railway network to illustrate the concepts of utilisation of resources, routing flexibility, reliability and impact of traffic change.

3.1.1 Railway analogy for circuit-switched networks

In its simplest form, a circuit-switched network can be compared with the railway network.

Utilisation of resources

In normal circumstances, a train operator will allocate a dedicated train with a set number of carriages for each route it operates. Importantly, the number of carriages for that service will be defined so that the service can ideally accommodate all passengers travelling during the peak hour (e.g. 8:00am in the morning and 5:00pm in the evening). Therefore, during peak hours, the train may be full, but for any other time during the day the train may only be partially occupied. A solution to optimise utilisation of the train is to reconfigure each train by dynamically adapting the number of carriages based on the demand throughout the day. However, this operation is not practical from an operational point of view as it is very labour-intensive and the train operator would need more operational staff.

Consequently, for a particular service, a variation in service utilisation will occur, depending on the time of the day. This is illustrated below in Figure 3.1, which depicts a train with 3 carriages, each with a capacity of 20 seats.

This is similar to a circuit-switched network, where circuits with dedicated and fixed capacity are set up between source and destination nodes in the network, in such a way that the network can accommodate traffic during peak time hours. Consequently, these circuits will be under-utilised during non-peak time hours, which is usually the vast majority of the time.

Routing flexibility

Typically in a railway network, the train operator defines a fixed set of routes to operate, where each route is defined by the city of origination, the city of destination and all the intermediate cities along that route. Therefore, if the operator has not defined a service between two end points, then it is not possible to travel on that route because no trains are available. This is shown below in Figure 3.2.

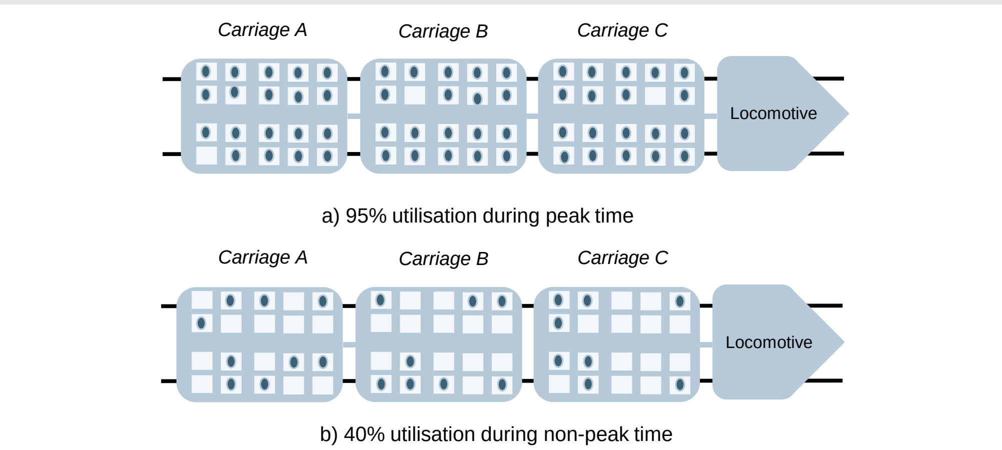


Figure 3.1: Example of train utilisation during peak and non-peak time hours
[Source: Analysys Mason, 2011]

"Typically in a railway network, the train operator defines a fixed set of routes to operate, where each route is defined by the city of origination, the city of destination and all the intermediate cities along that route. Therefore, if the operator has not defined a service between two end points, then it is not possible to travel on that route because no trains are available."

In circuit-switched networks, circuits are equivalent to train routes, which are established between source and destination nodes, via a number of transit nodes.

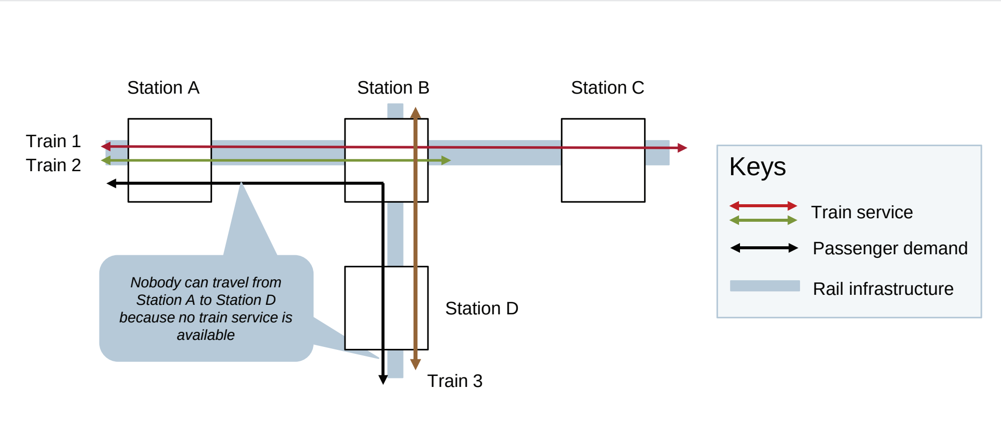


Figure 3.2: Pre-defined circuits in circuit-switched networks
[Source: Analysys Mason, 2011]

As illustrated in Figure 3.2, no passenger will be able to travel from Station A to Station D (assuming that passengers cannot change trains at Station B) because there is no pre-defined train service between these two stations, although the rail infrastructure exits.

Now, if we assume that there is a train service between Station B and D, passengers on Train 1 wanting to travel to Station D will need to get off the train in Station B and board Train 3. The transfer of passengers from Train 1 to Train 3 is equivalent to 'switching' in the circuit-switching paradigm (traffic is 'transferred' from one circuit to another).

In circuit-switched networks, circuits are equivalent to train routes, which are established between source and destination nodes, via a number of transit nodes. This means that, in a circuit-switched network, circuits have to be pre-established between any source and destination network node. If no pre-defined circuit exists between the source and destination node, then the traffic cannot be sent to its destination.

Multiplexing is the notion that passengers wanting to go from Stations A–C, A–B and A–D will all have to share the Station A–B rails. As such, in order to optimise the use of resources, all these passengers could take the Station A–B train (which will be more utilised) and then change at Station B to go onto Stations D or C. Multiplexing in circuit-switched networks consists of grouping circuits together to increase the utilisation of the trunk link.

Reliability

When operated well, train services are reliable and the expected time of arrival can be easily predicted because, at any point in time, the rail operator can forecast the exact number of trains there will be on the network and can therefore manage their spacing so that they do not interfere with each other. In other words, the railways offer a fully deterministic system, where time of arrival can be guaranteed to the user (except where there is a major problem on the line).

Circuit-switched networks are similar to train services, and can guarantee QoS because they use dedicated circuits with dedicated capacity for each service. This means that services transported in different circuits cannot interfere with each other.

Impact of traffic change

As mentioned above, train services are usually defined between two fixed stations and the number of carriages is also fixed. In this analogy, we consider two types of change:

- changes in the demand for a particular service
- changes in the route.

3.1.1 Railway analogy for circuit-switched networks continued

"Therefore, circuit-switched networks have limited flexibility to cope with significant changes in the volume of traffic on these networks. Accommodating these changes in real time can only be achieved if the circuits were over-provisioned in the first place, incurring significant capex."

We discuss each of these in turn.

> Changes in the demand for a particular route

If, for a particular route, there is a change in the demand due to, for example, an exceptional sports event such as a football final, additional capacity in the form of more passenger carriages will be required to accommodate the exceptional demand for that service, as many more passengers will want to use that service on that day. If this exceptional demand can be predicted in advance, then the train operator will be able to add carriages to the service, but this will involve some opex (i.e. the cost of attaching new carriages to the train, which is very labour-intensive). However, if the exceptional demand cannot be predicted in advance, unless the number of carriages was over-provisioned in the first place, the train operator will not be able to accommodate all the passengers wanting to travel as there will not be enough time to plan the addition of carriages to the existing route.

The situation for circuit-switched networks is similar. Circuits are provisioned for a given peak capacity and, if the demand were to suddenly increase, larger circuits would need to be provisioned, involving some re-configuration and associated opex. Alternatively, the operator could over-provision the circuit-switched network in the first place to cater for any dramatic increase in traffic, but this would incur significant capex (i.e. the cost of additional carriages). This issue is explored in more detail in Section 4.4.

> Changes in the route

If we consider our example in Figure 3.2, and that for some reason there was a surge in demand to go from Station A to Station D, then both Train 1 and Train 3 would need additional carriages to cope with the excess in demand. One solution to prevent passengers from changing trains would be to group them in dedicated carriages in Station A and then detach these carriages from Train 1 and attach them to Train 3. Detaching and re-attaching a carriage to a different train is very labour-intensive and incurs significant opex.

The same is true in circuit-switched networks, where traffic destined to a particular node can be grouped together on larger circuits and where circuits can be switched so that it reaches its destination.

Therefore, circuit-switched networks have limited flexibility to cope with significant changes in the volume of traffic on these networks. Accommodating these changes in real time can only be achieved if the circuits were over-provisioned in the first place, incurring significant capex.

3.1.2 Highway analogy for packet-switched networks

In essence, packet-switched networks can be compared with the highway/road transport network.

Utilisation of resources

On a typical road, different types of vehicle (cars, trucks, etc.) will all share the same road. Through their journey, some vehicles will aggregate onto a trunk road. This is illustrated in Figure 3.3.

If the trunk road is dimensioned such that it can carry the combined effect of the average traffic on each tributary road, then the trunk road will be optimally utilised. This remains valid as long as the sum of the traffic from each of the tributary roads remains the same (i.e. increases in the traffic from one tributary road are offset by drops in the traffic on another tributary road). Importantly, if dimensioned correctly, there is no need for the trunk road to have the same number of lanes as the number of tributary roads. This is shown in Figure 3.3, where just two lanes on the trunk road are sufficient to carry the traffic from three tributary roads.

Therefore, the advantage of a packet-switched network is that packets can use any of the available capacity on a link, which reduces the amount of un-used or redundant capacity. This is in marked contrast with the railway (circuit-switched networks) analogy, where a service can only use a dedicated resource, and even if that resource is under-utilised no other services can use it.

As noted above, the trunk road can only be dimensioned to be exactly equal to the sum of the average traffic from the tributary roads as long as the increases from some roads are offset by the decreases in others. In reality, the trunk road will need to be slightly larger than the sum of the average tributary traffic, to cope with the situation where the increases from some roads are not sufficiently offset by the decreases from others. This 'over-provisioning' is necessary to ensure that there is always sufficient capacity on the trunk road to carry the tributary traffic (or at least to a high degree of probability). However, it should be noted that the amount of over-provisioning required falls as the number of tributary roads increases.

Overall, and despite the need for some over-provisioning, the ability of packet-switched networks to aggregate traffic and use a pool of shared capacity means that trunk links on packet-switched networks typically require much less capacity than would be needed from an equivalent circuit-switched network. This effect is known as statistical multiplexing gain.

Routing flexibility

Using the highway/road network analogy, vehicles (traffic) can go wherever they want, using any road they want, as long as the driver follows the road signs for his/her destination along the road. This is very different from the railway network, which only supports services between a fixed set of origin and destination stations and which may involve one or several changes of train for the passengers.

In the packed-switched paradigm, packets of data (vehicles in our analogy) can be routed to any destination using the 'routing protocol', which is the equivalent to a driver following the road signs in our analogy. If one route is congested a driver can choose in real time to take another route.

Reliability

A key challenge for the highway network is that it is very difficult to predict when people are going to take their cars to travel to a destination of their choice. As a result, it is usually more difficult to predict the time of arrival when travelling by car (than by train) because it will depend on the number of cars on the road. This is especially true during the rush hour, i.e. the peak traffic period when more people travel, as congestion may occur on trunk roads if too many people choose to take that road.

As shown below in Figure 3.3, a number of cars and lorries want to access the trunk road, which consists of two different lanes, from different tributary roads. Depending on the traffic on each tributary road and on the capacity (number of lanes) of the trunk road, some vehicles may have to queue on the road junction more than they had anticipated, much like a packet has to queue in a router. In particular, ambulances and police cars would have to wait, which would cause a delay in dealing with life-threatening situations. The solution to this problem is to prioritise traffic and create dedicated lanes (queues) for different types of vehicles. This is illustrated in Figure 3.4.

Using the highway/road network analogy, vehicles (traffic) can go wherever they want, using any road they want, as long as the driver follows the road signs for his/her destination along the road.

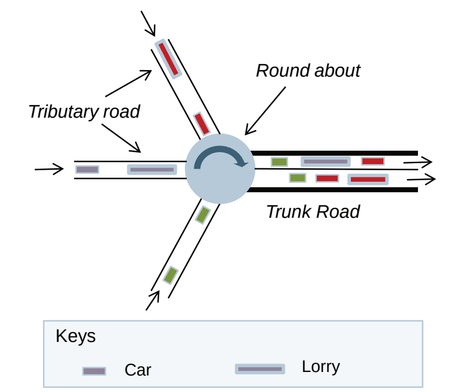


Figure 3.3: Vehicles aggregation on a trunk road
[Source: Analysys Mason]

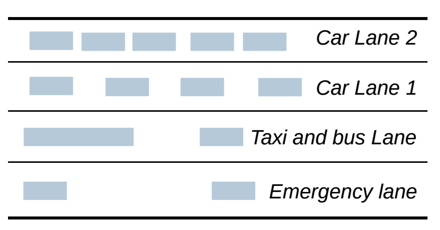


Figure 3.4: Emergency lane
[Source: Analysys Mason]

3.1.2 Highway analogy for packet-switched networks continued

"MPLS allows traffic engineering to be implemented in packet-switched networks, thus giving operators the ability to guarantee a minimum QoS for the traffic transported along each LSP."

The same idea applies to packet-switched networks. If no QoS (or priority) is applied to the traffic, then the traffic from tributary links at a given network node will all be served on a 'first come, first serve' basis, meaning that it is extremely difficult to predict how long it will take for a packet to get to its destination as it is highly dependent on the overall volume of traffic. This is usually described as a 'best effort' policy. For time-sensitive traffic such as voice, this situation would clearly be unacceptable as it would hamper the interactivity in the phone conversation.

Most modern packet-switched networks are no longer best effort, and can prioritise time-sensitive traffic (such as voice and video) over non-time sensitive traffic (such as Internet browsing). The Internet protocol (IP) has long had the ability to define different classes of service for different traffic types. In our analogy, this is equivalent to having some prioritisation at the roundabout so that all ambulances and police cars can jump the queue and do not incur unreasonable delays.

Coming back to the highway analogy, creating priority lanes without considering their respective capacities may not be enough to ensure the time of arrival for the different traffic types. The solution to this problem is to ensure that for each traffic type the lanes are dimensioned to accommodate their respective traffic. In order to do this, one needs visibility of the capacity on the road along every segment, and one must ensure that the capacity on every lane is sufficient to accommodate all types of traffic even during peak time hours.

In packet-switched networks, MPLS provides the ability to define express paths (equivalent to lanes in our analogy) between any two nodes in the network, and ensures that sufficient bandwidth is allocated to each express path in the network to guarantee a minimum QoS for the traffic carried on it. Establishing express paths (called label-switched path or LSP) on the basis of a holistic view of the network characteristics (e.g. available bandwidth, used bandwidth) is often referred to as traffic engineering. MPLS allows traffic engineering to be implemented in packet-switched networks, thus giving operators the ability to guarantee a minimum QoS for the traffic transported along each LSP.

The combination of defining classes of service and LSPs is extremely powerful as, in effect, it combines the advantages of packet-switched and circuit-switching technologies; the traffic from different services still uses the same shared resources, and each service can be guaranteed a minimum QoS in terms of delay and throughput, for example. This unique proposition explains why most operators have implemented some form of MPLS in their packet-switched networks.

Impact of traffic change

Similarly to what we did in the case of circuit-switched networks, we consider two types of changes in the case of packet-switched networks:

- changes in the demand for a particular service
- changes in the route.

We discuss each of these in turn.

> Changes in the demand for a particular route

Using the road analogy, provided that the increase in traffic on one of the tributary roads is compensated by a decrease in traffic on another tributary road, no congestion will occur on the trunk road.

However, an increase in traffic on a tributary road may cause that road to become congested. If priority lanes are implemented, the emergency vehicles will not be affected by that congestion, provided that the priority lane has enough capacity to support all emergency vehicles travelling on that lane.

This is similar to packet-switched networks, which exploit statistical multiplexing (not all traffic streams will peak at the same time). Also, as explained elsewhere in this white paper, MPLS enables operators to define express paths so that different levels of QoS (such as bandwidth) can be guaranteed for different types of traffic.

> Changes in the route

As mentioned previously, vehicles can go wherever they want, using any road they want, as long as the driver follows the road signs for his/her destination along the road.

In the packet-switching paradigm, packets of data (vehicles in our analogy) can be routed to any destination using the 'routing protocol', which is the equivalent to a driver following the road signs in our analogy.

Therefore, packet-switching is more naturally suited to cope with changes in the volume of traffic due to its statistical multiplexing and to the fact that dynamic routing is inherent to packet-switched networks.

3.2 Circuit-switched and packet-switched networks

Legacy PSTNs are based on circuit-switching technology, which allocates a dedicated physical path to each voice call and reserves an associated amount of dedicated bandwidth (usually a PSTN voice channel has a bandwidth of 64kbit/s) across the network.

This bandwidth is dedicated to the call connection for the duration of the call whether or not any audio voice is being exchanged between the callers.

Consequently, network planners and designers have to dimension their circuit-switched networks according to the number of calls in the busy hour, factoring in a blocking probability in their design to keep costs down. The blocking probability represents the probability that a caller will not be able to make his/her call because there are not enough circuits in the network to accommodate every single user to make a phone call at the same time.

Because PSTN services were the dominant services on legacy networks, operators have built their trunk network (core networks) to link different towns using circuit-switching technology. This is illustrated below in Figure 3.5.

In the 1960s, the advent of the Internet created a disruptive communications technology known as packet switching. IP emerged from a military program (DARPAnet) which was developed to maximise the probability that packets (information or data) were guaranteed to arrive at their destination irrespective of the state of the network (e.g. if one route had been blown up), but did not guarantee the route or the time it took for the packet to arrive at its destination. This new concept meant that information could now be sent in small packets through a shared network. The main advantage of this technology was that, whenever no information needed to be sent, no resources were utilised, enabling other traffic streams to use these resources instead. This is illustrated in Figure 3.6.

Today, packet-switching technology continues to be the technology of choice for the Internet, and IP is at its centre.

According to a recent study conducted by ACG research,[2] the ratio of time-division multiplexing (TDM) to IP traffic will dramatically change over the next five years. Today, TDM-encapsulated traffic still represents 50–70% of all traffic carried on the core transport networks, and the ACG study indicates that this ratio will decrease to 10% by 2016. IP traffic is expected to show the opposite trend, growing from 30–50% of all traffic carried on the core transport networks today to more than 90% by 2016. It is interesting to note that, according to most operators interviewed for this white paper, the majority of traffic within TDM circuits is packet-based. The findings of the ACG study are illustrated below in Figure 3.7.

IP traffic is expected to show the opposite trend, growing from 30–50% of all traffic carried on the core transport networks today to more than 90% by 2016.

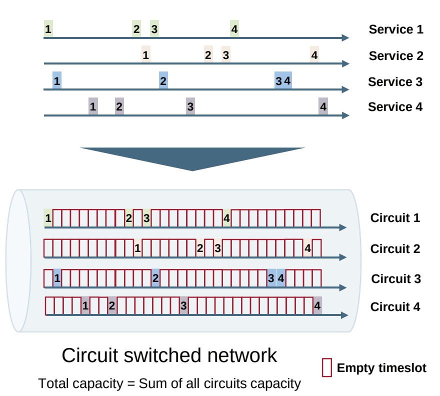


Figure 3.5: Circuit-switching concept illustration
[Source: Analysys Mason]

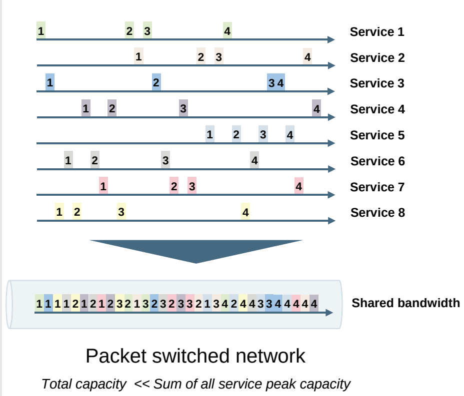


Figure 3.6: Packet-switching example
[Source: Analysys Mason]

[2] ACG Research (June 2010), OTN Survey.

3.2 Circuit-switched and packet-switched networks continued

"There are a number of options to transport packet-switched traffic in core networks. Deciding on which technology to use has a significant impact on an operator's capex and opex, as well as on the portfolio of services that an operator can offer, thus impacting revenues."

With an increasing pressure to reduce costs, most incumbent operators throughout the world are now replacing their circuit-switched based PSTN infrastructure with a packet-switched based IP network technology for providing voice services. This is usually referred to as next generation networks (NGN), which are driven by the operators' ability to consolidate different service networks into a single packet-switched network, thereby decreasing their capex and opex.

Defining appropriate classes of service in an NGN is of paramount importance because not all traffic carried on the network has the same requirements. For example, in order for two individuals to have a reasonable phone conversation, voice traffic has to be prioritised over other traffic such as Internet browsing. This is because a phone conversation happens in 'real time' and nobody would be satisfied with having to wait for two or three seconds before getting an answer or even parts of words from their counterpart, because voice packets have been delayed in the network due to congestion. In marked contrast, when a user downloads an Internet page, it is quite acceptable to have to wait just a little bit for the page to download or for the page to download one part at a time. As we have shown in our analogy above, both IP and MPLS offer different classes of service.

This example of the PSTN can be generalised to all networks, where packet-switched technology is increasingly dominating the architecture of operators' networks.

There are a number of options to transport packet-switched traffic in core networks. Deciding on which technology to use has a significant impact on an operator's capex and opex, as well as on the portfolio of services that an operator can offer, thus impacting revenues.

Below we describe OTN and MPLS technology, which are both being studied and considered by operators as the foundation to build a network to transport their packet-switched traffic.

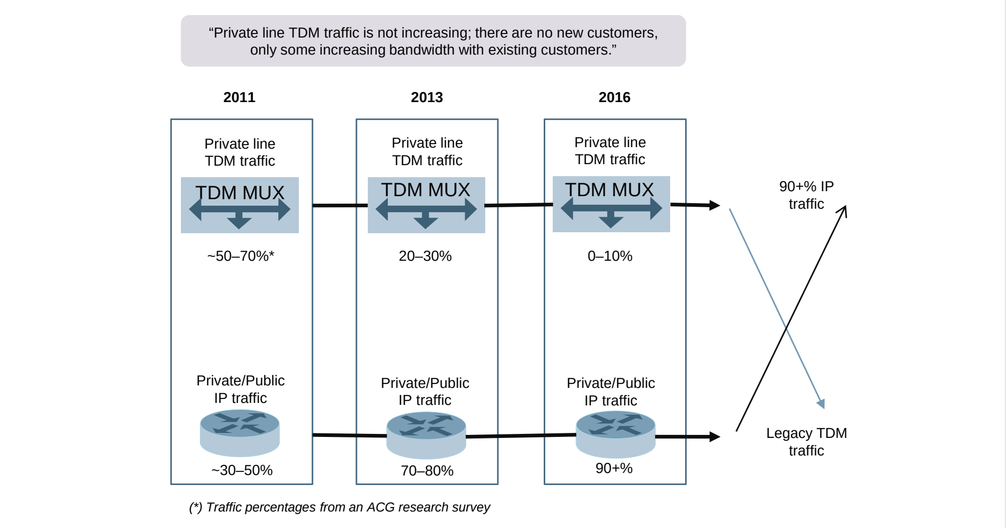


Figure 3.7: Forecast evolution of packet-switched and circuit-switched traffic
[Source: Analysys Mason, 2011]

3.3 OTN and MPLS

In essence, OTN is a circuit-switching technology, whereas MPLS is a technology that introduces traffic engineering (TE) and QoS guarantees in packet-switched networks.

OTN switching is currently not widely implemented by operators in their core network, but commercial products (OTN multiplexers) have been available for three years and their deployment is gathering momentum.

3.3.1 OTN

OTN, defined in 2003 by the International Telecommunication Union (ITU-T) in its G.709 recommendation[3], was created to assist the telecoms transport community to replace the legacy synchronous digital hierarchy (SDH) and synchronous optical network (SONET) TDM networks and provide a reliable and scalable transport technology for multi-Gigabit/s services, driven primarily by Gigabit Ethernet.[4] Similar to SDH, OTN is a circuit-switching technology, allocating fixed capacity on fixed circuits (see the railway analogy).

It is important to differentiate two key functionalities in OTN:

- OTN encapsulation (known as digital wrapper)
- OTN multiplexing (next generation of TDM switching)

OTN encapsulation

An initial step in the creation of OTN was a digital wrapper to support transport of various traffic types in a standard 'payload'. OTN also defined forward error correction (FEC) capabilities and nested operation, administration and management (OAM) overheads to support carriers' carrier operation. Referring to our railway analogy, the OTN digital wrapper functionality is equivalent to ensuring that a particular train service running between two-end stations has the necessary passenger-carrying capacity and arrives on time at the destination station, and that no passengers get lost along the way.

Currently, most wavelength division multiplexing (WDM) platforms use standardised OTN digital wrapper for performance management and make use of FEC as a means to extend the transmission reach, which reduces the number of regenerations in the network, thus reducing costs.

OTN multiplexing (OTH)

OTN was then enriched by the specification of a multiplexing hierarchy of Gigabits-per-second data rates, known as the optical transport hierarchy (OTH). Just like SDH, the OTH is based on TDM frames rather than packets.

Referring back to our analogy, OTN switching is equivalent to changing trains in a particular station. Services are usually defined between two-end stations. If the user needs to go to a destination that is not on route for that particular service, all passengers will need to be grouped into a single carriage and that carriage will have to be detached and re-attached to another train to reach the desired destination. Likewise, OTN switches circuits of discrete capacity called optical data unit (ODU). Figure 3.8 summarises the standardised ODU data rates.

It should also be noted that a special ODU called ODU flex can be used to map packet-based services, in integer number of ODU 0. For example, a 5Gbit/s Ethernet service can be mapped into four distinct ODU 0 circuits to transport that service.

OTN switching is currently not widely implemented by operators in their core network, but commercial products (OTN multiplexers) have been available for three years and their deployment is gathering momentum.

OTN circuit name	Data rate (Gbit/s)
ODU 0	1.244
ODU 1	2.499
ODU 2	10.037
ODU 3	40.319
ODU 4	104.794

Figure 3.8: ODU data rates
[Source: ITU G.709]

[3] ITU-T recommendation G.709/Y.1331 (February 2001), Interfaces for the optical transport network (OTN). Available at http://www.catr.cn/radar/itut/201007 P020100707580946344382.pdf

[4] SDH was not scaled for the transportation of multi-Gigabit services.

3.3.2 MPLS

"This is an issue with interactive and time sensitive applications: the packet has a perishable time on it, and it will be discarded if it does not arrive at its destination within that time."

In traditional IP networks, routing protocols disseminate information which is used to populate a routing table in the routers. Hence, when an IP packet is received, the router uses the packet's destination address to perform a routing look-up to determine the optimum next-hop in the path towards the destination.

Naturally, there may be a number of alternative paths towards the destination and the optimal path is typically selected based on the shortest number of hops. This operation is repeated at each intermediate router until the packet arrives to its correct destination.[5] In large nodes, the routing table look-up function takes a finite amount of time, which could introduce some delay and jitter in packet-switched networks.

Also, in standard IP networks, depending on the status of the network at any given time, packets from the same traffic stream could experience different delays depending on network conditions. This is an issue with interactive and time-sensitive applications: the packet has a perishable time on it, and it will be discarded if it does not arrive at its destination within that time. Furthermore, since packets are routed on a hop-by-hop basis, there is no 'big picture' view of network performance and an ability to respond to it quickly. Therefore, for example, it is possible for a particular link to become heavily congested and, yet, provided it is still in the path to the destination, it will continue to receive traffic, exacerbating the congestion. Thus, packets will be queued at the corresponding router, introducing unpredictable traffic delay and jitter and possibly even losses. Again, for real-time traffic, this situation would mean that the service would be impacted negatively.

MPLS, which was standardised by the International Engineering Task Force (IETF), was introduced to overcome all of the above issues, that is:

- provide a mechanism to alleviate the delay and jitter associated with traditional IP routing
- provide a mechanism to ensure that all packets of a particular traffic stream follow the same path and, therefore, arrive in order at their destination
- provide a mechanism to guarantee a minimum QoS in terms of bandwidth for each of the defined paths.

In order to overcome these issues, MPLS assigns short labels to network packets that describe how to forward them through the network. This effectively bypasses the routing protocols and establishes express paths between any node in the network. MPLS performs 'label' switching instead of routing table look-up, which is significantly faster and reduces the load placed on routers.

The fundamental principle of MPLS is as follows:

- the first MPLS capable router (R1) performs a table look-up, but instead of finding the next hop, it finds the final destination router
- a pre-determined path is then established between the source and destination routers (i.e. R1 and R9), which is uniquely identified by an MPLS label,[6] in each segment of the network
- intermediate routers (R2, R6, R7 and R5) then use the label to route the traffic, without needing to perform any additional IP look-ups
- at the final destination MPLS router (R9), the label is removed and the packet is delivered via normal IP routing.

This is illustrated in Figure 3.9.

MPLS allows traffic engineering to be implemented in a packet-switched network, thus giving operators the ability to guarantee a minimum QoS for the traffic transported along each LSP.

"In order to overcome these issues, MPLS assigns short labels to network packets that describe how to forward them through the network. This effectively bypasses the routing protocols and establishes express paths between any node in the network. MPLS performs 'label' switching instead of routing table look-up, which is significantly faster and reduces the load placed on routers."

MPLS allows traffic engineering to be implemented in a packet-switched network, thus giving operators the ability to guarantee a minimum QoS for the traffic transported along each LSP.

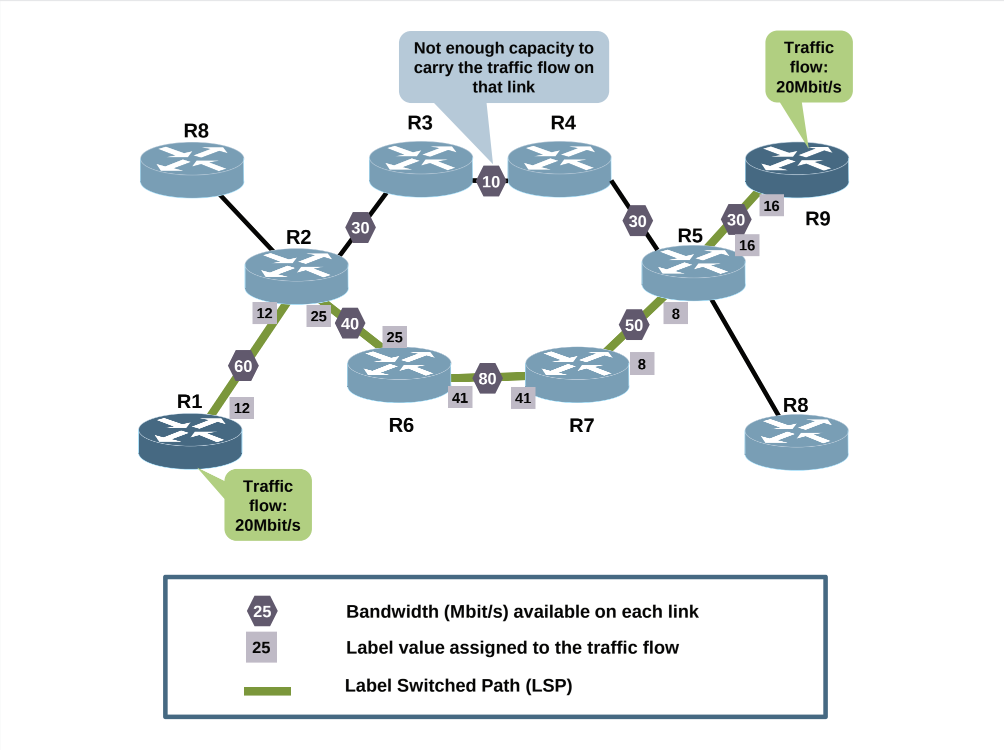


Figure 3.9: Label switched routes in an MPLS network
[Source: Analysys Mason, 2011]

[5] Each router makes its own independent routing decisions until the final destination is reached. In our analogy, this is equivalent to a driver making the decision on which way to go at a road junction.

[6] Please note that the label may be different in a different section of the network.

3.4 Carrier-grade Ethernet services

"Today, Ethernet services are one of the largest areas of revenue growth in packet switched networks for operators."

Ethernet has traditionally been a technology used in local area networks (LAN), covering distances of a few hundreds of meters (e.g. within an office or building), but was not considered to be a carrier-grade technology, suitable for operators to reliably provide services over long distances

However, this is no longer true. The Metro Ethernet Forum (MEF), a standardisation body, was created to define carrier-grade Ethernet services and allow Ethernet to be extended beyond the LAN environment. Today, Ethernet services are one of the largest areas of revenue growth in packet-switched networks for operators, as explained in Section 4.3.

The MEF has standardised the definition of two families of metro Ethernet services:

- **Ethernet line** (E-Line) to provide **point-to-point** connectivity. E-Line services are used to create Ethernet private-line services, Ethernet-based Internet access services, and point-to-point Ethernet virtual private networks (VPN).
- **Ethernet LAN** (E-LAN) to provide **multipoint-to-multipoint** (any-to-any) connectivity. E-LAN services are designed for multipoint Ethernet VPNs and native Ethernet transparent LAN services.

E-Line and E-LAN services are illustrated in Figure 3.10 and in Figure 3.11, respectively.

Since E-Line and E-LAN services can operate over dedicated or shared bandwidth, four key types of Ethernet service have emerged:

- Ethernet private line (EPL, E-Line with dedicated capacity)
- Ethernet virtual private line (EVPL, E-Line with shared capacity)
- Ethernet private LAN (E-LAN with dedicated capacity)
- Ethernet virtual private LAN (E-LAN with shared capacity).

Typically, circuit-switched services can provide point-to-point services with dedicated capacity. Therefore, circuit-switched networks can only provide Ethernet private line services. Also, TDM circuits are typically the same size in each direction, whereas an operator could create an asymmetric EPL or EVPL service if a customer has asymmetric traffic.

In marked contrast, packet-switched networks, which offer shared capacity by default, are more flexible and can provide the entire portfolio of carrier-grade Ethernet services as defined by the MEF, and in a more cost-effective manner than circuit-switched networks.

"Typically, circuit-switched services can provide point-to-point[7] services with dedicated capacity. Therefore, circuit-switched networks can only provide Ethernet private line services."

Since E-Line and E-LAN services can operate over dedicated or shared bandwidth, four key types of Ethernet service have emerged:

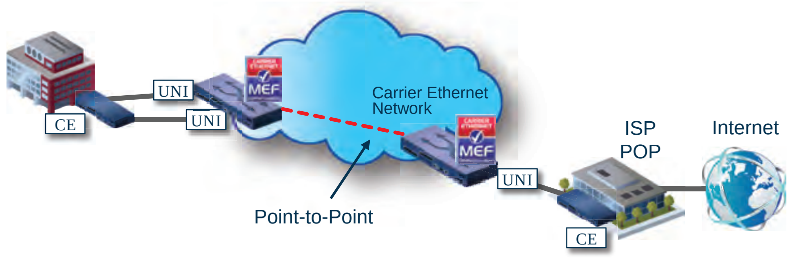


Figure 3.10: E-Line services
[Source: MEF]

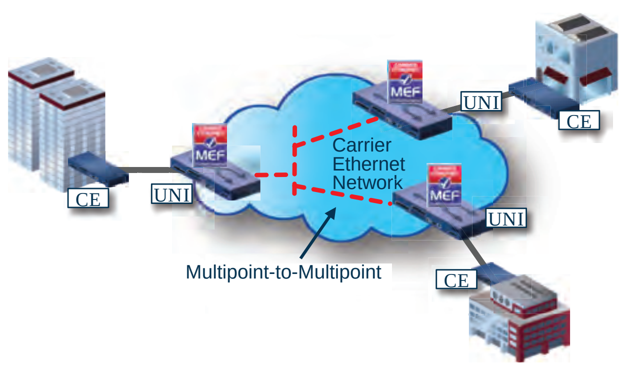


Figure 3.11: E-LAN services
[Source: MEF]

[7] There are circuit-switching technologies that can provide point-to-multipoint connectivity (e.g. resilient packet ring), but they are not widely implemented by equipment vendors.

4 CHALLENGES FACING OPERATORS FOR THEIR NETWORKS

This section covers the five major challenges currently facing operators for their core networks and how these challenges may impact their technical strategy decisions in order to meet their business objectives:

- How to bridge the gap between stagnating revenues and increasing network costs? (Section 4.1)
- How to cope with the increasing unpredictability of traffic patterns? (Section 4.2)
- How to maximise the use of network resources to optimise capex and opex? (Section 4.3)
- How to maximise revenue opportunities? (Section 4.4)
- How to guarantee appropriate levels of QoS for packet-switched traffic? (Section 4.5)

These are discussed in the following sub-sections.

4.1 Bridging the gap between stagnating revenues and increasing network costs

"One of the major problems facing operators is the increasing gap between their revenues and costs, which directly affects their profit margins."

One of the major problems facing operators is the increasing gap between their revenues and costs, which directly affects their profit margins. This is illustrated below in Figure 4.1.

Many operators are experiencing eroding profit margins because their costs and revenues are increasing at different rates. Operators' revenues are stagnating, mainly due to a decrease in voice revenues and increasing competition in other services. Their costs, on the other hand, have continued to rise as a result of the infrastructure expansion required to support new data services.

Most importantly, the service provider business model is being challenged, primarily because of the increasing disintermediation, forcing network service providers to carry an ever increasing amount of over-the-top (OTT) traffic. OTT services are services that are created outside the operator's network. Yet, they have to carry this traffic without extracting any additional income, as all the service revenues go to the owner of the content. Service provider revenues are restricted to the network access sold as flat-rate bandwidth plans. As a result, the core of the network has become a cost-centre commodity, and the goal becomes to relentlessly pursue a strategy and architecture that takes every single bit of cost out of that network, yet making sure that it remains flexible enough to accommodate all that varying traffic while meeting or exceeding the previously committed service level agreements (SLA).

One solution to this problem would be for the operator to assign a low priority for non-revenue generating traffic and only carry that traffic whenever there is sufficient capacity in the network. Whenever there is not enough capacity in the network, non-revenue generating traffic will be delayed, or, in the worst case, dropped. That way, the operator can limit the investment allocated to non-revenue generating traffic.[8]

It should be noted that, in a circuit-switched network such as OTN, differentiating between traffic is not possible because full capacity is always guaranteed for all traffic, by means of dedicated circuits. Therefore, operators can only adopt this new business model if they operate a core packet-switched network, such as an MPLS network, which can prioritise different types of traffic.

We believe that only native packet-switched networks, such as MPLS networks, can provide the sufficient flexibility, QoS differentiation by type of service, and control to enable operators to manage their costs and therefore maintain or increase their profitability.

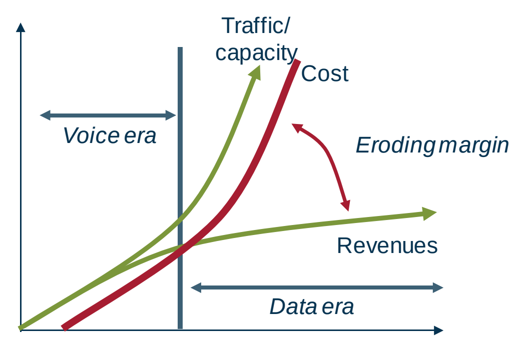


Figure 4.1: Increasing gap between revenues and costs
[Source: Analysys Mason, 2011]

4.2 Coping with the increasing unpredictability of traffic patterns

One of the main challenges for operators today is the increasing unpredictability of traffic in terms of where it is coming from and where it needs to go. The causes for this unpredictability are multiple:

- The consolidation of data centres and the advent of cloud networking allow content and service providers to migrate content and computing resources from location to location, based on where they need to be consumed. This creates substantial shifts in traffic patterns as sources and sinks of information can change instantaneously.
- Increased mobility of the content users presents additional challenges. Until recently, there was a clear relationship between the user and the user's location when accessing the network, as everybody was physically 'tethered' to the network. Today's radio access networks are increasingly capable of supporting high-bandwidth applications, including streaming video, and a plethora of mobile devices allows people to consume content no matter where they are. As a result, consumers have 'detached themselves from the network; they are mobile and they can do things on the go that they used to only be able to do sitting in front of their 'attached' computers.
- Exceptional events such as sports events (e.g. football finals, Olympics) and other events such as political elections which create high traffic loads in specific geographical areas for a short length of time.

The net effect of mobility and cloud computing is that aggregation networks become less efficient. Aggregation networks are static and are built based on knowing where the users are, where the content is stored, and where the applications are running. All of this is now fluid and dynamic, and hence the core transport network needs to assume this role and provide flexible ad hoc aggregation. We consider the advantages and disadvantages of circuit-switching and packet-switching technology in this context.

Traffic unpredictability in a circuit-switched network

Going back to our railway analogy, if there is a sudden high demand on the railway network for a route that is currently not served by existing trains, or when there are not enough carriages on existing trains to accommodate the surge in passengers, it will take quite a while for the train operator to adapt to these changes as s/he needs to:

- check if there is sufficient capacity on the railway networks
- add coaches to existing trains or add trains on the route
- implement a schedule that does not affect any existing services
- implement the new route into the train-routing schedule that defines pricing for the new route.

Until recently, there was a clear relationship between the user and the user's location when accessing the network, as everybody was physically 'tethered' to the network. Today's radio access networks are increasingly capable of supporting high-bandwidth applications, including streaming video, and a plethora of mobile devices allows people to consume content no matter where they are.

[8] This issue is directly linked to the net-neutrality debate, but such debate falls outside the scope of this white paper.

4.2 Coping with the increasing unpredictability of traffic patterns continued

"The net effect of mobility and cloud computing is that aggregation networks become less efficient."

Therefore, unless the new demand is known well in advance, it will be difficult, if not impossible, for the train operator to commission a new service in response to a short-term demand. The same is true for a circuit-switched network, as new circuits will have to be created to serve the new demand; if the demand changes often, this process can be quite labour-intensive and can use significant resources from the operational team, which will result in higher opex.

However, there is a different way of looking at this problem for circuit-switched networks. Operators have the choice to over-dimension their circuit-switched network from day one (similar to adding extra trains knowing they will be empty most of the time). This way, any increase in traffic in any parts of the network could be met with minimum or no network reconfiguration, thus optimising opex. Therefore, the operator will have to make one of two choices:

- over-dimension its circuit-switched network from day one and minimise its opex at the expense of a very large up-front capex investment, or
- make capex investments in line with the traffic demand at the risk of incurring very large opex due to frequent network reconfiguration or not being able to carry the surge in traffic and lose business from affected customers.

Traffic unpredictability in a packet-switched network

Going back to our road analogy, the highway operator does not need to know where the cars go in the first place, as cars can get to their destinations by following the signs. However, there is a limit as to how much traffic can be aggregated on a road or highway before the drivers start experiencing delays on their journey due to congestion.

This is similar to packet-switched networks, which are more flexible than circuit-switched networks in coping with unpredictable demand as the former provide a natural technology to aggregate demand, wherever it is coming from and wherever it is going. However, note that a packet-switched network can only aggregate so much traffic on a trunk link of a given capacity before the quality of experience for end users starts degrading (e.g. if the network is too over-utilised, the quality of experience may degrade depending on how high-priority traffic is carried).

Therefore, although the architecture of a packet-switched network is more flexible to cope with increased uncertainty, operators will have to weigh the impact of degrading their QoS for particular traffic types (and possible churn due to customer dissatisfaction). That is where the traffic-engineering capabilities of MPLS come into play. By segregating different traffic types into different classes and LSPs, the operator can optimise the resources reserved for its high-priority revenue-generating traffic and increase the contention ratio for non-revenue generating traffic, as mentioned in Section 4.1.

4.3 Maximising the use of network resources to optimise capex and opex

Maximising the use of existing assets is of paramount importance for the profitability of any business, and the telecoms industry is no exception.

One of the main challenges for operators today is the increasing unpredictability of traffic in terms of the amount being carried on their networks, where it is coming from, and where it needs to go.

In order to understand how the use of network resources can be maximised, it is important to first understand the bandwidth utilisation characteristics of IP and Ethernet traffic. Figure 4.2 illustrates the bandwidth utilisation profile of a Gigabit Ethernet file server.

It is clear from Figure 4.2 that the link utilisation spikes in short, infrequent intervals, and most of the time is very low or even nil. Therefore, dedicating 1Gbit/s worth of capacity for this traffic flow would be a significant under-utilisation of network resources. Since operators using OTN technology need to allocate fixed circuits with a fixed capacity to transport packet-switched traffic, they would need to allocate an ODU 0 (1.25Gbit/s), resulting in stranded capacity on that circuit that no other service can use. This represents a sub-optimum use of resources.

In order to overcome this problem, traffic can be groomed by the packet-switched network at the edge of the network and then transported on an OTN circuit. The problem associated with that solution is that the OTN circuits are of fixed capacity and, should the characteristics of the groomed traffic change in terms of capacity required, then manual intervention is needed to proportionally change the size of the circuit provided. This issue is further discussed in Section 5.3.

As explained in Section 3.1.2, despite the need for some over-provisioning, the ability of packet-switched networks to aggregate traffic and use a pool of shared capacity means that trunk links on packet-switched networks typically require much less capacity than would be needed from an equivalent circuit-switched network. Therefore, packet-switched technology optimises the use of resources available in the network.

One of the key principles in trying to optimise the use of resources in a core network is known as traffic grooming. This principle consists of consolidating traffic that is destined to a particular destination, so that it efficiently occupies the resources. Traffic grooming works quite differently in packet- and circuit-switched networks, as explained below.

Grooming of traffic in a circuit-switched network

In our railway analogy, traffic grooming in a circuit-switched network is comparable to detaching carriages that carry people and re-attach them to a another train. For the train operator, this involves the placement of every individual on the train to allocated seats in the same few carriages. The same principle applies to circuit-switched networks: circuits from an upstream traffic node (tributary link) have to be mapped into the circuits of the trunk link. This is shown in Figure 4.3.

The consolidation of resources or grooming in circuit-switched networks requires a 1:1 mapping between the circuits from the tributary link and the available circuits of the trunk links. This mapping has to be performed through the management system. However, if a new circuit appears on one of the tributary links or if a circuit of a tributary link becomes empty, that 1:1 mapping has to be performed again, which, in some situations, requires manual intervention from the operational engineer located in the network operation centre (NOC). This constitutes a significant burden for the operator and has an associated opex. This is a rapidly escalating problem as traffic patterns are increasingly changing, as discussed in Section 4.2 of this white paper.

Grooming of traffic in packet-switched networks

In marked contrast, grooming traffic in packet-switched networks is more flexible because there is no circuit defined and packets from different streams are

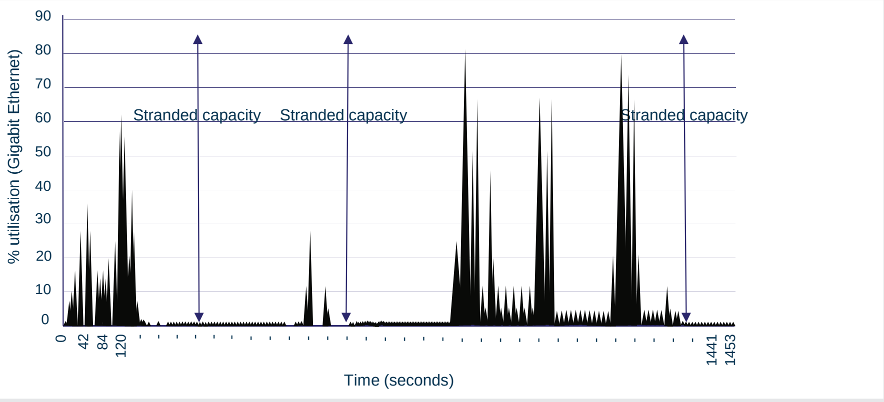


Figure 4.2: File server bandwidth utilisation
[Source: IEEE[13]]

4.3 Maximising the use of network resources to optimise capex and opex continued

"Nowadays, packet networks routinely carry voice traffic, as illustrated by the adoption of NGNs by operators."

just aggregated onto an output consolidated stream in the core network. The only intervention required by the operator is to increase the capacity of the trunk link when the incoming traffic reaches a certain level. Therefore, reconfiguration of packet-switched networks will occur significantly less frequently than in circuit-switched networks, resulting in a lower opex requirement for the operational team. There is a range of ways to provision capacity in a network, as illustrated below in Figure 4.4.

Given a set of demands on a network, one can over-provision capacity to accommodate all traffic flows at their peak bandwidth simultaneously, as illustrated in (a) in Figure 4.4. This method of capacity provisioning is equivalent to circuit-switching capacity provisioning and is designed to achieve absolute certainty (i.e. there is enough capacity for all traffic flow to peak at the same time). However, this approach is too conservative and is likely to result in significant over-provisioning of capacity, as it does not take advantage of statistical multiplexing gain (i.e. when some traffic flows will peak, others will trough, compensating for one another, as explained in Section 3.1.2).

Another approach to capacity provisioning is illustrated in (b) in Figure 4.4, implying the provision of capacity on the trunk link to accommodate all traffic flows at their average bandwidth simultaneously. This assumes an ideal scenario where all the peaks and troughs of the flows balance out perfectly due to statistical multiplexing. This approach is likely to result in congestions at some point in time due to the stochastic nature of each traffic flow and is therefore too optimistic.

A more realistic method of provisioning the trunk link capacity is illustrated in (c) in Figure 4.4 and consists of a compromise between method (a) and (b) by provisioning capacity for the average bandwidth for n flows and provisioning peak capacity for k flows (assuming the total number of traffic flow is n+k). The number of traffic flows provisioned for peak capacity (k) will vary depending on the network characteristics, the total number of flows, and the kind of services to be delivered. k can be viewed as the level of over-provisioning to provide the required QoS in the network. Using this capacity-provisioning methodology ensures that the operator can enjoy the benefits of statistical multiplexing gain, while at the same time allowing for k flows to peak at the same time, without affecting the QoS of any other flows. It should be noted that our case study in Section 5 assumes the above capacity-provisioning methodology.

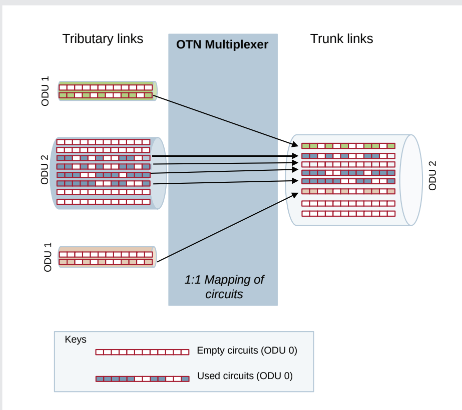


Figure 4.3: Grooming of traffic in circuit-switched networks [Source: Analysys Mason]

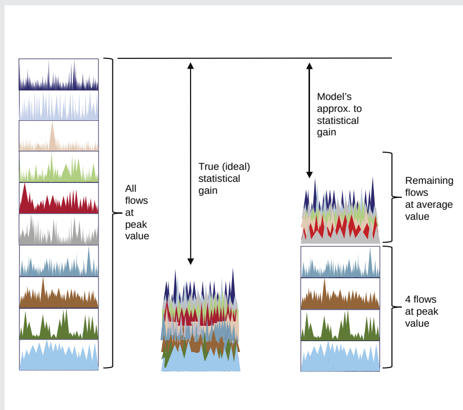


Figure 4.4: Capacity provisioning in packet-switched networks [Source: Analysys Mason]

4.4 Maximising revenue opportunities

[9] Total Telecom (August 2011), Carrier Ethernet key to telecoms growth. Available at http://www.totaltele.com/view.aspx?ID=467030.

[10] Total Telecom (2011), Make Carrier Ethernet simple, telcos tell vendors. Available at http://www.totaltele.com/view.aspx?ID=465979.

[11] Total Telecom (August 2011), Carrier Ethernet key to telecoms growth. Available at http://www.totaltele.com/view.aspx?ID=467030.

[12] Ibid.

Operators are seeing rapid growth in demand for carrier Ethernet services, for both business and wholesale services. Industry analysts, including Infonetics and Ovum, continue to forecast strong growth in worldwide carrier Ethernet services – a USD20 billion market in 2011, set to grow to USD50 billion by 2014.[9]

Operators are seeing rapid growth in demand for carrier Ethernet services, for both business and wholesale services.

The most dramatic growth in carrier Ethernet services is expected to come from mobile backhaul. International market research firm Infonetics Research expects Ethernet microwave revenues to grow at a compound annual growth rate (CAGR) of 41% over the period 2011–2015.

The problem facing mobile carriers – on top of downward price pressures – has been the surge in data traffic since the iPhone was launched in 2007, plus the fact that the smaller footprint of 3G cell sites requires more cell sites with scalable backhaul capabilities. Another key driver for carrier-grade Ethernet services has been video applications. For example, Netflix is now dominating bandwidth demand in North America and smart phones are pushing up the use of mobile video.

Operators are rapidly responding to this increase in demand by deploying packet-based infrastructure in their networks to support the delivery of carrier-Grade Ethernet metro services:

- A UK operator reported in 2010 that carrier Ethernet was its fastest-growing data service, with its Ethernet business growing more than 20% per annum.
- Tata Communications, which launched its Ethernet global offering in 2006, has seen the service revenues double each year till 2009.
- A US operator went global by extending its Ethernet virtual private LAN service to 14 European and Asia–Pacific countries in 2009.
- BT Wholesale has been offering carrier Ethernet services through its 100-node MPLS network for a few years, and is continuing to innovate in providing high-availability wholesale Ethernet products, driven by high demand from other operators. Interestingly, Tim Hubbard, head of data solutions at BT Wholesale, stated recently that[10] *"customers want Ethernet; Apple makes a lot of money from people who want iPhones, why can't we make a lot of money from people who want Ethernet?"*.

A recent survey[11] suggested that nearly two thirds of worldwide carriers expect to spend more on carrier Ethernet than on legacy wide area network (WAN) equipment during the next 18 months (with only 14% expecting to pay more on SONET/SDH than carrier Ethernet).[12]

In the past five years, equipment vendors such as Ciena, ADVA and ECI that have been traditionally supplying transport equipment have been incorporating more and more Ethernet features in their products to respond to the vast demand for providing metro Ethernet services. Matt Hayes, a consulting systems engineer at Ciena, stated back in 2009 that *"now many RFPs have carrier Ethernet in their titles"*. This shows that operators are not looking for 'transport only' solutions anymore.

Finally, it should be noted that Ethernet services are well adapted to customers' requirements in terms of providing only what they need (and no more). Metro Ethernet services are defined in such a way that operators can provide additional increments of bandwidth to match the traffic to be increased in increments of bandwidth, so that customers only pay for what they need. In this way, customers can adopt a 'pay-as-you-go' approach, enabling them to better control their costs, which is very important in this difficult financial climate.

There is therefore a significant opportunity for operators to generate new revenue streams, if their network infrastructures are able to support the full portfolio of carrier-grade Ethernet services, and only a flexible packet-switched network (e.g. IP/MPLS network) will enable the efficient delivery of such services in an economical way.

4.5 Guaranteeing appropriate levels of QoS for packet-switched traffic

Packet-switched networks have evolved dramatically over time. In the early days of packet switching, all networks were 'best effort' and consequently there was a justified scepticism as to whether packet networks were good enough to carry voice. Nowadays, packet networks routinely carry voice traffic, as illustrated by the adoption of NGNs by operators discussed in Section 3.2. The focus has shifted entirely from whether packet networks were capable of carrying high-priority, high-QoS demanding traffic, to instead focus on using the technology to combine high-QoS demanding traffic and low-priority traffic on the same network at the lowest-possible cost.

In terms of transport reliability, packet-switched networks will always require the functionality provided by the WDM transmission layer. In fact, packet equipment vendors are already offering interfaces that use OTN encapsulation on their core packet equipment. As described in Section 3.3.1, using OTN for its digital wrapper functionality to ensure reliable transmission is very different from using OTN as a technology to switch circuits.

[13] Source: "We've got a new standard: IEEE P802.3az Energy-Efficient Ethernet ratified", IEEE, 2010

5 CASE STUDY: COMPARISON OF COSTS AND REVENUES IN OTN AND MPLS NETWORKS

This section assesses the impact on capex and potential revenues of implementing different architectures to support packet-based services.

It is very difficult to identify the optimum techno-economic solution by considering capex in isolation. For example, lower investment may reduce the potential for new revenues, because operators with different network architectures and/or different technologies may not be able to offer the same service portfolio.

For this reason, this study also looks at the opex implications of choosing different technical strategies, but we intentionally do not provide any quantitative results because opex requirements are heavily dependent on the particular business model chosen by each individual operator. Instead, we provide some insight regarding what network opex components are affected by the technical strategy decision (see Section 5.3).

We analyse the following three technology scenarios and identify the optimum one by comparing the business case they each offer, using a typical long-distance reference network model:

- scenario 1: MPLS switching network
- scenario 2: OTN switching network
- scenario 3: MPLS with OTN bypass.

5.1 Variables and assumptions

"In order to assess the impact of technology choice on an operator's business case (i.e. on its costs and potential revenue), we assume a simple core network topology."

In the remainder of this section we use five variables and associated assumptions:

- network topology
- traffic characteristics and traffic matrix
- technology scenarios (i.e. MPLS vs. OTN)
- cost of equipment
- price charged by operators for Gigabit Ethernet services.

We describe each of our variables and assumptions below.

5.1.1 Network topology assumptions

In order to assess the impact of technology choice on an operator's business case (i.e. on its costs and potential revenue), we assume a simple core network topology, as illustrated in Figure 5.1.

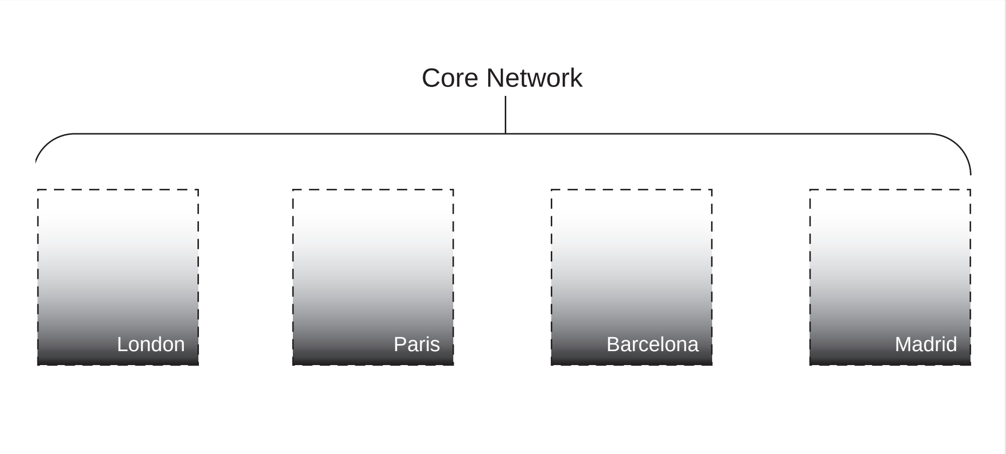


Figure 5.1: Assumed core network topology
[Source: Analysys Mason, 2011]

As shown above, our reference topology assumes a long-haul network serving London, Paris, Barcelona and Madrid. We believe that these distances are typical of a trans-European operator or of a US operator. We assume that each of these nodes is connected by a DWDM network, allowing a different number of signals to be transmitted on the same fibre, all on different wavelengths.

5.1.2 Traffic matrix and traffic characteristics assumptions

Traffic matrix

In order to derive the capital cost of the network for different architecture choices we are considering a packet-based[14] traffic matrix, as illustrated in Figure 5.2.

In order to be representative of a real network, we consider the following different types of traffic:

- carrier Ethernet traffic (revenue generating)
- OTT traffic, such as YouTube and peer-to-peer (non-revenue generating).

In our model, the traffic matrix consists of 138 different streams of traffic.[15] The source–destination pair for each stream of traffic is one of the following:[16]

- London to Paris
- London to Barcelona
- London to Madrid
- Paris to Barcelona
- Paris to Madrid
- Barcelona to Madrid.

The exact traffic matrix is illustrated in Figure 5.2 (and described in detail in Annex A).

Please note that Figure 5.2 only represents the average traffic throughput between the different source-destination node pairs.

Also, we assume that 20% of the traffic is OTT traffic and 80% is carrier Ethernet services.

Traffic characteristics

For each traffic stream, we define two parameters:

- **Average throughput –** the average traffic bandwidth over time. We assume that the average throughput is always guaranteed for each traffic stream in an MPLS network.
- **Peak throughput –** the maximum traffic bandwidth that can be reached by each traffic stream. We assume that the peak throughput is always guaranteed for each traffic stream in an OTN architecture.

We call the ratio between peak traffic throughput and average traffic throughput the peak-to-average ratio (P/A ratio).

A key consideration in our model is that, in a circuit-switched architecture (scenario 2, described in Section 5.1.3 below), the OTN pipes have to be dimensioned for the peak throughput for each traffic flow. Each of these traffic flow is then mapped onto dedicated ODU 0 circuit(s) equivalent to 1.25Gbit/s of capacity), which is the smallest defined bandwidth for establishing a circuit between two end points in an OTN. We assume that the OTN switch is ODU-flex capable.[17]

In marked contrast, in a packet-switched network (scenarios 1 and 3, described in Section 5.1.3 below), the network is dimensioned for the average traffic throughput, with enough 'over-provisioning' to accommodate up to seven traffic streams to peak simultaneously. In our model, the 'over-provisioning' represents between 4% and 16% additional bandwidth, over and above the average traffic throughput, depending on the P/A ratio considered in the simulation.

We call the ratio between peak traffic throughput and average traffic throughput the peak-to-average ratio (P/A ratio).

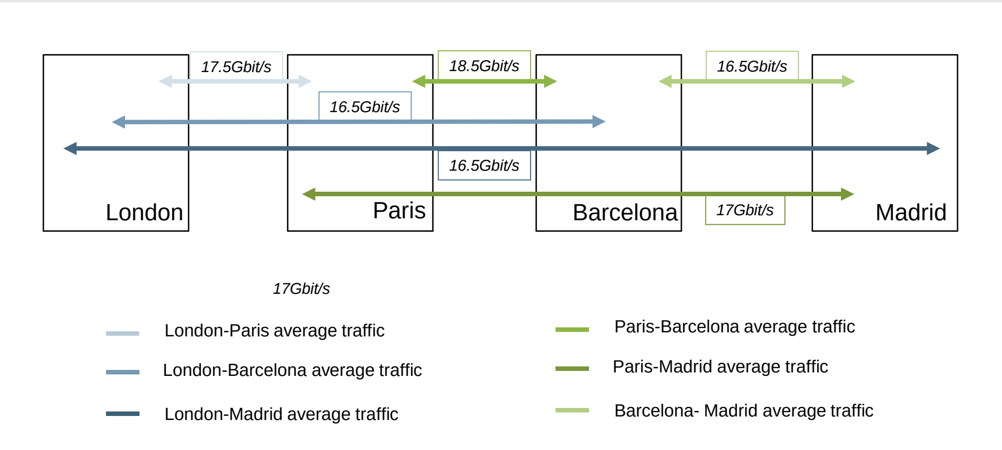


Figure 5.2: Assumed average traffic matrix
[Source: Analysys Mason, 2011]

[14] We do not model any TDM traffic as this is outside the scope of this study.

[15] 23 traffic streams for each source-destination pair.

[16] We assume bi-directional traffic on all links.

[17] See ODU-flex definition in Section 3.3.1.

5.1.3 Technology scenario assumptions

"For each scenario, we assume that the underlying Layer 1 transmission is provided through a DWDM network, which is already in place."

Based on the above network topology and traffic matrix, we consider three different scenarios to assess costs and associated revenues:

- scenario 1: MPLS switching network
- scenario 2: OTN switching network
- scenario 3: MPLS with OTN bypass.

For each scenario, we assume that the underlying Layer 1 transmission is provided through a DWDM network, which is already in place. We assume that no regeneration is required between each of the major nodes as this will depend on the type of DWDM equipment used. It should be noted that we do not consider the costs associated with optical line amplifiers, because we assume that the WDM system is already in place and would be a common cost for all scenarios.

Scenario 1: MPLS switching network

Scenario 1 involves implementing MPLS switches at all major sites of the network, as shown in Figure 5.4.

Scenario 1 allows maximum flexibility for the operator, as it:

- allows the operator to quickly adapt to any changes in traffic patterns without any reconfiguration of the network
- maximises the utilisation of resources in the network, since it is in essence a packet-switched network and optimises use of bandwidth due to packet statistical multiplexing
- enables the implementation of the full carrier Ethernet portfolio[18] as defined by the MEF and therefore maximises the opportunity for revenues
- enables the implementation of QoS, with different priorities for different traffic streams.[19]

Scenario 2: OTN switching network

Scenario 2 involves implementing OTN switches at all major sites of the network, with edge Ethernet switches[20] at each site. The network architecture considered for scenario 2 is illustrated in Figure 5.5.

The main advantage of scenario 2 is that it allows operators to:

- provide circuit-switched (TDM) and packet-switched (Ethernet) services with performance monitoring and maximum QoS
- provide sub-wavelength aggregation for Gigabit Ethernet traffic.

However, providing Ethernet services encapsulated into circuits means that the operator's core network has to be dimensioned according to peak traffic, if every traffic stream is to be provided transparently to the client purchasing these services (i.e. each Gigabit Ethernet traffic flow can be monitored individually). As explained (see Section 3.2), transporting Gigabit Ethernet using 'circuits' creates stranded bandwidth which cannot be used (see the empty timeslots in Figure 3.5).

Also, as mentioned elsewhere in this white paper, by definition, an OTN architecture cannot provide the full portfolio of carrier-grade Ethernet services, as private virtual line[21] or private virtual LAN[22] can only be provided by an MPLS network. Given the exponential growth of these services (as documented in Section 4.3), operators that deploy an OTN architecture with no MPLS capability risk missing out on a significant source of revenue.

Scenario 3: MPLS with OTN bypass

Scenario 3 is essentially the same as scenario 1, except that traffic in transit at a particular core node is bypassed at the OTN layer, without entering the MPLS switch at that node (as illustrated in Figure 5.6). The main advantage of this scenario is that traffic that is in transit uses OTN interfaces, which are generally priced at a lower level than MPLS interfaces.

In this scenario, we differentiate between local ports (required to deliver the local traffic) and line ports (that will be connected to the WDM transponders on the 'line side').

However, the main issue associated with this scenario is the increased amount of equipment required in the network (compared to scenarios 1 and 2). This means higher opex and capex for the network operator, which has to support and maintain both OTN and MPLS equipment.

Summary of assumptions

As shown in Figure 5.3, scenarios 1 and 3 are dimensioned according to average traffic, with an overprovisioning of 4–16% of capacity to accommodate cases where up to seven traffic streams peak at the same time. In contrast, scenario 2 is dimensioned according to peak traffic.

It is interesting to note the inefficiency of the ODU 0 mapping for the OTN (i.e. scenario 2). For a P/A ratio of 1.5, the peak traffic to be carried is 102.5Gbit/s×1.5=153.75Gbit/s. However, since each individual traffic flow will have to be mapped onto a different circuit, the total capacity required in the OTN network (scenario 2) will be 192×ODU 0[24], or 240Gbit/s, as indicated in Figure 5.3 (see annex A for traffic matrix). This means, that on average, the utilisation of ODU 0 circuits in the OTN will only be 63% for the traffic matrix we consider.

	Total provisioned average traffic (Gbit/s)	Overprovisioning	Total provisioned peak traffic (Gbit/s)	Traffic mapping
Scenario 1	102.5	4–16%	N/A	N/A
Scenario 2	N/A	N/A	Between 240 and 330 [23]	ODU 0
Scenario 3	102.5	4–16%	N/A	(1.25Gbit/s)

Figure 5.3: Summary of traffic assumptions for the different scenarios
[Source: Analysys Mason, 2011] N/A = Not applicable

It is interesting to note the inefficiency of the ODU 0 mapping for the OTN (i.e. scenario 2). For a P/A ratio of 1.5, the peak traffic to be carried is 102.5Gbit/s×1.5=153.75Gbit/s.

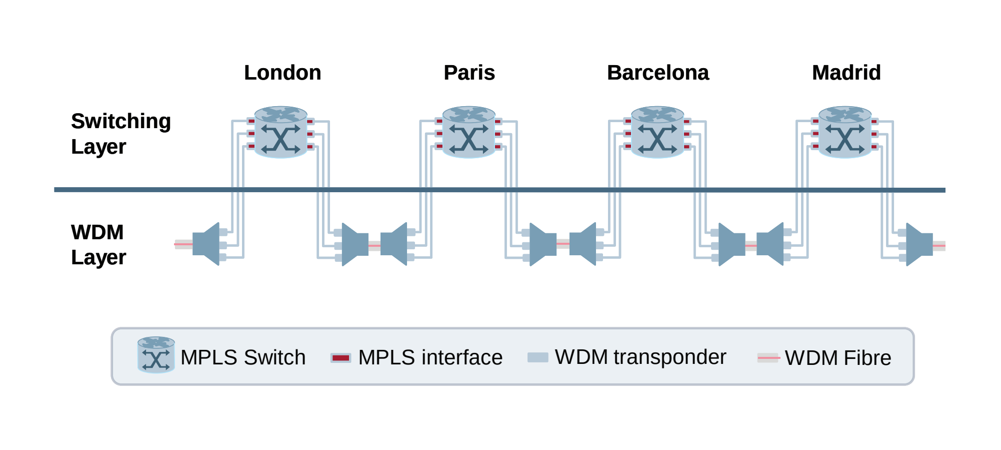


Figure 5.4: Scenario 1: MPLS with WDM transport
[Source: Analysys Mason, 2011]

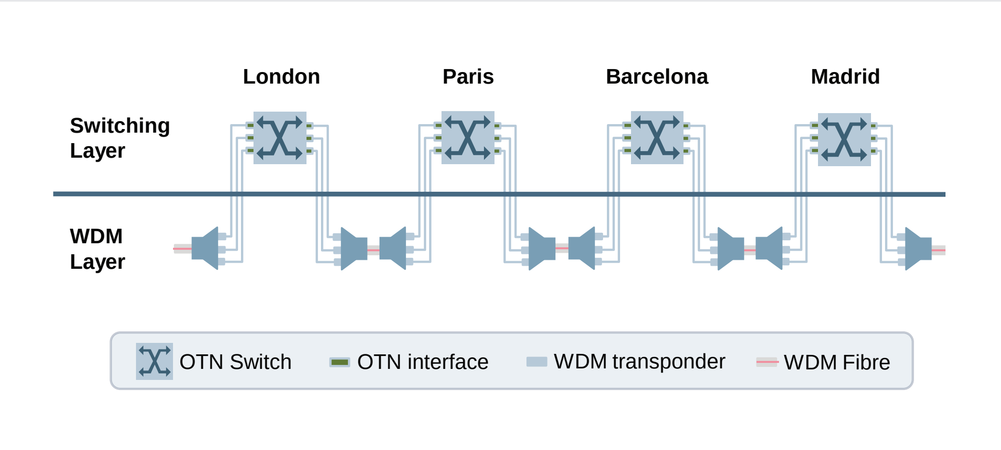


Figure 5.5: Scenario 2: OTN with WDM transport [Source: Analysys Mason]
[Source: Analysys Mason, 2011] N/A = Not applicable

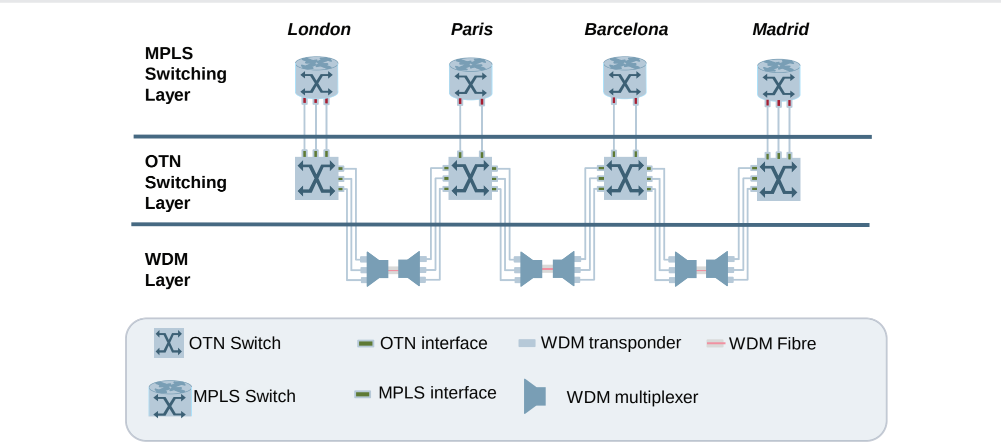


Figure 5.6: Scenario 3: MPLS with OTN bypass and WDM transport
[Source: Analysys Mason, 2011]

[18] Ethernet private line, Ethernet private LAN, Etherent virtual private line and Ethernet virtual private LAN.
[19] It should be noted that some of the services in our traffic matrix have a guaranteed peak throughput.
[20] It should be noted that edge switches are not represented in Figure 5.4 and their costs are not modelled.
[21] A point-to-point service that uses shared network resources.
[22] A point-to-multipoint service that uses shared network resources.
[23] For P/A ratios of 1.5 and 3, respectively.
[24] 18xGE traffic flows, with 500 Mbit/s peak traffic, each requiring 4xODU-0, and 120GE traffic flows requiring 1xODU-0 each.

5.1.4 Scenario costing assumptions

"In this case study, we assume that the MPLS–to-OTN port cost ratio is 1.3". "

We assume that all equipment deployed in a scenario is costed by port. This implies that all equipment is reasonably full with service cards and that the key driver is the cost of the interface card of that equipment; this costing method is reasonably well accepted in the telecoms industry.

In effect, the cost of the common cards and chassis for each type of equipment is absorbed in the cost of the ports.

Also, in order to compare the different scenarios, we assume a normalised cost per port. Results from our primary research into the cost of equipment are summarised in Figure 5.7.

As shown in Figure 5.7, the capital cost of an OTN port provides the reference cost, and all other equipment interface costs are normalised to this cost. The relative costs shown in Figure 5.7 are based on an average discounted cost across a number of vendors we interviewed. In this case study we assume that the MPLS-to-OTN port cost ratio is 1.3.[25]

Also, according to the same interviews, a long-haul DWDM transport system 10Gbit/s port typically costs 80% as much as an OTN port.

Equipment type	Relative cost per port (range)
OTN switch	1
MPLS switch	Between 1 and 2
DWDM transport system	0.8

Figure 5.7: Relative cost per interface
[Source: Analysys Mason]

5.1.5 Service pricing assumptions

For this white paper, we also surveyed the prices of carrier Ethernet services from different operators. We differentiate between two types of service:

A key result from the survey was that a shared EVPL Gigabit Ethernet service provided on a shared MPLS network with a guaranteed throughput of 300Mbit/s was only 25% less expensive than a dedicated EPL Gigabit Ethernet service, providing the peak capacity of 1Gbit/s.

- **Ethernet private line (EPL)** – point-to-point Ethernet circuits offered over OTN with full peak throughput guaranteed, and
- **Ethernet virtual private line (EVPL)** – point-to-point Ethernet circuits offered over MPLS with average throughput guaranteed.

The results are shown in Figure 5.8 below.

We obtained these prices by considering inter-town circuits in Europe.

A key result from the survey was that a shared EVPL Gigabit Ethernet service provided on a shared MPLS network with a guaranteed throughput of 300Mbit/s was only 25% less expensive than a dedicated EPL Gigabit Ethernet service, providing the peak capacity of 1Gbit/s. It should be noted that the EVPL service can burst up to 1Gbit/s but only 300Mbit/s of capacity is guaranteed at any moment in time.

The argument of many operators is that the cost of Ethernet service is mainly driven by the interface, and providing additional capacity in the network does not usually involve any reconfigurations. Also, in Figure 5.8, the operator price ratio between a dedicated Gigabit Ethernet and a 10 Gigabit Ethernet is 3.

Service type	Capacity guaranteed (Mbit/s)	Peak capacity (Mbit/s)	Relative service price
Gigabit Ethernet (EPL)	1000	1000	1
Gigabit Ethernet (EVPL)	700	1000	0.85
Gigabit Ethernet (EVPL)	500	1000	0.8
Gigabit Ethernet (EVPL)	300	1000	0.75
10 Gigabit Ethernet (EPL)	10 000	10 000	3
10 Gigabit Ethernet (EVPL)	7000	10000	2.55
10 Gigabit Ethernet (EVPL)	5000	10000	2.4
10 Gigabit Ethernet (EVPL)	3000	10000	2.25

Figure 5.8: Relative prices of services
[Source: Analysys Mason, 2011]

[25] Section B.2 provides a cost sensitivity analysis, by varying the MPLS port cost between 1 and 2.

5.2 Capex and revenue results

"A summary of our results is illustrated in Figure 5.9 and Figure 5.10 for P/A ratios of 2 and 3, respectively."

In this section we summarise results for all three scenarios for the following metrics, based on the assumptions described in Section 5.1:

- provisioned capacity
- capex
- revenue
- capex efficiency.

Please refer to Annex A for a detailed discussion of each of these metrics. A summary of our results is illustrated in Figure 5.9 and Figure 5.10 for P/A ratios of 2 and 3, respectively.

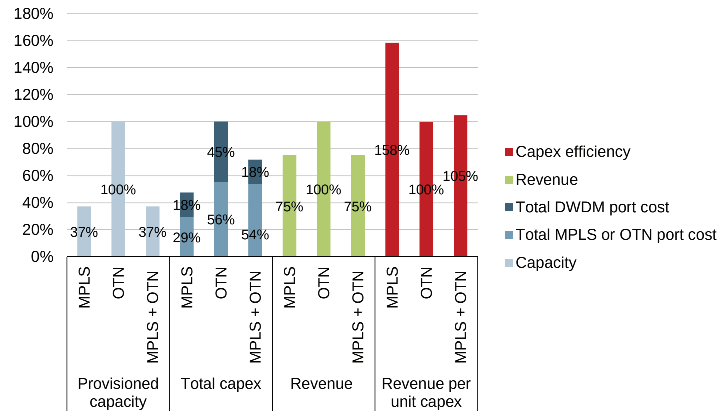


Figure 5.9: Case study summary for P/A=2
[Source: Analysys Mason]

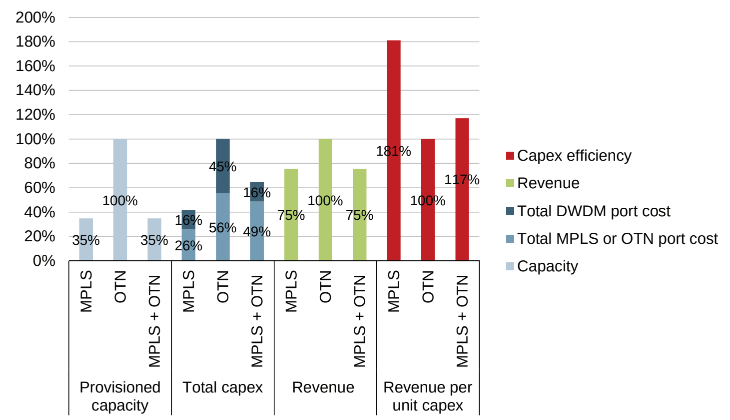


Figure 5.10: Case study summary for P/A=3
[Source: Analysys Mason]

5.2.1 Provisioned capacity

In our case study, in order to carry the same traffic flows, an operator with an MPLS network only needs to provision 37% of the capacity compared to an OTN operator for a P/A ratio of 2, and 35% for a P/A ratio of 3. This is because:

- In an MPLS network (scenario 1), capacity is provisioned according to average traffic bandwidth, taking advantage of statistical multiplexing; and the same is true for an MPLS network with OTN bypass (scenario 3). However, an OTN operator (scenario 2) provisions capacity according to peak traffic bandwidth, on fixed-capacity circuits.
- The lowest-capacity circuit that can be used in an OTN architecture to transport a Gigabit Ethernet service is ODU 0 (1.25Gbit/s), which means that some traffic will be significantly over provisioned (e.g. a traffic flow with a peak of 500Mbit/s will use a dedicated 1.25Gbit/s circuit).

This combination of fewer ports and fewer WDM interfaces means that the capex for an MPLS network will be 47% or 42% of the capex for an OTN network (for P/A ratios of 2 and 3, respectively).

5.2.2 Capex

Although we assume the unit cost of an MPLS port is 33% higher than an OTN port, the lower capacity required in an MPLS network means that there are significantly fewer ports in an MPLS network than in an OTN (for the same traffic matrix). The lower number of MPLS ports more than compensates for the higher unit cost of MPLS ports.

In an MPLS network with OTN bypass (scenario 3), the ports on the line side are cheaper OTN ports (rather than MPLS ports). However, additional OTN and MPLS ports are required for the local traffic (see Figure 5.6), which cancels out the benefits of using cheaper OTN ports for bypassing the transit traffic.

Also, since less capacity needs to be provisioned in an MPLS network, fewer wavelengths are required to transport the traffic between sites, which helps to reduce costs further (i.e. fewer WDM transponders are required in an MPLS network than in an OTN). It is notable that WDM transponders account for nearly 45% of the total capex in an OTN network.

This combination of fewer ports and fewer WDM interfaces means that the capex for an MPLS network will be 47% or 42% of the capex for an OTN network (for P/A ratios of 2 and 3, respectively).

Also, the overall capex for an MPLS network with OTN bypass (scenario 3) is always greater than the capex associated with scenario 1 (MPLS network) and always lower than the capex associated with scenario 2 (OTN) for all P/A ratios (see Figure B.3 in Annex B.2).

5.2.3 Revenue

"the MPLS operators we interviewed would typically charge 25% less for a Gigabit Ethernet service than an OTN operator, but would only provision one third as much capacity. The lower revenue partially offsets the tremendous cost advantage enjoyed by an MPLS operator, but overall it still has the potential to be much more profitable than an OTN operator, as illustrated in our analysis of capex efficiency."

We conducted market research on what operators typically charge for Ethernet services provided on an MPLS versus those provided on an OTN.

On an MPLS network, we found that Ethernet services are typically sold in such a way that only a proportion of the peak throughput is guaranteed for each service, to take advantage of statistical multiplexing. In contrast, an OTN operator will typically guarantee the full throughput (i.e. a full 1Gbit/s for Gigabit Ethernet services). Therefore, an MPLS-based operator typically offers a small discount because they do not provide absolute certainty that the network will be able to carry the peak traffic of all traffic flows at any time. To handle the same traffic matrix, the MPLS operators we interviewed would typically charge 25%[26] less for a Gigabit Ethernet service than an OTN operator, but would only provision one third as much capacity. The lower revenue partially offsets the tremendous cost advantage enjoyed by an MPLS operator, but overall it still has the potential to be much more profitable than an OTN operator, as illustrated in our analysis of capex efficiency.

5.2.4 Capex efficiency (revenue per invested capex)

The business case for choosing the most efficient architecture is dictated by profitability. In order to assess profitability, we define capex efficiency as the relative revenue for each USD of capex invested in the network. In other words, we define capex efficiency as revenue divided by network capex.

As shown in Figure 5.9 and Figure 5.10 earlier, the capex efficiency for an MPLS network is significantly higher than for an OTN: for a P/A ratio of 2, the capex efficiency of an MPLS network is 58% higher than an OTN; and for a P/A ratio of 3 it is 81% higher. In general, the higher the P/A, the higher the return on capex for an MPLS network compared to an OTN.

This means that for every USD of capex invested in the network, an MPLS network will provide 58% and 81% additional revenues for the operator compared to an OTN (for P/A ratios of 2 and 3, respectively). As shown in our detailed results in Annex A, the higher the P/A ratio, the more advantageous MPLS is over OTN.

However, for an MPLS network with OTN bypass (scenario 3), the capex efficiency is comparable to that of an OTN (scenario 2) for a P/A of 2. For a P/A ratio of 3, the capex efficiency for scenario 3 is 17% higher than for an OTN, but still significantly lower than for an MPLS network (scenario 2). This means that, overall, adding OTN ports to an MPLS network to bypass transit traffic with cheaper ports results in a significant degradation in revenue per unit capex compared to an MPLS network (scenario 1).

5.2.5 What does the result really mean in terms of capex and revenue?

MPLS is more suited to traffic unpredictability

From our interviews with operators, it is clear that determining the actual P/A ratio is quite challenging, and it is probably impossible to make an accurate forecast of how the P/A ratio is going to evolve in the short term. Traffic with random characteristics is, by its nature, unpredictable.

Considering the static analysis illustrated in Figure 5.9 and Figure 5.10, MPLS provides a better return on capex investment for each of the P/A ratios considered. In a real network, however, it is not possible to forecast the P/A ratio, primarily due to the increasingly unpredictable nature of the traffic. The majority of operators interviewed for this paper expect the P/A ratio to increase over time, even for the highly aggregated trunk links in the core network, but no operator is able to predict how much it might increase. In this dynamic environment, MPLS networks provide an even better prospect than OTN, because the higher the P/A ratio, the more profitable an MPLS-based operator will be compared to an OTN-based operator (as illustrated in Figure B.6 in Annex A). In this context, it is clear that MPLS technology will be more suited to the unpredictable nature of future traffic.

MPLS provides a more sustainable business model than OTN technology

Overall, our case study illustrates that, in an OTN, capex is strongly coupled with an increase in network capacity, which means the operator is unable to dissociate traffic bandwidth from costs. This is a major issue, as this business model is unsustainable if revenue stagnates, which means that operators using an OTN network, will see their margins erode as the traffic bandwidth requirement increases (see Figure 4.1).

In marked contrast, operators that use an MPLS network have the flexibility to dissociate bandwidth increase from provisioned capacity (and therefore cost), leading to a much more sustainable business model. Dissociating bandwidth from capex can, for example, be achieved by either:

- implementing different classes of service for revenue-generating and non-revenue-generating traffic (e.g. best effort); or
- increasing the contention ratio in the network, in order to offer an increased range of services over the same provisioned capacity (but with a reduced service level agreement).

Bypassing transit traffic using OTN technology will not profit the MPLS operator's business case

Perhaps a less expected result from this case study is that the capex efficiency of an MPLS network with OTN bypass (scenario 3) is lower than for a native MPLS network (scenario 1), but higher than that for an OTN (scenario 2).

MPLS with OTN bypass incurs higher capex than a native MPLS network, principally because a significant number of additional MPLS and OTN ports are required for the local traffic (to interconnect the OTN multiplexer and the MPLS switch, as shown in Figure 5.5). The additional cost associated with these local ports outweighs the cost saving made by using cheaper OTN ports (compared to MPLS ports) on the line side. Therefore, according to our results, an operator that uses OTN bypass architecture (scenario 3) will always earn less revenue per invested capex than an operator with a native MPLS network (scenario 1).

Overall, our case study illustrates that, in an OTN, capex is strongly coupled with an increase in network capacity, which means the operator is unable to dissociate traffic bandwidth from costs.

[25] Please refer to the pricing benchmark presented in Section 5.1.5, where full Gigabit Ethernet (with guaranteed peak bandwidth) is charged at 25% more than a Gigabit Ethernet flow with 300Mbit/s guaranteed.

5.3 Opex considerations

"In this paper we are evaluating opex associated with core networks, which, as Figure 5.11 indicates, typically represents a significant 22% of overall opex for a service provider."

Opex is always a contentious subject for operators as it very much depends on their own business model (e.g. issues such as sourcing strategy, cost of labour, capital investment in management systems, and organisational structure).

Indeed, the opex quoted in different white papers widely vary and the cause for this variation is not often clear.

In this paper, instead of trying to identify the exact opex associated with each scenario considered, we provide some insight regarding what network opex components are affected by the decision regarding technical strategy.

5.3.1 Scale of opex involved

Firstly, it is important to consider how much the core network contributes to the overall opex of an operator. A typical breakdown of network opex is provided in Figure 5.11.

In this paper we are evaluating opex associated with core networks, which, as Figure 5.11 indicates, typically represents a significant 22% of overall opex for a service provider. So, any opportunity to reduce core network opex is likely to make a substantial difference to the overall business plan and bottom-line margin.

In the rest of this section, we concentrate on network and IT and personnel opex associated with the core network.

In order to compare the impact of the different core architectures considered in this paper, we consider the following elements of core network opex:

- network maintenance (personnel)
- capacity planning and management (personnel)
- power consumption (network and IT).

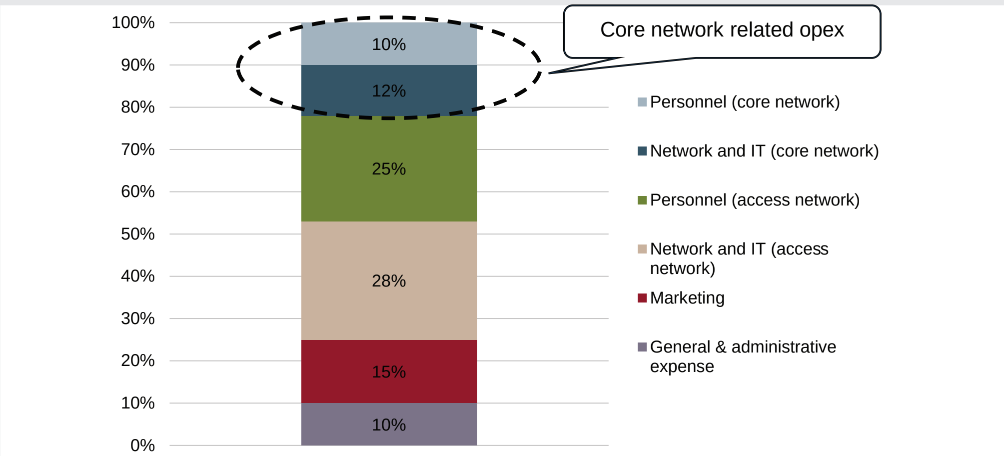


Figure 5.11: Example of opex breakdown for a fixed operator
[Source: Analysys Mason, 2011]

5.3.2 Maintenance opex

Depending on the business model, network maintenance is performed by different entities at various levels; for this paper, we have assumed the following operational model[27]:

- Level 1 and 2 (L1 and L2) maintenance is performed by the operator's dedicated operational teams
- Level 3 and 4 (L3 and L4) maintenance is performed by the equipment vendor, in the form of a maintenance contract.

Level 1 and 2 maintenance

As presented in Figure B.3 in Section B.2, for the same traffic matrix, an OTN would have more than twice as many ports as an MPLS network (for a P/A ratio of 2, an MPLS network would have 40 MPLS ports and an OTN would have 98; for a P/A ratio of 3, an MPLS network would still have 40 MPLS ports but an OTN would need 112). Assuming that both MPLS and OTN ports have the same reliability[28], there will be between 145% and 180% more faults on an OTN than on an MPLS network[29]. However, it would not be reasonable to assume that the L1 and L2 maintenance opex is directly proportional to the number of faults in the network, as a baseline maintenance team would be required even if there were very few faults in the network. However, for simplicity we assume that L1 maintenance opex is a linear function of the number of faults in the network, as we are just trying to show the relative opex difference between an MPLS and an OTN. Using this assumption, an operator with an MPLS network (scenario 1) may only incur between 36% and 41% as much opex as an operator with an OTN (scenario 2), purely because of the difference in the total number of ports.

An MPLS network that uses OTN bypass (scenario 3) needs more ports than a native MPLS network (scenario 1), and so requires significantly more Level 1(L1) and Level 2(L2) maintenance opex than a native MPLS network (as shown in Figure 5.12 and Figure 5.13). However, the L1 and L2 opex associated with an MPLS network using OTN bypass (scenario 3) is significantly less than that needed for an OTN (scenario 2).

It should be noted that an operator with an MPLS network using OTN bypass (scenario 3) has to maintain two different technologies, which will require additional training or the recruitment of staff who specialise in each technology.

Level 3 and 4 maintenance

The annual fee charged by equipment vendors for level 3 and 4 maintenance contracts typically represents between 8% and 15% of the cumulative equipment capex. Therefore the higher the network capex, the higher the maintenance fee from the equipment vendor. For the same traffic matrix, we showed in Section that the capex for an MPLS network would be 47% or 42% of the capex for an OTN (for a P/A ratio of 2 and 3, respectively). Therefore, the Level 3 and 4 maintenance contracts can be expected to follow the same trend.

The expected levels of Level 3 and Level 4 maintenance opex for all three scenarios are summarised in Figure 5.12 and Figure 5.13.

It should be noted that an operator with an MPLS network using OTN bypass (scenario 3) has to maintain two different technologies, which will require additional training or the recruitment of staff who specialise in each technology.

[27] The assumed operational model is just one example of those currently used in the industry.

[28] Technically, port reliability is called mean time between failure (or MTBF).

[29] For P/A ratios of 2 and 3, respectively.

5.3.2 Maintenance opex continued

"The expected levels of Level 3 and Level 4 maintenance opex for all three scenarios are summarised in Figure 5.12 and Figure 5.13."

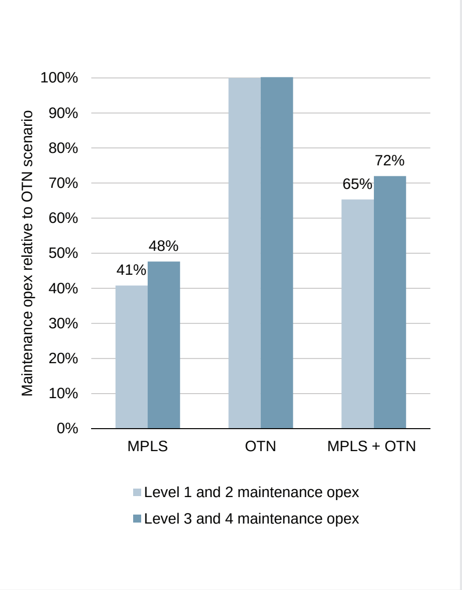


Figure 5.12: Relative Maintenance opex for a P/A ratio of 2 [Source: Analysys Mason, 2011]

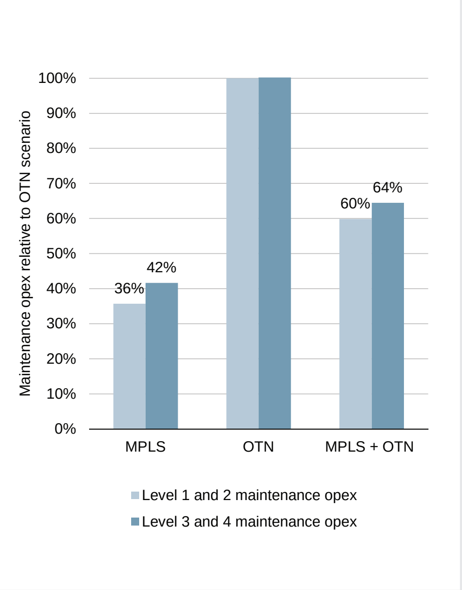


Figure 5.13: Relative Maintenance opex for a P/A ratio of 3 [Source: Analysys Mason, 2011]

5.3.3 Capacity planning and management opex

As discussed in Section 4.3, the grooming of traffic at the edge of the network is vital in optimising resource utilisation on the network.

In a network, the increasing unpredictability of where the traffic is going to come from and where it will be destined for means that, in a circuit-switched environment, it will be increasingly difficult to optimise the resource of the network.

However, because of the increasing traffic uncertainty, traffic flows are dynamically created and torn down to and from different sources and destinations. In our railway analogy in Section 3.1, this is equivalent to the customer demand constantly changing over time; in order to optimise the use of its resources, the train operator would therefore have to constantly adjust the number of carriages on existing services between stations, which would be very labour intensive and therefore drive up opex.

In a network, the increasing unpredictability of where the traffic is going to come from and where it will be destined for means that, in a circuit-switched environment, it will be increasingly difficult to optimise the resource of the network. This is because circuits will have to be provisioned 'on the fly', which will be labour intensive (requiring significant resources from the operational team) and will result in higher opex.

However, there is a different way of addressing this issue for a circuit-switched network. Operators have the option of over-dimensioning their circuit-switched network from day one (similar to adding extra carriages knowing they will be empty most of the time initially). This approach would enable any increase in traffic in any part of the network to be met with minimal (or no) need for network reconfiguration, thereby minimising opex but increasing capex. The operator must therefore choose between:

- **Option 1** – over-dimensioning its circuit-switched network from day one, in order to minimise its opex in return for very substantial up-front capex investment.
- **Option 2** – making capex investments in line with the traffic demand, with the risk of incurring very large opex due to the need for frequent network reconfiguration (or else being unable to carry a surge in traffic and losing business from the affected customers).

We note that Option 1 has been proposed by one vendor of long-haul equipment, whereby long-haul systems are pre-equipped with, say, 100Gbit/s of capacity and that capacity is provisioned and paid for as the demand arises. However, as stated above, this very large up-front capital investment does not match the characteristics of the traffic that is carried on the network in a packet-oriented model of Ethernet-based services. In this context, AT&T commented: *"network providers cannot economically serve their customers by radically over-provisioning bandwidth throughout their networks to guarantee the same low-latency, low-jitter, and low-loss performance at all times for all applications, whether those applications are performance-sensitive or not."*[30]

[30] See http://www.att.com/Common/about_us/public_policy/AT&TNet_Neutrality_Comments1_14_09.pdf.

5.3.4 Power consumption opex

"For the MPLS network with OTN bypass, power consumption is around 1.6 times higher than for the MPLS network (for P/A ratios of both 2 and 3)."

Power consumption is been subjected to increasing scrutiny by operators due to rising energy prices and, to a lesser extent, ecological concerns.

For this paper, we undertook primary and secondary research to benchmark the power consumption per port for each technology considered (i.e. MPLS, OTN and WDM). The power consumption per port for fully equipped chassis is summarised in Figure 5.14.

The results of our research for the OTN and WDM ports were as expected, and in line with the technical equipment description sheets published by equipment vendors.

In contrast, the results of our research into the power consumption of MPLS ports were initially surprising as we expected the power consumption of MPLS ports to be higher than OTN or WDM ports, but it was comparable. We validated our results with leading vendors of MPLS equipment and discovered that, the power consumption of core MPLS switches has fallen dramatically in the past three years for the following reasons:

- MPLS switches use purpose-built appliances that are optimised for MPLS switching and do not perform full IP-routing functionalities. This minimises packet processing, which in turn significantly reduces the power consumption per bit.
- MPLS switches use novel queuing techniques (e.g. virtual output queuing) which reduce the on-board memory required and minimise the number of components a packet has to go through while in the switch. This increases the number of packets per second that the system can process using the same or less power.
- The ever-increasing density integration of chips has led to a dramatic reduction in the number of discrete components required. Higher-density integration also means higher efficiency in the cooling of equipment, again minimising power consumption.

Based on the consumption per port shown in Figure 5.14, we evaluated the overall power consumption for all three scenarios studied in this paper. The results are shown in Figure 5.15 and Figure 5.16 (for P/A ratios of 2 and 3, respectively).

In Figure 5.15 and Figure 5.16, it can be seen that total power consumption for the MPLS network is significantly lower than for the OTN network, mainly due to the lower number of ports: MPLS network power consumption is 40% and 36% that of the MPLS network (for P/A ratios of 2 and 3, respectively).

For the MPLS network with OTN bypass, power consumption is around 1.6 times higher than for the MPLS network (for P/A ratios of both 2 and 3).

This is a significant result, as it indicates that the opex associated with power will be substantially lower for an MPLS-based operator than for an OTN-based operator.

	MPLS port	OTN port	WDM port
Energy consumption from research (Watt)	1.5–2.5	2-3	2-3
Assumed energy consumption (Watt)	2	2	2

Figure 5.14: Power consumption per port for different technologies
[Source: Analysys Mason]

5.3.4 Power consumption opex continued

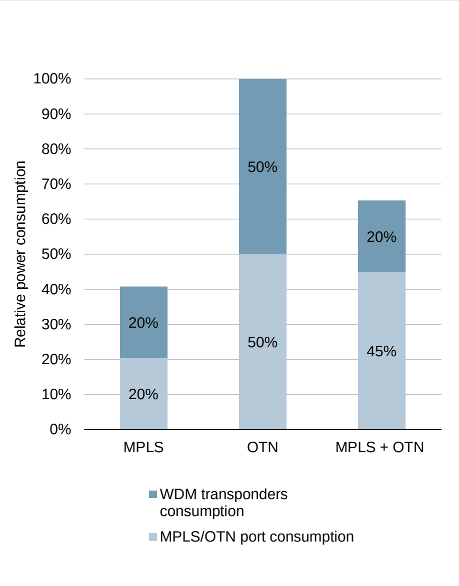


Figure 5.15: Power consumption for a P/A ratio of 2
[Source: Analysys Mason, 2011]

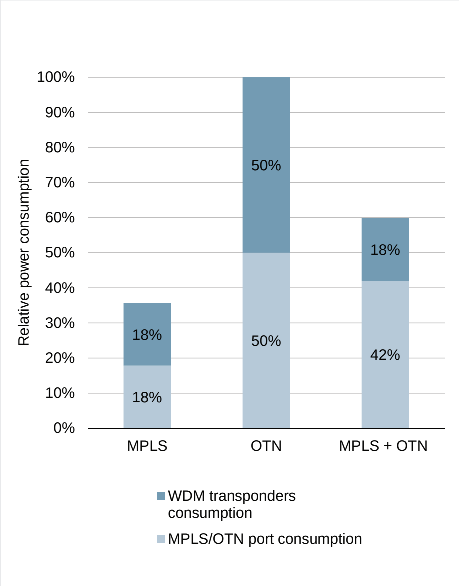


Figure 5.16: Power consumption for a P/A ratio of 3
[Source: Analysys Mason, 2011]

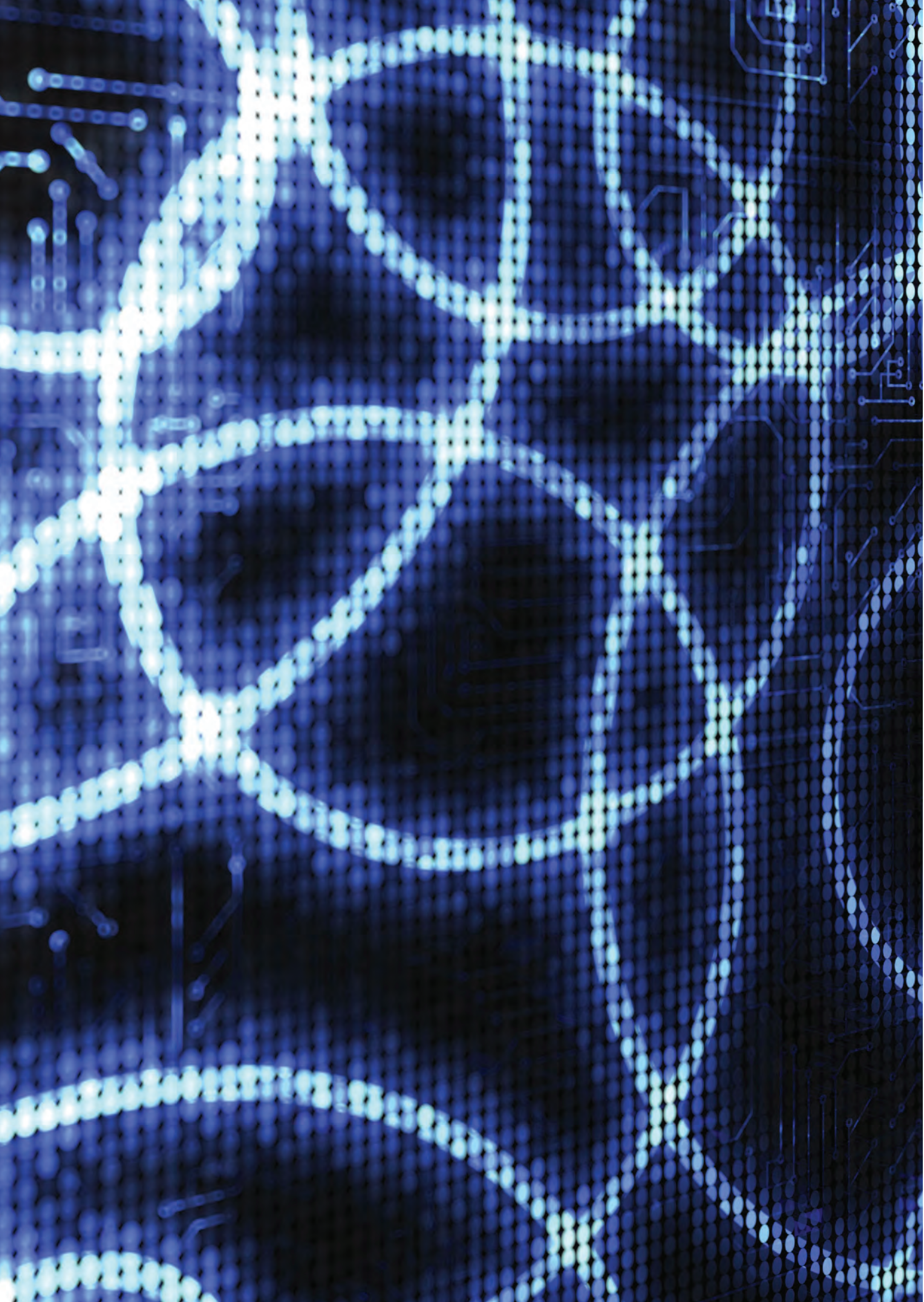
In Figure 5.15 and Figure 5.16, it can be seen that total power consumption for the MPLS network is significantly lower than for the OTN network, mainly due to the lower number of ports: MPLS network power consumption is 40% and 36% that of the MPLS network (for P/A ratios of 2 and 3, respectively).

5.3.5 What does this result mean in terms of opex?

From the above opex analysis it is clear that operation and maintenance of an MPLS network will involve significantly less opex than for an OTN, for the following reasons:

- an MPLS network (scenario 1) will incur less than half the maintenance opex of an OTN (scenario 2), mainly driven by the overall higher number of ports and cumulative capex
- an MPLS network will require significantly less network reconfiguration to reflect changing traffic patterns than an OTN, resulting in a reduced opex for capacity planning and management
- an MPLS network typically consumes 40% less energy than an OTN, which will help operators to reduce their energy costs and meet their 'green objectives'.

Based on the above observations, it is clear that an MPLS-based operator will incur significantly less opex than an OTN operator. This provides further support for a business model where costs do not increase in proportion with bandwidth requirements.



6 CONCLUSIONS

From our analysis, it is evident that MPLS technology is not only more cost-effective but also more flexible than OTN technology for providing packet-switched services. In this respect, an MPLS architecture will be the optimum investment for an operator, for the following reasons:

- MPLS enables an operator to dissociate traffic bandwidth and capacity provisioning, which is key in controlling costs and therefore breaking away from eroding margins.
- MPLS makes it possible to differentiate between different traffic types (e.g. revenue-generating versus non-revenue-generating) and to adjust their capex spending accordingly.
- MPLS provides the ability for the operator to offer the full range of carrier Ethernet services, which represent one of the fastest-growing markets.
- MPLS is more suited to accommodating changes in traffic patterns, which, with the advent of cloud computing and the increase in user mobility, is becoming an increasing issue.
- MPLS will enable the operator to generate between 58% and 81% more revenues than OTN, for the same capex investment.
- An MPLS-based operator will incur less opex compared to an OTN-based operator, which will have significantly more ports to operate and maintain.
- MPLS architecture and technology enable an operator to significantly reduce its power consumption, saving costs and helping it to meet its green agenda.

Therefore, a native MPLS architecture is the only one which offers the flexibility for operators to adapt their business model in line with the changes currently being experienced in the telecoms industry, by providing a way to differentiate revenue-generating and non-revenue-generating traffic, and to control capex and opex.

Annex A Traffic matrix

Figure A.1: Traffic matrix for an overall P/A ratio of 1.5 [Source: Analysys Mason]

This annex provides a description of all traffic flows between the different network nodes assumed for this white paper.

It should be noted that for scenario 1 (MPLS) and scenario 3 (MPLS with OTN bypass), network capacity was provisioned to guarantee the average traffic throughput for all traffic flows, while at the same time guaranteeing enough capacity for seven traffic flows peak throughput.[31] For scenario 2 (OTN), network capacity was provisioned to guarantee the peak traffic throughput for all traffic flows simultaneously.

Finally, note that the traffic matrix in Figure A.1 below has an overall P/A ratio of 1.5. The P/A ratio was varied by increasing the peak bandwidth for each flow, while keeping the average bandwidth constant.

Traffic flow index	Traffic type	Average bandwidth (Mbit/s)	Peak bandwidth (Mbit/s)	P/A ratio	Source	Destination
01	Carrier Ethernet (10GE)	4000	5000	1.25	London	Paris
02	Carrier Ethernet (10GE)	4000	5000	1.25	Paris	Barcelona
03	Carrier Ethernet (10GE)	4000	5000	1.25	Barcelona	Madrid
04	Carrier Ethernet (10GE)	4000	5000	1.25	London	Barcelona
05	Carrier Ethernet (10GE)	4000	5000	1.25	London	Madrid
06	Carrier Ethernet (10GE)	4000	5000	1.25	Paris	Madrid
07	Carrier Ethernet (10GE)	3333	5000	1.5	London	Paris
08	Carrier Ethernet (10GE)	3333	5000	1.5	Paris	Barcelona
09	Carrier Ethernet (10GE)	3333	5000	1.5	Barcelona	Madrid
10	Carrier Ethernet (10GE)	3333	5000	1.5	London	Barcelona
11	Carrier Ethernet (10GE)	3333	5000	1.5	London	Madrid
12	Carrier Ethernet (10GE)	3333	5000	1.5	Paris	Madrid
13	Carrier Ethernet (GE)	500	500	1	London	Paris
14	Carrier Ethernet (GE)	500	500	1	London	Paris
15	Carrier Ethernet (GE)	500	500	1	Paris	Barcelona
16	Carrier Ethernet (GE)	500	500	1	Paris	Barcelona
17	Carrier Ethernet (GE)	500	500	1	Barcelona	Madrid
18	Carrier Ethernet (GE)	500	500	1	Barcelona	Madrid
19	Carrier Ethernet (GE)	500	500	1	London	Barcelona
20	Carrier Ethernet (GE)	500	500	1	London	Barcelona
21	Carrier Ethernet (GE)	500	500	1	London	Madrid
22	Carrier Ethernet (GE)	500	500	1	London	Madrid
23	Carrier Ethernet (GE)	500	500	1	Paris	Madrid
24	Carrier Ethernet (GE)	500	500	1	Paris	Madrid
25	Carrier Ethernet (GE)	416	500	1.2	London	Paris
26	Carrier Ethernet (GE)	416	500	1.2	London	Paris
27	Carrier Ethernet (GE)	416	500	1.2	Paris	Barcelona

[31] flows 1, 14, 30,60, 84, 103, 133

Annex A Traffic matrix continued -

Figure A.1: Traffic matrix for an overall P/A ratio of 1.5 [Source: Analysys Mason]

Traffic flow index	Traffic type	Average bandwidth (Mbit/s)	Peak bandwidth (Mbit/s)	P/A ratio	Source	Destination
28	Carrier Ethernet (GE)	416	500	1.2	Paris	Barcelona
29	Carrier Ethernet (GE)	416	500	1.2	Barcelona	Madrid
30	Carrier Ethernet (GE)	416	500	1.2	Barcelona	Madrid
31	Carrier Ethernet (GE)	416	500	1.2	London	Barcelona
32	Carrier Ethernet (GE)	416	500	1.2	London	Barcelona
33	Carrier Ethernet (GE)	416	500	1.2	London	Madrid
34	Carrier Ethernet (GE)	416	500	1.2	London	Madrid
35	Carrier Ethernet (GE)	416	500	1.2	Paris	Madrid
36	Carrier Ethernet (GE)	416	500	1.2	Paris	Madrid
37	Carrier Ethernet (GE)	357	500	1.4	London	Paris
38	Carrier Ethernet (GE)	357	500	1.4	London	Paris
39	Carrier Ethernet (GE)	357	500	1.4	Paris	Barcelona
40	Carrier Ethernet (GE)	357	500	1.4	Paris	Barcelona
41	Carrier Ethernet (GE)	357	500	1.4	Barcelona	Madrid
42	Carrier Ethernet (GE)	357	500	1.4	Barcelona	Madrid
43	Carrier Ethernet (GE)	357	500	1.4	London	Barcelona
44	Carrier Ethernet (GE)	357	500	1.4	London	Barcelona
45	Carrier Ethernet (GE)	357	500	1.4	London	Madrid
46	Carrier Ethernet (GE)	357	500	1.4	London	Madrid
47	Carrier Ethernet (GE)	357	500	1.4	Paris	Madrid
48	Carrier Ethernet (GE)	357	500	1.4	Paris	Madrid
49	Carrier Ethernet (GE)	312	500	1.6	London	Paris
50	Carrier Ethernet (GE)	312	500	1.6	London	Paris
51	Carrier Ethernet (GE)	312	500	1.6	Paris	Barcelona
52	Carrier Ethernet (GE)	312	500	1.6	Paris	Barcelona
53	Carrier Ethernet (GE)	312	500	1.6	Barcelona	Madrid
54	Carrier Ethernet (GE)	312	500	1.6	Barcelona	Madrid
55	Carrier Ethernet (GE)	312	500	1.6	London	Barcelona
56	Carrier Ethernet (GE)	312	500	1.6	London	Barcelona
57	Carrier Ethernet (GE)	312	500	1.6	London	Madrid
58	Carrier Ethernet (GE)	312	500	1.6	London	Madrid
59	Carrier Ethernet (GE)	312	500	1.6	Paris	Madrid
60	Carrier Ethernet (GE)	312	500	1.6	Paris	Madrid
61	Carrier Ethernet (GE)	277	500	1.8	London	Paris
62	Carrier Ethernet (GE)	277	500	1.8	London	Paris

Annex A Traffic matrix continued -

Figure A.1: Traffic matrix for an overall P/A ratio of 1.5 [Source: Analysys Mason]

Traffic flow index	Traffic type	Average bandwidth (Mbit/s)	Peak bandwidth (Mbit/s)	P/A ratio	Source	Destination
63	Carrier Ethernet (GE)	277	500	1.8	Paris	Barcelona
64	Carrier Ethernet (GE)	277	500	1.8	Paris	Barcelona
65	Carrier Ethernet (GE)	277	500	1.8	Barcelona	Madrid
66	Carrier Ethernet (GE)	277	500	1.8	Barcelona	Madrid
67	Carrier Ethernet (GE)	277	500	1.8	London	Barcelona
68	Carrier Ethernet (GE)	277	500	1.8	London	Barcelona
69	Carrier Ethernet (GE)	277	500	1.8	London	Madrid
70	Carrier Ethernet (GE)	277	500	1.8	London	Madrid
71	Carrier Ethernet (GE)	277	500	1.8	Paris	Madrid
72	Carrier Ethernet (GE)	277	500	1.8	Paris	Madrid
73	Carrier Ethernet (GE)	250	500	2	London	Paris
74	Carrier Ethernet (GE)	250	500	2	London	Paris
75	Carrier Ethernet (GE)	250	500	2	Paris	Barcelona
76	Carrier Ethernet (GE)	250	500	2	Paris	Barcelona
77	Carrier Ethernet (GE)	250	500	2	Barcelona	Madrid
78	Carrier Ethernet (GE)	250	500	2	Barcelona	Madrid
79	Carrier Ethernet (GE)	250	500	2	London	Barcelona
80	Carrier Ethernet (GE)	250	500	2	London	Barcelona
81	Carrier Ethernet (GE)	250	500	2	London	Madrid
82	Carrier Ethernet (GE)	250	500	2	London	Madrid
83	Carrier Ethernet (GE)	250	500	2	Paris	Madrid
84	Carrier Ethernet (GE)	250	500	2	Paris	Madrid
85	Carrier Ethernet (GE)	227	500	2.2	London	Paris
86	Carrier Ethernet (GE)	227	500	2.2	London	Paris
87	Carrier Ethernet (GE)	227	500	2.2	Paris	Barcelona
88	Carrier Ethernet (GE)	227	500	2.2	Paris	Barcelona
89	Carrier Ethernet (GE)	227	500	2.2	Barcelona	Madrid
90	Carrier Ethernet (GE)	227	500	2.2	Barcelona	Madrid
91	Carrier Ethernet (GE)	227	500	2.2	London	Barcelona
92	Carrier Ethernet (GE)	227	500	2.2	London	Barcelona
93	Carrier Ethernet (GE)	227	500	2.2	London	Madrid
94	Carrier Ethernet (GE)	227	500	2.2	London	Madrid
95	Carrier Ethernet (GE)	227	500	2.2	Paris	Madrid
96	Carrier Ethernet (GE)	227	500	2.2	Paris	Madrid
97	Carrier Ethernet (GE)	208	500	2.4	London	Paris
98	Carrier Ethernet (GE)	208	500	2.4	London	Paris
99	Carrier Ethernet (GE)	208	500	2.4	Paris	Barcelona
100	Carrier Ethernet (GE)	208	500	2.4	Paris	Barcelona

Annex A Traffic matrix continued -

Figure A.1: Traffic matrix for an overall P/A ratio of 1.5 [Source: Analysys Mason]

Traffic flow index	Traffic type	Average bandwidth (Mbit/s)	Peak bandwidth (Mbit/s)	P/A ratio	Source	Destination
101	Carrier Ethernet (GE)	208	500	2.4	Barcelona	Madrid
102	Carrier Ethernet (GE)	208	500	2.4	Barcelona	Madrid
103	Carrier Ethernet (GE)	208	500	2.4	London	Barcelona
104	Carrier Ethernet (GE)	208	500	2.4	London	Barcelona
105	Carrier Ethernet (GE)	208	500	2.4	London	Madrid
106	Carrier Ethernet (GE)	208	500	2.4	London	Madrid
107	Carrier Ethernet (GE)	208	500	2.4	Paris	Madrid
108	Carrier Ethernet (GE)	208	500	2.4	Paris	Madrid
109	Carrier Ethernet (GE)	192	500	2.6	London	Paris
110	Carrier Ethernet (GE)	192	500	2.6	London	Paris
111	Carrier Ethernet (GE)	192	500	2.6	Paris	Barcelona
112	Carrier Ethernet (GE)	192	500	2.6	Paris	Barcelona
113	Carrier Ethernet (GE)	192	500	2.6	Barcelona	Madrid
114	Carrier Ethernet (GE)	192	500	2.6	Barcelona	Madrid
115	Carrier Ethernet (GE)	192	500	2.6	London	Barcelona
116	Carrier Ethernet (GE)	192	500	2.6	London	Barcelona
117	Carrier Ethernet (GE)	192	500	2.6	London	Madrid
118	Carrier Ethernet (GE)	192	500	2.6	London	Madrid
119	Carrier Ethernet (GE)	192	500	2.6	Paris	Madrid
120	Carrier Ethernet (GE)	192	500	2.6	Paris	Madrid
121	Carrier Ethernet (GE)	178	500	2.8	London	Paris
122	Carrier Ethernet (GE)	178	500	2.8	London	Paris
123	Carrier Ethernet (GE)	178	500	2.8	Paris	Barcelona
124	Carrier Ethernet (GE)	178	500	2.8	Paris	Barcelona
125	Carrier Ethernet (GE)	178	500	2.8	Barcelona	Madrid
126	Carrier Ethernet (GE)	178	500	2.8	Barcelona	Madrid
127	Carrier Ethernet (GE)	178	500	2.8	London	Barcelona
128	Carrier Ethernet (GE)	178	500	2.8	London	Barcelona
129	Carrier Ethernet (GE)	178	500	2.8	London	Madrid
130	Carrier Ethernet (GE)	178	500	2.8	London	Madrid
131	Carrier Ethernet (GE)	178	500	2.8	Paris	Madrid
132	Carrier Ethernet (GE)	178	500	2.8	Paris	Madrid
133	OTT traffic	3333	5,000	1.5	London	Paris
134	OTT traffic	3333	5,000	1.5	Paris	Barcelona
135	OTT traffic	3333	5,000	1.5	Barcelona	Madrid
136	OTT traffic	3333	5,000	1.5	London	Barcelona
137	OTT traffic	3333	5,000	1.5	London	Madrid
138	OTT traffic	3333	5,000	1.5	Paris	Madrid

Annex B Detailed results

This annex provides the detailed results obtained in our case study. It is laid out as follows:

- Section **B.1** presents the capacity that has to be provisioned on the different scenarios to support the traffic matrix presented in with an increasing peak-to-average (P/A) ratio. In our simulation, we vary the P/A ratio between 1.5 and 3.0, which was selected to be representative of what interviewed operators currently see in their core network links.[32] The P/A ratio was increased by increasing the peak rate of each individual traffic stream, while keeping the same average rate for all traffic. Varying the P/A ratio enables us to compare the cost difference between the different architectures when the traffic pattern changes.
- Section **B.2** covers the core network capex associated with the different scenarios to support the above provisioning of capacity for each of the scenarios.
- Section **B.3** presents our results in terms of expected revenues for the different architectures analysed in this white paper.
- Section **B.4** concludes with the analysis by considering both costs and revenues together to derive the capex efficiency of the architecture, where capex efficiency is a measure of the potential revenues per unit capex invested in the network.

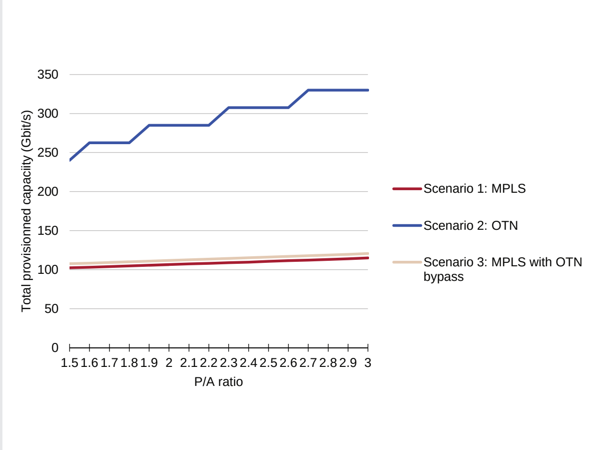


Figure B.1: Capacity provisioned for each of the scenarios
[Source: Analysys Mason, 2011]

B.1 Capacity-provisioning analysis

As mentioned in Section 4.1, it is becoming increasingly important for operators to be able to dissociate the increase in traffic in the network with the costs associated with provisioning capacity for that network, especially for non-revenue generating traffic.

In an OTN, the operator must provision capacity according to peak traffic for each of the traffic flow in the network in increments of 1.25Gbit/s circuits. This is because, in OTN, the smallest circuit capacity is ODU 0.

In marked contrast, in MPLS networks, capacity can be provisioned for each traffic flow according to average traffic bandwidth by taking advantage of statistical multiplexing (i.e. when some traffic flows will peak, others will trough, compensating for one another as explained in Section 4.4). However, in our case study, we have assumed some capacity over-provisioning to allow up to seven traffic flows to peak simultaneously. This capacity-provisioning approach is thought to be conservative for packet-switched networks and is equivalent to methodology (c) in Figure 4.4, where k=7.

Based on the above methodology, Figure B.1 shows the capacity provisioned for the different networks for each of the technology scenarios to support the traffic matrix provided in Section 5.1.2. It should be noted that, we varied the overall traffic P/A ratio from 1.5 to 3 by increasing the peak traffic of each traffic flow (see Annex A for more detail).

Analysis of OTN capacity provisioning

Figure B.1 shows that the total capacity provisioned on an OTN (scenario 2) is strongly correlated to the increase in peak traffic, increasing from 240 000Mbit/s to 330 000Mbit/s. It is interesting to note that a doubling in peak traffic does not correspond to a doubling in capacity provisioned on the OTN. This is because, for a P/A ratio of 1.5, some traffic flows will peak at 500Mbit/s, and a 1.25Gbit/s circuit (ODU 0) is the smallest circuit that can be used to map that traffic. As the P/A ratio increases to 3.0, these traffic flows will peak to 1Gbit/s, which can still be accommodated by the same 1.25Gbit/s circuit, not requiring any additional capacity, because the initial circuit was significantly over-provisioned in the first place.

It can also be observed in Figure B.1 that the increase in capacity in an OTN occurs in incremental and discrete steps. This is because, in OTNs, the minimum incremental capacity in an OTN is an ODU 0 circuit, so any increment in capacity for any circuit will be in steps of 1.25Gbit/s.[33]

Analysis of MPLS capacity provisioning

The capacity provisioned in an MPLS network (scenarios 1 and 3) is significantly less than that provisioned in an OTN. For a P/A ratio of 1.5 and 3.0, the total capacity provisioned in the MPLS network is 102 500Mbit/s and 115 000Mbit/s, respectively. In other words, when the P/A ratio doubles, the capacity provisioned in an MPLS network only increases by 13%. This capacity increase is due to the over-provisioning to allow up to seven traffic flows to peak at the same time.[34]

Therefore, for the same traffic matrix, an MPLS network requires between 57% and 65% less capacity to be provisioned in the network compared with an OTN, primarily due to statistical multiplexing.

Below we quantify how this difference in capacity provisioning translates into capex.

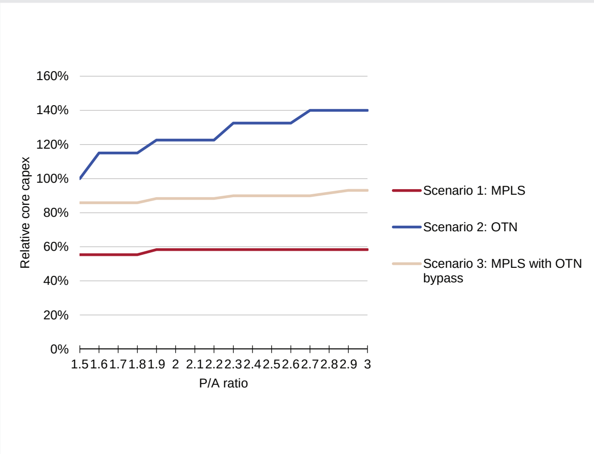


Figure B.2: Core capex comparison for different traffic P/A ratio
[Source: Analysys Mason, 2011]

B.2 Core network capex analysis

Sensitivity analysis of peak-to-traffic ratio

For this exercise, we kept the MPLS-to-OTN port cost ratio constant to 1.3 and we assumed a WDM-to-OTN interface cost ratio of 0.8. The results are shown below in Figure B.3, where the reference cost (100%) is the capex of an OTN architecture (scenario 2) with a P/A ratio of 1.5.

Figure B.3 shows that the total capex for scenarios 1 and 2 follows the same trend as the relative increase in capacity provisioning: for the OTN, costs increase in steps with P/A, whereas for an MPLS network, the cost remains relatively constant as the P/A ratio increases.

The cost of an MPLS network with OTN bypass architecture (scenario 3) sits in between the cost of scenario 1 and scenario 2.

This is expected as scenario 3 is dimensioned according to average traffic (as opposed to the OTN architecture), but has a significantly greater number of overall ports than a native MPLS architecture due to the addition of OTN ports.

It can also be observed from Figure B.2 that, for a P/A ratio of 1.5, the MPLS architecture results in a 42% capex saving compared to an OTN architecture. This capex saving increases to 58% for a P/A ratio of 3.0.

A similar trend can be observed for scenario 3 (MPLS with bypass OTN), which is between 17% and 47% cheaper than the native OTN solution. Note that scenario 3 provides the added flexibility of transporting TDM traffic efficiently, which, depending on the operator, can be a significant source of revenues.

The total number of ports for each of the considered scenarios is illustrated below in Figure B.3 for a P/A ratio of 2.0.

For scenario 1, it is important to note that, despite the fact the MPLS ports are 1.3 times more expensive than OTN ports, the reduction in the total number of ports in the MPLS scenario more than compensates for the unit cost differential. The cost difference due to the total number of ports required for scenarios 1 and 2 is further exaggerated by the fact that for every OTN and MPLS port, a wavelength has to be deployed in the DWDM network. Therefore, for scenario 1, the network requires 40 MPLS ports and 40 WDM transponders, whereas for scenario 2 the network requires 98 OTN ports and 98 WDM transponders.

In the case of scenario 3, bypassing the packet-switched traffic in transit on the OTN device means that fewer MPLS ports are required than in scenario 1 (24 MPLS ports in scenario 3 compared with 40 MPLS ports in scenario 3), but 64 OTN ports need to be added to support both the bypass functionality and the hand-over of local traffic to the MPLS switch, although the number of DWDM ports is minimised to 40.

Therefore, from an operator's point of view, core network capex can be better controlled using an MPLS architecture with a change in traffic pattern (P/A ratio) compared to an OTN architecture.

Scenario	OTN port #	MPLS port #	DWDM interface #
Scenario 1 (MPLS)	0	40	40
Scenario 2 (OTN)	98	0	98
Scenario 3 (MPLS + OTN bypass)	64	24	40

Figure B.3: Number of 10Gbit/s interfaces required for each scenario with a traffic P/A ratio =2
[Source: Analysys Mason, 2011]

[32] At the edge of the network, much higher P/A ratios are observed due to the lack of grooming, but in this white paper we only consider core networks, which are highly aggregated links.

[33] Assuming ODU-flex is enabled on the network.

[34] Without any over-provisioning, the capacity would remain constant at 205 000Mbit/s for varying P/A ratios.

[35] Assuming an MPLS-to-OTN cost ratio of 1.3.

Annex B Detailed results continued

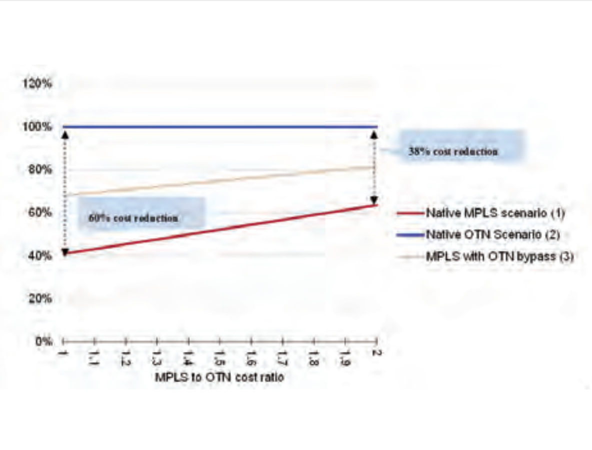


Figure B.4: Analysys of costs for different MPLS-to-OTN cost port ratio and for a P/A ratio of 2.0 [Source: Analysys Mason, 2011]

Sensitivity analysis of MPLS-to-OTN port cost ratio

In our equipment cost survey, we found that the difference in cost between an OTN port and an MPLS port of the same capacity could be up to 100% more expensive. In order to quantify the cost impact of an MPLS port on the overall cost of the solution, we present a cost-sensitivity analysis based on the cost of an MPLS port compared to an OTN port. The results are shown above in Figure B.4 for a P/A ratio of 2.0.

It can be seen that when the relative cost of an MPLS port is doubled, the cost reduction of an MPLS architecture compared to an OTN architecture decreases from 60% to 38%. This is because the cost of MPLS ports is not the only cost in the network (the network also includes costs associated with DWDM equipment).

B.3 Revenue analysis

Revenues have to be one of the most important investment considerations for an operator in any business case. Here we compare revenues for both an MPLS and an OTN architecture, by considering the traffic matrix defined in Section 5.1.2 and assuming the service prices listed in Section 5.1.5.

We have assumed that the revenues associated with both an MPLS and an OTN scenarios are independent of the P/A ratio. This is because, in an MPLS network, the operator will charge its customers according to the average bandwidth guaranteed, irrespective of the P/A ratio. Also, in an OTN architecture, the operator will typically charge its customers according to how many resources are used in the network, which will be in increments of ODU 0 (1.25Gbit/s) capacity and for the peak bandwidth of that flow. Also, it would be impractical for the operator to charge incremental fees as the P/A ratio increases.

We conducted market research on what operators typically charge for Ethernet services when provided over MPLS versus OTN. Typically, in an MPLS network, Ethernet services are sold in such a way that only a proportion of the peak throughput is guaranteed for each service to take advantage of statistical multiplexing. This is in marked contrast to OTN-based operators, which will charge guaranteeing the full throughput (i.e. full 1Gbit/s for Gigabit Ethernet services). Therefore, the MPLS-based operator typical takes a small discount to reflect the lack of 100% throughput without any degradation to the service. To handle the same traffic matrix, the MPLS operators we interviewed would typically charge 25%[36] less for a Gigabit Ethernet service, but only provisioning one third of the capacity compared to an OTN operator. The lower revenues somewhat offset the tremendous cost advantage, but still, overall, an MPLS network operator has the potential to be much more profitable than and OTN operator, as shown below.

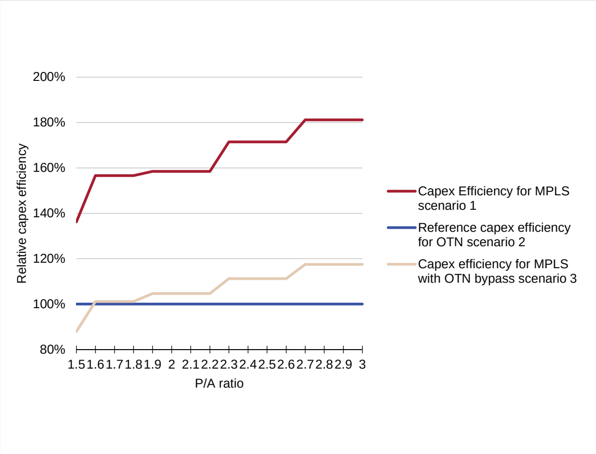


Figure B.5: Relative capex efficiency of the different network scenarios [Source: Analysys Mason, 2011]

B.4 Capex-efficiency analysis

Having calculated the costs and revenues for each of the scenarios, we now analyse the relative capex efficiency for each scenario compared with the OTN scenario. We define capex efficiency as the relative revenue for each USD of capex invested in the network. In other words, we define capex efficiency as revenue divided by network capex.

The capex efficiency for different traffic P/A ratios is illustrated oppositein Figure B.5.

Figure B.5 shows that the capex efficiency for the MPLS network (scenario 1) is significantly higher than that associated with an OTN architecture (scenario 2) for all P/A ratios. It can also be seen that the relative[37] capex efficiency of the MPLS network increases with the P/A ratio: the capex efficiency is 158% for a P/A ratio of 2.0, increasing to 181% for a P/A of 3.0. This is mainly explained by the fact that, in the MPLS network, capacity provisioning can be dissociated from demand bandwidth by exploiting statistical multiplexing. Also, as mentioned elsewhere in this white paper, the lower revenues per traffic flow in the case of the MPLS network have a smaller impact on the profitability of the network than the tremendous cost savings, providing the MPLS network operator the potential to be much more profitable than an OTN operator (because more revenues can be generated for each USD of capex invested).

The fact that OTN operators can only provision for peak capacity and that OTN architectures can only do so in minimum increments of 1.25Gbit/s means that OTN operators will no longer be able to compete with MPLS operators because their costs and associated pricing are higher. Therefore, we believe that OTN create an unsustainable business model for packet-switched traffic.

Changes in the characteristics of traffic with the rise of Ethernet services, coupled with packet traffic replacing circuit traffic, is increasing the potential for higher revenues from over-subscribed services and creative pricing models, as well as providing the only sustainable model available to carriers today.

[36] Please refer to the pricing benchmark presented in Section 5.1.5, where a full Gigabit Ethernet (with guaranteed peak bandwidth) is charged 25% more than a Gigabit Ethernet flow with 300Mbit/s guaranteed.

[37] Compared to the OTN.

Annex C Glossary of terms

CAGR	Compound annual growth rate
CIR	Committed information rate
DWDM	Dense wavelength division multiplexing
E-Line	Ethernet Line
EPL	Ethernet private line
EVPL	Ethernet virtual private line
FEC	Forward error correction
GE	Gigabit Ethernet
IETF	International Engineering Task Force
IP	Internet protocol
ITU-T	International Telecommunication Union
LAN	Local area network
LSP	Label-switched path
MEF	Metro Ethernet Forum
MPLS	Multi-protocol label switching
NGN	Next-generation network
NOC	Network operations centre
OAM	Operation, administration and management
ODU	Optical data unit
OTH	Optical transport hierarchy
OTN	Optical transport network
OTT	Over the top
PIR	Peak information rate
PSTN	Public-switched telephone network
QoS	Quality of service
SDH	Synchronous digital hierarchy
SLA	Service level agreement
SONET	Synchronous optical network
TDM	Time division multiplexing
VPN	Virtual private networks
WAN	Wide area network
WDM	Wavelength division multiplexing

Contact us

www.analysysmason.com

Cambridge
Analysys Mason Limited
St Giles Court
24 Castle Street
Cambridge, CB3 0AJ
UK

Tel: +44 (0)845 600 5244
Fax: +44 (0)845 528 0760
cambridge@analysysmason.com

Dubai
Al Shatha Tower, 3110
Dubai Internet City
P O Box 502064
Dubai
UAE

Tel: +971 4 446 7473
Fax: +971 4 446 9827
dubai@analysysmason.com

Dublin
Analysys Mason Limited
Suite 242
The Capel Building
Mary's Abbey, Dublin 7
Ireland

Tel: +353 (0)1 602 4755
Fax: +353 (0)1 602 4777
dublin@analysysmason.com

Edinburgh
Analysys Mason Limited
Apex 3
95 Haymarket Terrace
Edinburgh, EH12 5HD
Scotland
UK

Tel: +44 (0)845 600 5244
Fax: +44 (0)845 528 0760
edinburgh@analysysmason.com

London
(Registered office)
Analysys Mason Limited
Bush House
North West Wing
Aldwych
London, WC2B 4PJ
UK

Tel: +44 (0)845 600 5244
Fax: +44 (0)845 528 0760
london@analysysmason.com

Madrid
Analysys Mason Limited
Sucursal en España
José Abascal 44 4°
28003 Madrid
Spain

Tel: +34 91 399 5016
Fax: +34 91 451 8071
madrid@analysysmason.com

Manchester
Analysys Mason Limited
5 Exchange Quay
Manchester, M5 3EF
UK

Tel: +44 (0)845 600 5244
Fax: +44 (0)845 528 0760
manchester@analysysmason.com

Milan
Analysys Limited Italia
Via Durini 27
20122 Milan
Italy

Tel: +39 02 76 31 88 34
Fax: +39 02 36 50 41 09
milan@analysysmason.com

New Delhi
Analysys Mason India
Private Limited
BD – 4th Floor
Big Jo's Tower
Netaji Subhash Place
Pitampura
New Delhi 110034
India

Tel: +91 11 4700 3100
Fax: +91 11 4700 3102
newdelhi@analysysmason.com

Paris
Analysys Mason
66 avenue des Champs Elysées
75008 Paris
France

Tel: +33 (0)1 72 71 96 96
Fax: +33 (0)1 72 71 96 97
paris@analysysmason.com

Singapore
Analysys Mason Pte Limited
#10-02 Robinson Centre
61 Robinson Road
Singapore 068893

Tel: +65 6493 6038
Fax: +65 6720 6038
singapore@analysysmason.com

Washington DC
Analysys Mason Limited
818 Connecticut Avenue NW
Suite 300
Washington DC 20006
USA

Tel: (202) 331 3080
Fax: (202) 331 3083
washingtondc@analysysmason.com

For general enquiries
enquiries@analysysmason.com