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Ammar HAMAD

PERFORMANCE ANALYSIS AND MANAGEMENT OF RPR (RESILIENT PACKET RING) RINGS ATTACHED TO A NEW LARGE LAYER 2 (L2) NETWORKS (NLL2N)

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THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS:

M. Michel Kadoch, thesis director
Department of Electrical Engineering, École de technologie supérieure (ETS)

M. David Bensoussan, member
Department of Electrical Engineering, École de technologie supérieure (ETS)

Ms. Sylvie Ratté, committee president
Department of Software Engineering and IT, École de technologie supérieure (ÉTS)

M. Hamid Mcheick, external examiner independent
Department of Computer Sciences and Mathematics, Université du Québec à Chicoutimi (UQC)

THIS THESIS WAS PRESENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND THE PUBLIC

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ANALYSER LA PERFORMANCE ET LA GESTION QUAND LES ANNEAUX DE RPR (RESILIENT PACKET RING) SONT ATTACHÉS À UNE LARGE COUCHE 2 (L2) DANS UN RÉSEAU (NLL2N)

Ammar HAMAD

RÉSUMÉ

Les volumes de trafic Internet se développent, nécessitant une capacité de transmission de plus en plus importante et provoquant une croissance de l'infrastructure. Le trafic Internet croissant exige également une gestion bien contrôlée et le maintien d'une bonne performance. Un examen plus approfondi révèle que l'infrastructure de l'Internet repose sur une architecture hiérarchique à trois niveaux. Elle est constituée des réseaux dorsaux, des réseaux métropolitains et des réseaux d'accès locaux. Les réseaux métropolitains (MAN), ou les réseaux métros pour simplifier le nommage, interconnectent les réseaux de base avec les réseaux d'accès locaux qui, eux, transportent les données de et vers les utilisateurs individuels. En employant des technologies avancées des réseaux locaux (LAN) tel que Gigabit Ethernet (GbE), l'accès à large bande tel que la boucle d'abonné numérique (DSL) et les câbles modems. Les réseaux d'accès fournissent des quantités croissantes de bande passante. La plupart des réseaux de métro existantes sont basées sur des réseaux optiques synchrones, la technologie hiérarchique synchrone (SONET / SDH) et la technologie de réseau à commutation de circuits. Semblable à des commutateurs Ethernet, mais tout à fait différent des multiplexeurs (insertion/extraction) de SONET/SDH, les commutateurs RPR peuvent être débranchés et retirés de réseau d'une façon dynamique. Aucune préparation n'est nécessaire et rien de plus que quelques millisecondes est nécessaire pour remettre le réseau en service en cas de panne. RPR et Ethernet ont beaucoup de points communs. L'interface MAC de RPR, dans son utilisation par défaut, est exactement la même que le MAC d'Ethernet. Les trames de RPR ressemblent beaucoup aux trames d'Ethernet, avec quelques champs de plus. Tout service qui tourne au-dessus d'Ethernet fonctionne également au-dessus de RPR. De la même manière, tout service fournit par Ethernet est également fourni par RPR. Ethernet et RPR fonctionnent, dans des réseaux commutés, de façon transparente. RPR est étroitement aligné avec Ethernet et complètement interopérable avec d'autres MAC 802. RPR a été implémenté dans les réseaux locaux et les réseaux métropolitains et il fonctionne adéquatement, cependant il n'a pas été implémenté ou testé avec un grand réseau niveau 2 (Modèle OSI). Avoir les anneaux RPR attachés directement à un grand réseau «Layer 2», comme SONET / SDH, Ethernet, Gigabit Ethernet, sera un défi intéressant car cela va nous permettre d'adapter RPR à tous ces réseaux de niveau 2 (Couche 2 de Modèle OSI).

Dans notre recherche, nous proposons une autre alternative pour concevoir des réseaux métropolitains (MAN), des réseaux locaux (LAN) ou des réseaux étendus (WAN). RPR sera déployé comme la dorsale de réseau du transport. RPR sera attaché directement à différents réseaux de niveau 2. Il pourrait être placé entre deux réseaux SONET / SDH ou entre deux segments Gigabit Ethernet et ainsi de suite. Le nouveau grand réseau ou la grande configuration que nous proposons sera nommé: le Niveau 2 Nouveau Grand Réseau (New Large Layer 2 Network (NLL2N)). Nous allons utiliser les anneaux RPR pour interconnecter divers topologies dans un campus ou dans un environnement d'entreprise ce qui fournira une valeur à ajouter pour le client et apportera un transporteur de qualité dans leur infrastructure de réseau. Durant notre recherche, nous allons investiguer RPR sur Ethernet (RPRoE), RPR sur SONET (RPRoSONET), SONET sur Ethernet (SONEToE) et nous allons démontrer que RPR, Ethernet et SONET pourraient être intégrés dans le même réseau de niveau 2. Nous allons expliquer et détailler l'utilisation de RPRoE, de SONEToRPR et l'intégration de chacun d'eux pour créer un nouveau grand réseau de niveau 2 (NLL2N). Nous allons également souligner les avantages de celui-ci. La gestion et la performance de notre architecture proposée, ainsi que sa performance pour diverses configurations de réseau avec différents scénarios de trafic, seront évaluées par le biais de l'analyse des expériences et des simulations.

Mots clés: Traffic Internet, Capacité de transmission, Réseau dorsale, Réseau Local, Réseau métropolitain, Réseau commuté , Réseau de transport, Giga Ethernet, Trame Ethernet, Modèle OSI, Gestion de performance, Simulation, Analyse

PERFORMANCE ANALYSIS AND MANAGEMENT OF RPR (RESILIENT PACKET RING) RINGS ATTACHED TO A NEW LARGE LAYER 2 (L2) NETWORKS (NLL2N)

Ammar HAMAD

ABSTRACT

The volume of Internet traffic is growing, which calls for the transmission capacity of the underlying infrastructure to be continuously extended. It also requires a tide management which can maintain a good performance. A closer look at Internet infrastructure reveals that it architecturally relies on a three level hierarchy consisting of backbone networks, metropolitan area networks, and local access networks. The Metropolitan Area Networks (MANs), or metro networks for short, interconnect the backbone networks with the local access networks that carry the data from and to the individual users. By employing advanced Local Area Network (LAN) technologies (*i.e.,* Gigabit Ethernet (GbE)), and broadband access, (*i.e.,* Digital Subscriber Loop (DSL) and cable modems), access networks provide increasing amounts of bandwidth. Most existing metro networks are based on Synchronous Optical NETwork/Synchronous Digital Hierarchy (SONET/SDH) technology, a circuit-switched networking technology. Similar to Ethernet switches, and quite unlike SONET/SDH add/drop multiplexers, RPR switches can be plugged into and removed from a ring dynamically. No advance provisioning is required and nothing more than a few milliseconds of outage is resulted. RPR and Ethernet share a lot in common. RPR's logical MAC interface, in its default usage, is exactly the same as Ethernet's. RPR's frames look very similar to Ethernet frames, with slightly more fields added. Any service that runs on top of Ethernet also runs on top of RPR. Every service that Ethernet provides is also available by RPR. Ethernet and RPR work together seamlessly in bridged/switched networks. RPR is closely aligned with Ethernet and completely interoperable with other 802 MACs. RPR has been implemented in LAN and MAN network and works adequately, but it has not been implemented or tested with a large L2 network. Having RPR rings attached directly to a large L2 networks, of different types of SONET/SDH, Ethernet, and GbE will be an interesting challenge because we have to adapt RPR rings to all these L2 networks. In our research, we are proposing an alternate way to design campus (MAN), Local Area Network (LAN) and Wide Area Network (WAN). And, to employ RPR rings for the backbone transport. RPR rings will be attached directly to a different L2 networks. It could be placed between two SONET/SDH rings or between two GbE segments and so on. Our new large networks or large configurations that we propose will be named: New Large L2 Network (NLL2N). Using RPR rings to interconnect various locations on a campus or in an enterprise environment provide a superior value to the customer and bring Carrier Ethernet qualities to the backbone transport network. During our research, we will investigate RPR over Ethernet (RPRoE), RPR over SONET (RPRoSONET), SONET over Ethernet (SONEToE) and we will demonstrate that RPR, Ethernet, and SONET could be integrated together in the same Layer 2 Network. In our research we will explain and detail the use of RPRoE and SONEToRPR, and the integration of all of them to create a New Large Layer 2 Network (NLL2N) and point out the benefits

of it. We comprehensively evaluate the management and the performance of our proposed architecture, as well as, the underlying performance enhancing techniques for various network configurations and traffic scenarios, by means of experiments analysis and simulations.

Keywords: RPR bridging, RPR rings, RPR switching, RPR frame, Transiting frame, Gigabit Ethernet, Local Area Network, MAC address, Physical layer, MAC layer, SONET/SDH, Shortest path routing, Committed information, Excess information rate, Fairness algorithm, Reserved, Reclaimable, Packet optimization, TDM traffic, Quality of Service, New Large Layer 2 Network, Address learning

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LIST OF ABREVIATIONS

ETS	École de Technologie Supérieure
VPN	Virtual Private Network
QoS	Quality of Service
MAC	Media Access Control
PHYs	PHYsical layer transceivers
NLL2N	New Large L2 Networks
L2	Layer 2
RPR	Resilient Packet Ring
ATM	Asynchronous Transfer Mode
WDM	Wavelength-Division Multiplexing
OADM	Optical Add/Drop MUltiplexer
OEO	Optical-Electrical-Optical
WXC	Wavelength cross-connects
FTTH	Fiber to the home
LAN	Local Area Network
OPS	Optical Packet Switching
OBS	Optical Burst Switching
DSL	Digital Subscriber Loop
PtP	Point to Point

PtMP	Point-to-MultiPoint
MC	Media Convertor
PON	Passive Optical Network
MAN	Metropolitan Area Network
SONET	Synchronous Optical NETwork
SDH	Synchronous Digital Hierarchy
ADM	Add/Drop Multiplexer
HORNET	Hybrid Optoelectronic Ring NETwork
CSMA	Carrier Sense Multiple Access
SCM	Sub-Carrier Multiplexing
ASK	Amplitude Shift Keying
FSK	Frequency Shift Keying
WAN	Wide Area Network
MTU	Maximum Transmission Unit
PTQ	Primary Transit Queue
STQ	Secondary Transit Queue
FDDI	Fiber Distributed Data Interface
FRTT	Fairness Round-Trip Time
STS	Synchronous Transport Signal

INTRODUCTION

Campus networks by nature are usually widely distributed. In a typical (LAN/MAN/WAN) environment, the connectivity between various data centers can range anywhere from tens to hundreds of sites. Most campuses firewall or protect each of the departments individually but usually share a backbone transport network that interconnects all sites to provide uniform network connectivity.

Large enterprise networks mimic some aspects of campus networks. However, enterprise networks are usually more controlled in terms of allowing connectivity and access to unqualified and unauthorized software. From a topology perspective, a medium to large enterprise would have multiple buildings and departments interconnected by a backbone transport network with each department connected to the core transport network by a router, firewall, Virtual Private Network (VPN). Significant resources and effort are spent to maintain the backbone network to provide resiliency, proper quality of service (QoS), and equal best-effort traffic utilization to departments and groups on campus. RPR can help network managers meet these requirements. RPR provides survivable dual counter-rotating optical rings with several advantages over traditional enterprise network architectures, including support of over-subscription and variable bandwidth per span as well as the provision of advanced traffic routing capabilities. RPR is among the standards the IEEE has defined to enable carrier-class Ethernet.

RPR was standardized by the IEEE 802.17 Working Group in 2004. The primary focus of IEEE 802.17 has been to standardize the media access control (MAC) layer technology for enabling carrier-class RPR over SONET/SDH or Ethernet physical layer transceivers (PHYs). Currently, the IEEE 802.17 Working Group is in the process of standardizing 802.17b, which enhances the RPR bridging methodology for Ethernet packets sourced and/or destined to stations off the ring.

Next-generation metro networks have to bridge the metro gap in order to tap into the vast amount of backbone bandwidth, enable new emerging services, and stimulate revenue growth. To this end, RPR is likely to be attached to large L2 network and we will analyze the management and the performance with this new network including fairness algorithm, STP and Mutlicasting.

Structure of the Thesis

In the following we present the outline of this work to provide an overview of the structure of this thesis.

Chapter 1

Literature review: we introduce the state of the art beginning with optical WDM communications networks, overview of the optical broadband access evolution, metropolitan area packet-switched and ending with the IEEE 802.17 resilient packet ring, SONET/SDH, and GbE;

Chapter 2

Objectives of Research and Originality: It describes the objectives of our research and its originality;

Chapter 3

RPR over Ethernet: It describes the conference paper that explains and detail the use of RPR over Ethernet. (2014 IEEE Communication Society – The 5th International conference on Smart Communication in Network Technologies);

Chapter 4

SONET over RPR: It demonstrated that SONET and RPR could be integrated together and it explained and detailed the use of SONET over RPR. (2015 14TH IEEE/ACIS International Conference on computer and Information Science 2015);

Chapter 5

SONET over Ethernet: This paper integrates SONET over Ethernet creating thus compatibility between these two protocols without going through unnecessary conversions. (EDAS Conference and Journal Management System);

Chapter 6

Using RPR, Ethernet, and SONET to create a New Large Layer 2 Network (NLL2N): It demonstrates the possibility of integrating the Resilient Packet Ring (RPR), Ethernet and Synchronous Optical NETwork (SONET) and creating a New Large Layer 2 Networks (NLL2N);

Chapter 7

Results and analysis

Chapter 8

Conclusion and recommendations;

Chapter 9

Bibliography.

CHAPTER 1

LITERATURE REVIEW

This chapter provides a detailed overview of the literature pertaining to optical WDM communications networks, optical networking technologies, metropolitan area packet-switched WDM networks (RingO and Hornet), and Resilient Packet Ring (RPR).

1.1 Optical WDM Communications Networks

1.1.1 Progress and challenges

We are moving toward a society which requires that we have access to information at our fingertips when we need it, where we need it, and in whatever format we need it [Mukherjee (2000), Ahmed and Shami (2012)]. The information is provided to us through a global mesh of communications networks whose current implementations, *e.g.,* today's Internet and asynchronous transfer mode (ATM) networks, do not have the capacity to support the foreseeable bandwidth demands. Fiber-optic technology can be considered the savior for meeting the above-mentioned need because of its unique capabilities: Huge bandwidth (nearly 50 terabits per second ($^{Tb}/_{s}$)), low signal attenuation ($0.2^{dB}/_{km}$), low signal distortion, and small space requirement. Our challenge is to turn the promise of fiber optics into reality to meet the information network demands of the next decades. Wavelength-division multiplexing (WDM) is an approach that avoids the huge opto-electronic bandwidth mismatch by requiring that each client's equipment operates only at electronic rate, but multiple WDM channels from different clients may be multiplexed on the same fiber. With WDM, the huge bandwidth of the optical fiber is divided into several dozens or even hundreds of lower bandwidth wavelength channels, each of which operates at electronically processable speeds. WDM devices are easier to implement than single-channel high-speed systems since, generally, all components in a WDM device need to operate only at electronic speed; as result, many WDM devices are available in the marketplace today. Research and development on optical WDM networks have matured considerably over the past few years, and the capacity of deployed systems has grown exponentially, as evidenced by the large number of publications and products.

1.1.2 What Worked and What Did Not

1.1.2.1 What Worked

Clearly, the two major successes of fiber optic communication have been enterprise data links and service provider transmission links and networks [Ramaswami (2006), Maier *et al.* (2009)]. Enterprise data links use a variety of protocols (100 $^{\mathrm{Mb}}/_{\mathrm{s}}$ Ethernet, Gigabit Ethernet, 10 Gigabit Ethernet, Fibre channel, etc.) and are widely deployed. The majority of these networks operate over the widely deployed multimode fiber plant found in enterprises. Service provider transmission networks operate over single-mode fiber witch enables higher bandwidth transmission rates over longer distances. Today, optical fiber transmission systems can support a couple of hundred wavelengths using WDM, each operating at up to 40 $^{\mathrm{GB}}/_{\mathrm{s}}$, all over a single fiber. Here are few examples of what worked:

- Optical add/drop and reconfigurable optical add/drop multiplexers: An optical add/drop multiplexer (OADM) is an element that allows one or more wavelengths to be dropped and added while allowing the remaining wavelengths to pass through optically, without undergoing optical-electrical-optical (OEO) conversion. Today, a new generation of OADMs, called reconfigurable OADMs (ROADMs), are increasingly deployed which allow any wavelength to be dropped and added without impacting other wavelengths. Typically, ROADMs are deployed in optical ring networks;
- Wavelength cross-connects (WXC) are typically deployed in optical mesh networks. They switch a wavelength from a given input port to another output port independent of the other wavelengths;
- Tunable lasers address two important problems in WDM networks. They eliminate the operational cost associated with having to manufacture and stock multiple wavelength-

specific lasers to address different wavelengths by component suppliers, equipment makers, and the ultimate server provider or end-user customer. In addition, tunable lasers allow connections to be provisioned dynamically on demand without manual intervention, when coupled with ROADMs and WXCs;

- Optical protection: Resilience is an important part of network design. Protection switching plays a key role in enabling this resiliency. The goal of protection switching is to detect failures and reroute traffic around these failures as quickly as possible, typically ranging from within tens of milliseconds to several seconds.

1.1.2.2 What Did not work

Fiber to the home (FTTH) has been talked about since the mid-1990s but is starting only now to materialize. Many factors have impacted this delayed deployment. One was the huge capital investment required to build out the fiber plant. Another was the lack of end-user bandwidth demand. A third factor was the lack of competitive pressure on the telephone companies. A final factor was the effect of telecom regulation requiring the incumbent local exchange providers to unbundle their local plant. Here are few examples for what did not work:

- WDM broadcast-and-select local area networks (LANs) remained prototypes for two reasons: high cost and their inability to provide fast packet switching. Even today we are extremely challenged to accomplish stable sub-microsecond switching between wavelengths and get to practical cost points compared to other technologies such as Ethernet;
- Optical packet switching (OPS): Major impediments still exist to make optical packet switching (OPS) a reality. Large optical switches that can switch in microseconds do not exist, and the smaller ones that can suffer from high loss and polarization dependence are expensive to fabricate;
- Optical burst switching (OBS) is a technique that falls between optical packet switching and circuit switching. The idea is to transmit data in units of bursts, which can be thought

of as rather long packets with durations of, say, milliseconds to even seconds. OBS is perhaps easier to implement than optical packet switching because networks can be designed without optical buffers. However, OBS is significantly more complex to implement than static or dynamic circuit-switched optical networks.

1.2 Overview of The Optical Broadband Access Evolution

The present fast development of new broadband telecommunication services makes the upgrade of the access infrastructure a necessity [Chanclou *et al.* (2006)]. To run video, voice as well as advanced Internet applications, residential customers require the availability of high-speed solutions. Different solutions for the access network segment have been under development over the last several years. The most important among these solutions was digital subscriber loop (xDSL). At present, the optical fiber solution is receiving more attention by telecommunication operators than in the past.

Two alternative solutions exist to introduce optical fiber in the access loop: point-to-point (PtP) and point-to-multipoint (PtMP) systems. The first alternative, the PtP system, uses a media converter (MC) to achieve an optical fiber connection with dedicated fiber running from the central office to each end-user. The MC access system supports Ethernet access. PtP is a very flexible solution for an operator and it can be managed remotely because the equipment in the network (Ethernet switch) is intelligent. The second alternative, the PtMP system, typically uses a Passive Optical Network (PON) with a tree topology and passive optical splitter. PONs have several advantages over other access network architectures. One approach for realizing next-generation optical access networks is the use of WDM. It can be used to superimpose several single-wavelengths TDMA PONs over the access fiber line. This approach enables to multiply the capacity of the PONs without requiring a costly upgrade of the existing fiber infrastructure since only the end devices need to be upgraded to support WDM.

1.3 Metropolitan Area Packet-Switched WDM Networks

From the optical networking perspective, the future Internet may be viewed as a three-level hierarchy consisting of backbone networks, metropolitan area networks, and access networks. The backbone will provide abundant bandwidth by employing WDM links that are interconnected with reconfigurable optical add-drop multiplexers (ROADMs) and reconfigurable optical cross-connects (ROXCs). Metropolitan area networks (MANs) interconnect the backbone networks with the access networks. The access networks carry the data from and to the individual users. Most existing metro networks are based on synchronous optical network/synchronous digital hierarchy (SONET/SDH) technology, a circuit-switched networking technology. In SONET/SDH, circuits (connections operating at fixed data rates) are established between pairs of network nodes at data rates usually ranging from 155 $^{\text{Mbit}}/_{\text{s}}$ to 2.5 $^{\text{Gbit}}/_{\text{s}}$ (OC-3 to OC-48). The circuits are established by the source node and dropped at the destination node using electronic add-drop multiplexers (ADMs). SONET/SDH based metro networks suffer from a number of shortcomings:

- Capacity scaling limitations: upgrading the network capacity to adapt to traffic growth normally requires expensive 'forklift upgrades' where a large fraction of the equipment needs to be replaced which involves high costs and interruption of normal operation;
- Poor bandwidth utilization: bursty, asymmetric IP traffic is handled only inefficiently due to SONET/SDH's lack of statistical multiplexing and fast responsiveness;
- High provisioning time: provisioning of additional circuits for new customers usually takes several weeks to months which are unacceptable in the highly competitive metro market;
- High system complexity: all circuits need to be groomed (multiplexed) into SONET/SDH's rigid TDM structure which requires lots of electronic processing and results in high equipment cost, inflexibility, and complex operation and maintenance.

In order to address these concerns a number of new WDM metro architectures have been proposed [Herzog *et al.* (2004)]. In the following, we discuss two WDM ring architectures that received a great deal of attention.

1.3.1 RINGO

The packet-switched RING Optical network (RINGO) [Carena *et al.* (2004)] has unidirectional fiber ring network architecture. It features N nodes, where N also equals the number of wavelengths. Each node is equipped with an array of fixed-tuned transmitters (FTs) and one fixed-tuned receiver (FR) operating on a given wavelength that identifies the node. That is, node j drops wavelength λ_j from the ring. Thus, in order to communicate with node j, a given node i has to transmit data by using the laser operating on wavelength λ_j, as illustrated in Figure 1.1.

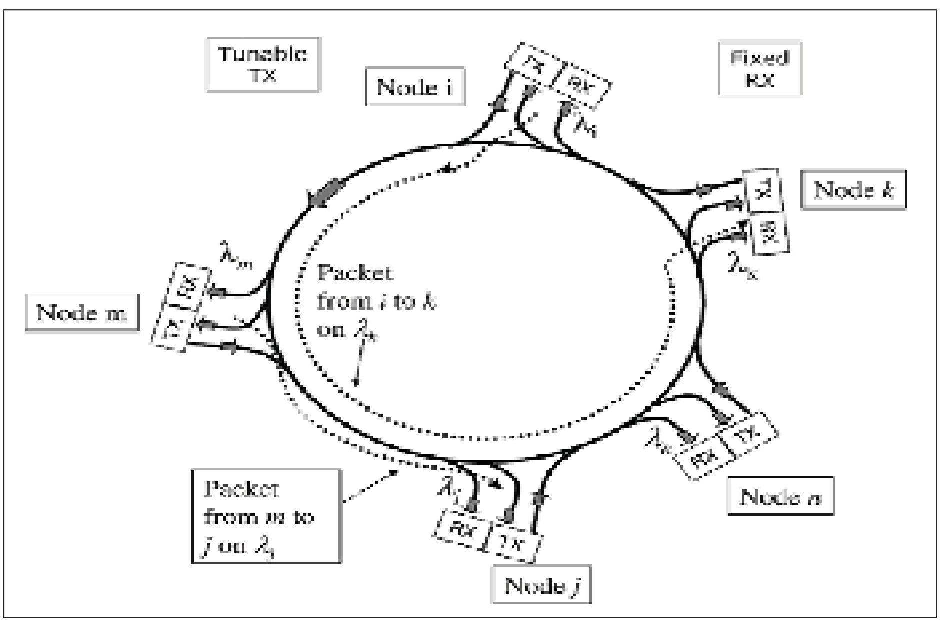

Figure 1.1 Architecture of the RINGO network
Taken from Carena *et al.* (2004)

All wavelengths are slotted with the slot length equal to the transmission time of a fixed-size data packet plus guard time. Each node performs λ-monitoring, i.e., it checks the state of the wavelength whether it is busy or idle, on a slot-by-slot basis to avoid channel collisions. This approach is a multichannel generalization of the empty-slot approach. In the empty-slot approach, one bit at the beginning of each slot indicates the state of the corresponding slot, i.e., whether the slot is free (empty) or occupied. A monitoring node is allowed to use only empty slots for its transmissions.

Figure 1.2 depicts the RINGO node structure in greater detail. At each node all wavelengths are demultiplexed. The drop wavelength is routed to a burst-mode receiver while the status of the remaining wavelengths is monitored by using $^{90}/_{10}$ taps and an array of photodiodes. The burst-mode receiver recovers the clock for each optical packet very quickly and does not need to receive a continuous signal. The $^{90}/_{10}$ taps splits 10% of the optical power from the fiber. Subsequently, the wavelengths are multiplexed on to the outgoing ring fiber. By using a $^{50}/_{50}$ combiner and an external modulator, the node is able to send data packets by activating one or more fixed-tuned transmitters. The $^{50}/_{50}$ combiner collects signals from two input ports and equally combines them onto one output port. Both input signals experience thereby a combining loss of 3 dB.

1.3.2 HORNET

The Hybrid Optoelectronic Ring NETwork (HORNET) is a unidirectional WDM ring network [White *et al.* (2003)]. All wavelengths are slotted with the slot length equal to the transmission time of a fixed-size packet (plus guard time). Each wavelength is shared by several nodes for data reception. Every node is equipped with one fast tunable transmitter and one fixed-tuned burst-mode receiver. As shown in Figure 1.3, the node structure consists of a slot manager, a smart drop, and a smart add module.

Access to all wavelengths is governed by means of a carrier sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol. When a node transmits a packet it multiplexes a sub-carrier tone onto the packet at a sub-carrier frequency that corresponds to the wavelength on which the packet is sent. The destination address of the packet

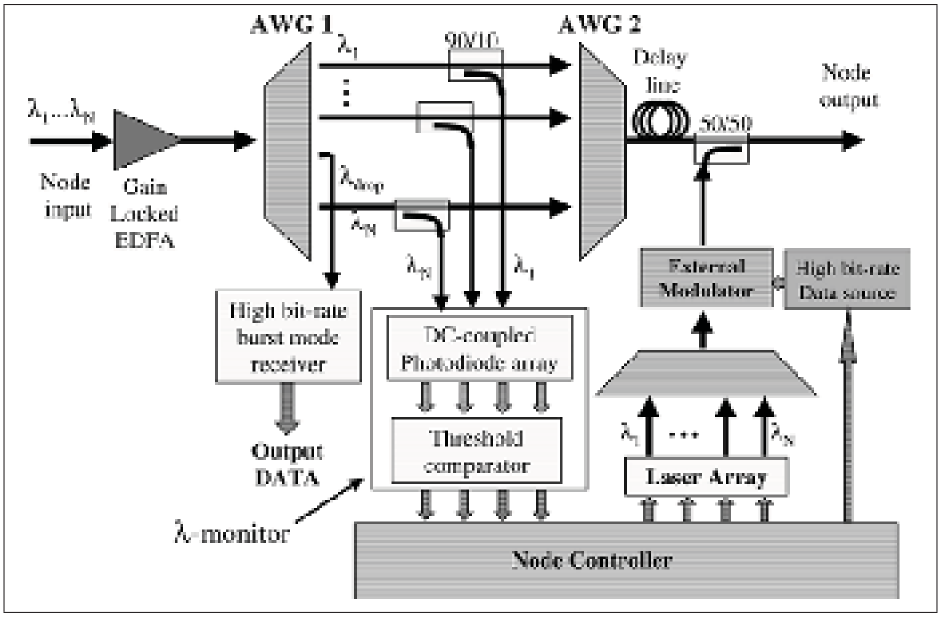

Figure 1.2 Structure of RINGO node
Taken from Carena *et al.* (2004)

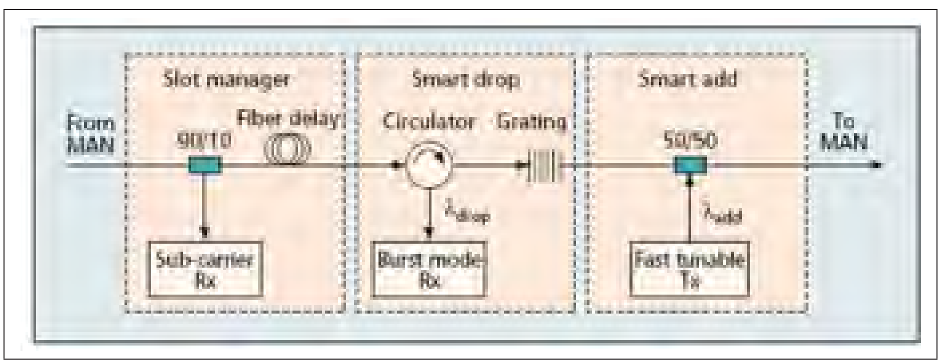

Figure 1.3 HORNET node structure
Taken from White *et al.* (2003)

is modulated onto the sub-carrier multiplexing (SCM) tone using a combination of amplitude shift keying (ASK) and frequency shift keying (FSK). For carrier sensing, the slot manager taps off a small amount of optical power and detects it with one photodiode. The payload data from all wavelengths collide at baseband while the SCM tones remain intact. The composite SCM signal is demultiplexed into the individual SCM tones using a collection of bandpass filters. The SCM tone corresponding to the drop wavelength of the node is FSK demodulated while the other SCM tones are ASK demodulated. The outcome of the ASK demodulation indicates the absence or presence of a packet on the corresponding wavelength. This allows the node to determine whether a wavelength is free for a packet transmission, which is conducted with the smart add module. The outcome of the FSK demodulation indicates whether there is a packet on the node's drop wavelength. If there is a packet, it is taken off the ring with the node's burst-mode receiver. The outcome of the FSK demodulation also gives the destination address of the packet. If the destination address does not match the node's address, then the node forwards the packet using its smart add module.

1.4 IEEE 802.17 Resilient Packet Ring (RPR) [Davik *et al.* (2004)]

1.4.1 Fundamentals of RPR

Resilient Packet Ring (RPR), which was standardized in 2004 as IEEE 802.17 RPR, is based on two counter-rotating fiber rings that carry data and control information [Davik *et al.* (2004), IEE (2004), Spadaro *et al.* (2004)]. Packet ring-based data networks were pioneered by the Cambridge Ring [Needham and Herbert (1982)], and followed by other important network architectures. Rings are built using several point-to-point connections. When the connections between the stations are bidirectional, rings allow for resilience (a frame can reach its destination even in the presence of a link failure). A ring is also simpler to operate and administrate than a complex mesh or an irregular network. Networks deployed by service providers in MANs or wide area networks (WANs) are often based on SONET/ SDH rings. Many SONET rings consist of a dual-ring configuration in which one of the rings is used as the backup ring, and remains unused during normal operation, utilized only in the case of failure of the primary ring. The static bandwidth allocation and network monitoring requirements increase the total cost of a SONET network. While Gigabit Ethernet does not require static allocation and provides cost advantages, it cannot provide desired features such as fairness and auto-restoration. Since RPR is being standardized in the IEEE 802 LAN/MAN families of network protocols, it can inherently bridge to other IEEE 802 networks and mimic a broadcast medium. RPR implements a MAC protocol for access to the shared ring communication medium that has a client interface similar to that of Ethernet's.

Furthermore, RPR uses the available ring bandwidth more efficiently than SONET/SDH by making use of destination stripping and shortest path routing both enabling spatial bandwidth reuse. With destination stripping, a packet sent along the ring from source node A to destination node B is removed from the ring by node B. The transmission of the packet only consumes bandwidth on the ring segment between node A and B as opposed to legacy ring systems that use source stripping where after passing its destination B the packet continues its travel around the ring until it reaches the source node A. Destination stripping has the advantage over source stripping that bandwidth is only consumed on the ring links between A and B so that other simultaneous transmissions can take place on the remaining links. In other words, destination stripping enables spatial reuse of the ring bandwidth by transmitting multiple packets simultaneously on different ring segments. For uniform traffic destination stripping doubles the ring capacity compared to source stripping. The spatial reuse of the ring bandwidth is further increased by making use of shortest path routing. Since RPR is based on a bi-directional fiber ring a source node can choose the ring direction with the smallest hop distance to the destination node. Shortest path routing further reduces the average number of links used for a transmission between two nodes enabling even larger spatial reuse. For uniform traffic, shortest path routing doubles the capacity of a destination stripping ring compared to sending each packet randomly in either or all packets in the same direction. Figure 1.4 shows an example scenario where spatial reuse is obtained on the outer RPR fiber ring, whereby station 2 transmits to station 4 at the same time as station 6 transmits to station 9. Every station on the ring has a buffer, called transit queue (see Figure 1.4), in which frames transiting the station may be temporarily queued. Each station acts according to two basic rules. The first rule is that the station may only start to add a packet if the transit queue is empty and there are no frames in transit. Second, if a transiting frame arrives after the station has started to add a frame, this transiting frame is temporarily stored (for as long as it takes to send the added frame) in the transit queue. Obviously, these two simple principles need some improvement to make up a full working protocol that distributes bandwidth fairly. How this is achieved in RPR will be revealed in the next sections.

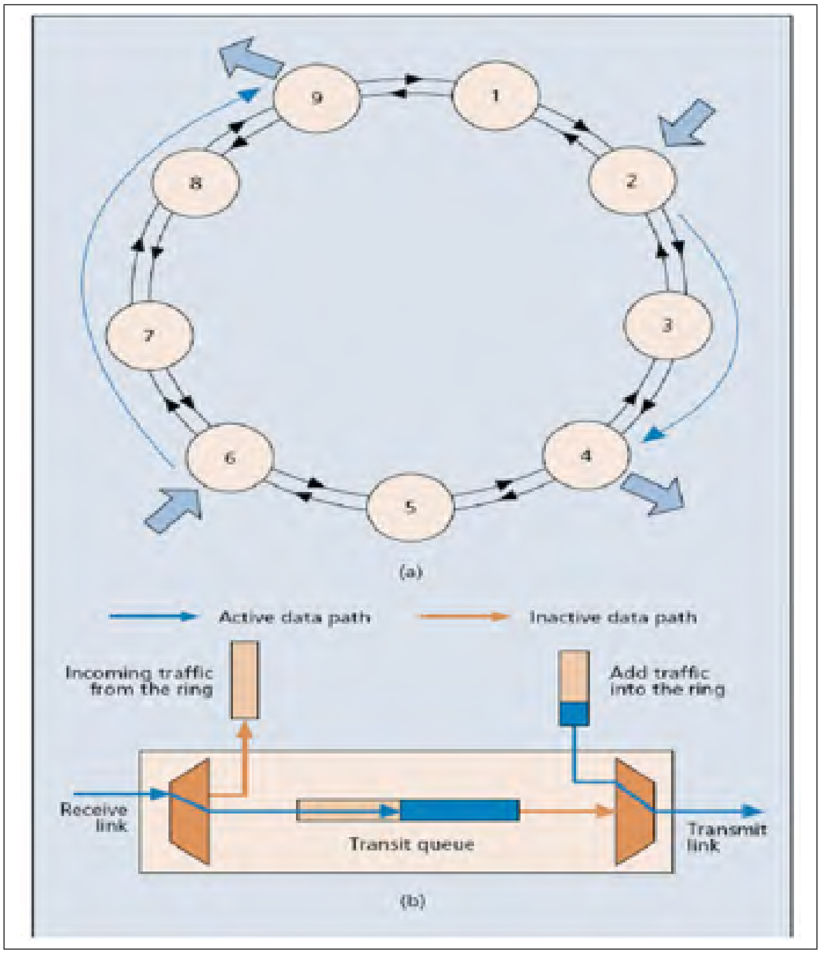

Figure 1.4 RPR network: a) destination stripping and spatial reuse; b) station's attachment to only one ringlet, showing the transit queue
Taken from Davik *et al.* (2004)

1.4.2 Station design and packet priority

The stations on the RPR ring implement a MAC protocol that controls the stations' access to the ring communication medium. Several physical layer interfaces (reconciliation sub-layers) for Ethernet (called PacketPHYs) and SONET/SDH are defined. The MAC entity also implements access points which clients can call in order to send and receive frames and status information. RPR provides a three-level class-based traffic priority scheme. The objectives of the class based scheme are to let class A be a low-latency low-jitter class, class B be a class with predictable latency and jitter, and class C be a best effort transport class. It is worthwhile to note that the RPR ring does not discard frames to resolve congestion. Hence, when a frame has been added onto the ring, even if it is a class C frame, it will eventually arrive at its destination. Class A traffic is divided into classes A0 and A1, and class B traffic is divided into classes B-CIR (committed information rate) and B-EIR (excess information rate). The two traffic classes C and B-EIR are called fairness eligible (FE), because such traffic is controlled by the fairness algorithm described in the next section. In order to fulfill the service guarantees for class A0, A1, and B-CIR traffic, bandwidth needed for these traffic classes is pre-allocated. Bandwidth pre-allocated for class A0 traffic is called reserved and can only be utilized by the station holding the reservation. Bandwidth pre-allocated for class A1 and B-CIR traffic is called reclaimable. Reserved bandwidth not in use is wasted. Bandwidth not pre-allocated and reclaimable bandwidth not in use may be used to send FE traffic.

A station's reservation of class A0 bandwidth is broadcast on the ring using topology messages (topology discovery is discussed later). Having received such topology messages from all other stations on the ring, every station calculates how much bandwidth to reserve for class A0 traffic. The remaining bandwidth, called unreserved rate, can be used for all other traffic classes. An RPR station implements several traffic shapers (for each ringlet) that limit and smooth add and transit traffic. There is one shaper for each of A0, A1, and B-CIR as well as one for FE traffic. There is also a shaper for all transmit traffic other than class A0 traffic, called the downstream shaper. The downstream shaper ensures that the total transmit traffic from a station, other than class A0 traffic, does not exceed the unreserved rate. The other shapers are used to limit the station's add traffic for the respective traffic classes. The shapers for classes A0, A1, and B-CIR are preconfigured; the downstream shaper is set to the unreserved rate, while the FE shaper is dynamically adjusted by the fairness algorithm. While a transit queue of one maximum transmission unit (MTU) is enough for buffering of frames in transit when the station adds a new frame into the ring, some flexibility for scheduling of frames from the add and transit paths can be obtained by increasing the size of the transit queue. For example, a station may add a frame even if the transit queue is not completely empty.

Also, a larger queue may store lower-priority transit frames while the station is adding high priority frames. The transit queue could have been specified as a priority queue, where frames with the highest priority are dispatched first. A simpler solution, adopted by RPR, is to optionally have two transit queues. Then high-priority transit frames (class A) are queued in the primary transit queue (PTQ), while class B and C frames are queued in the secondary transit queue (STQ). Forwarding from the PTQ has priority over the STQ and most types of add traffic. Hence, a class A frame traveling the ring will usually experience not much more than the propagation delay and some occasional transit delays waiting for outgoing packets to completely leave the station (RPR does not support preemption of packets). Figure 1.5 shows one ring interface with three add queues and two transit queues. The numbers in the circles indicate a crude priority on the transmit link. An RPR ring may consist of both one- and two-transit-queue stations. The rules for adding and scheduling traffic are local to the station, and the fairness algorithm described below works for both station designs.

1.4.3 MAC protocol

1.4.3.1 Ring access

RPR nodes operate in one of two modes: (i) single-queue mode or (ii) dual-queue mode. In single-queue mode, the transit path consists only of the PTQ. If the PTQ is not full, highest priority is given to the local control traffic. At the absence of local control traffic, priority is given to in-transit ring traffic over station traffic. In dual-queue mode, the transit path comprises both PTQ and STQ. The PTQ is used exclusively for class A traffic while the STQ stores packets belonging to class B and C traffic. In dual-queue mode, if both PTQ and STQ are not full, highest priority is given to local control traffic (similar to single-queue mode). If there is no local control traffic, PTQ traffic is served always first. If the PTQ is empty, the local

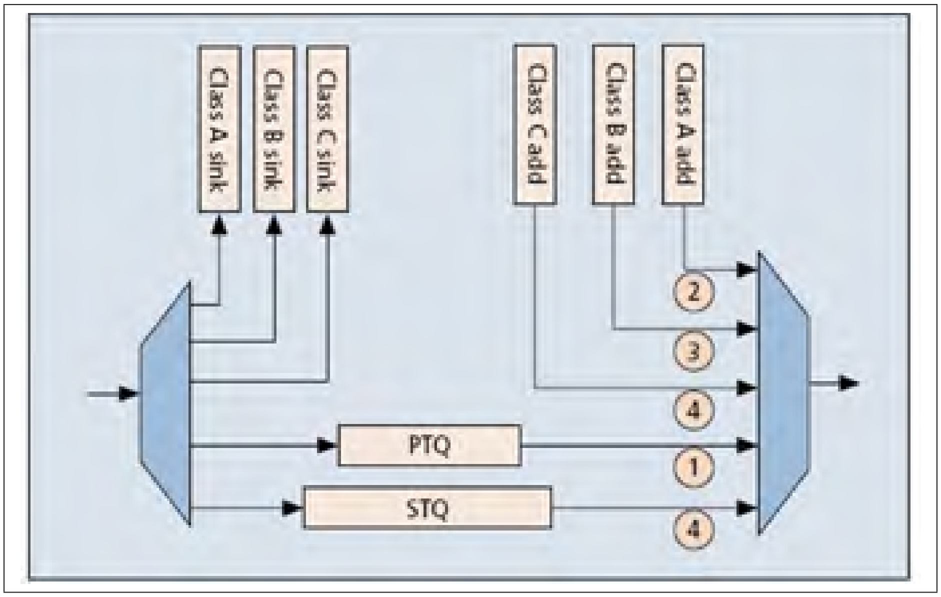

Figure 1.5 The attachment to one ring by a dual-transit-queue station. The numbers in the circles give a very crude indication of transmit link priority
Taken from Davik *et al.* (2004)

transmission queue (stage queue) is served until STQ reaches a certain queue threshold. When the STQ reaches that threshold, STQ in-transit ring traffic is given priority over station traffic such that in-transit packets are not lost due to buffer overflow. Thus, the transit path is lossless and a packet put on the ring is not dropped at downstream nodes.

Rings are the dominant topology in metropolitan networks primarily for their protection properties which are discussed in more detail in Section 1.4.3.3; that is, even under a single link or node failure, full connectivity among all ring nodes is maintained. Moreover, rings have reduced deployment costs from those of star or mesh topologies as ring nodes are only connected to their two nearest neighbors vs. to a centralized point (star) or multiple points (mesh) [Yuan *et al.* (2004), Assi *et al.* (2002)]. Unfortunately, current technology choices for high-speed metropolitan rings provide a number of unsatisfactory alternatives. Legacy SONET/SDH ring networks allocate bandwidth statically between source-destination node pairs. Internet traffic however is bursty and the connections (circuits) between the individual nodes must be provisioned for the traffic peak rate in average resulting in under utilization of the available bandwidth. To use the bandwidth more efficiently, next generation metro networks should support statistical multiplexing where the bandwidth is dynamically shared between the nodes. In addition to that, in a SONET-based ring network, a source node must generate a separate copy for each destination for the delivery of multicast/broadcast traffic, and almost half of the entire bandwidth is used for the management of the ring. However, the use of circuits prevents unused bandwidth from being reclaimed by other flows and results in low utilization under bursty traffic. On the other hand, a Gigabit Ethernet (GigE) ring can provide full statistical multiplexing, but suffers from poor utilization and unfairness. Low utilization arises because the Ethernet spanning tree protocol requires that one link be disabled to preclude loops, thereby preventing traffic from being forwarded along the true shortest path to the destination. Unfairness occurs in GigE, for example, in which nodes will obtain different throughputs to the hub node depending on their spatial location on the ring and input traffic patterns. Finally, legacy ring technologies such as fiber distributed data interface (FDDI) do not employ spatial reuse. That is, by using a rotating token that a node must hold to transmit, only one node can transmit at any given time.

1.4.3.2 Fairness control

In the basic buffer insertion access method, a station may only send a frame if the transit queue is empty. Thus, it is very easy for a downstream station to be starved by upstream ones. In RPR, the solution to the starvation problem is to force all stations to behave according to a specified fairness algorithm. The objective of the fairness algorithm is to distribute unallocated and unused reclaimable bandwidth fairly among the contending stations and use this bandwidth to send class B-EIR and class C (FE) traffic. When defining fair distribution of bandwidth, RPR enforces the principle that when the demand for bandwidth on a link is greater than the supply, the available bandwidth should be fairly distributed between the contending sender stations. A weight is assigned to each station, so a fair distribution of bandwidth need not be an equal one. When the bandwidth on the transmit link of a station is exhausted, the link and station are said to be congested, and the fairness algorithm starts working. The definition of congestion is different for single- and dual-queue stations, but both types of stations are congested if the total transmits traffic is above certain thresholds. In addition, a single-queue station is congested if frames that are to be added have to wait a long time before they are forwarded, and a dual-queue station is congested if the STQ is filling up (and hence transit frames have to wait a long time before they are forwarded). The most probable cause of congestion is the station itself and its immediate upstream neighbors. So, by sending a so-called fairness message upstream (on the opposite ring), the probable cause of the congestion is reached faster than by sending the fairness message downstream over the congested link. Figure 1.6 shows how the attachment to one ring asks the other attachment to queue and send a fairness message. In the following we focus on fairness on one ring.

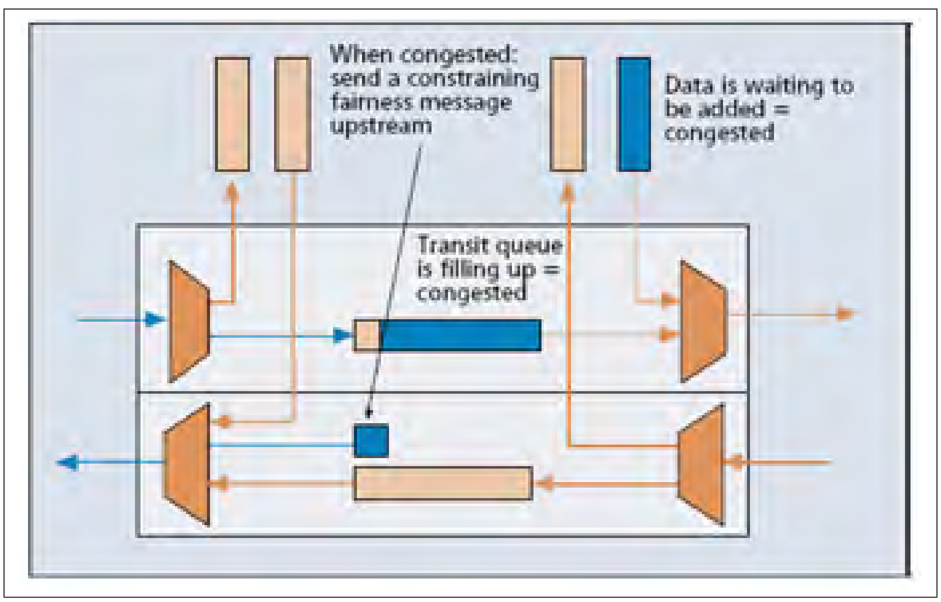

Figure 1.6 When a station becomes congested it sends a fairness message upstream
Taken from Davik *et al.* (2004)

The fairness algorithm on the other ring works exactly the same way. When a station becomes congested it calculates a first approximation to the fair rate by either dividing the available bandwidth between all upstream stations that are currently sending frames through this station, or using its own current add rate. This calculated value is sent upstream to all stations that are contributing to the congestion, and these stations must adjust their sending rate of FE traffic accordingly. The recipients of this message together with the originating station constitute a congestion domain. There are two options specified for the fairness algorithm. In the conservative mode the congested station waits to send a new fair rate value until all stations in the congestion domain have adjusted to the fair rate, and this change is observed by the congested station itself. The estimate of the time to wait (called the Fairness Round-Trip Time, FRTT) is calculated by sending special control frames across the congestion domain. The new fair rate may be smaller or larger than the previous one, depending on the observed change. In the aggressive mode, the congested station continuously (fairness packets are sent with a default interval of 100 μs) distributes a new approximation to the fair rate. When the station finally becomes uncongested, it sends a fairness message indicating no congestion. A station receiving a fairness message indicating no congestion will gradually increase its add traffic (assuming the station's demand is greater than what it is currently adding). In this way (if the traffic load is stable) the same station will become congested again after a while, but this time the estimated fair rate will be closer to the real fair rate, and hence the upstream stations in the congestion domain do not have to decrease their traffic rate as much as previously.

1.4.3.3 Resilience

RPR is designed with a protection mechanism aiming at restoring traffic within 50 ms in case of a link or station failure [Kvalbein and Gjessing (2005)]. Every station on the ring is reachable through either one of the ringlets, which allows one ringlet to serve as a secondary path for traffic of the other. Each station maintains a topology image, with information on the hop count to the other stations on both ringlets. The operation of the RPR protection mechanism is transparent to higher layer protocols like IP, except for the performance degradation that will be experienced following a failure. RPR has two protection mechanisms, wrapping and steering. With wrapping, packets arriving at point of failure are wrapped over to the other ringlet, and follow this ringlet to the destination. Wrapping gives a very short response time to a failure, and minimizes packet loss. The focus of this work is on the steering protection mechanism. With steering, when a failure occurs between the source and the receiver, the source station moves traffic over from the normal primary ringlet, to the ringlet on which the receiver can still be reached, termed the secondary ringlet, as shown in Figure 1.7. This protection mechanism, called steering, might introduce packet reordering, if packets traversing the new path experience a shorter buffering delay in the transit nodes than the packets in transit along the old path. Hence, a mechanism is needed in order to guarantee that no packets sent before the failure occurred will arrive at the destination after packets start arriving from the new ringlet.

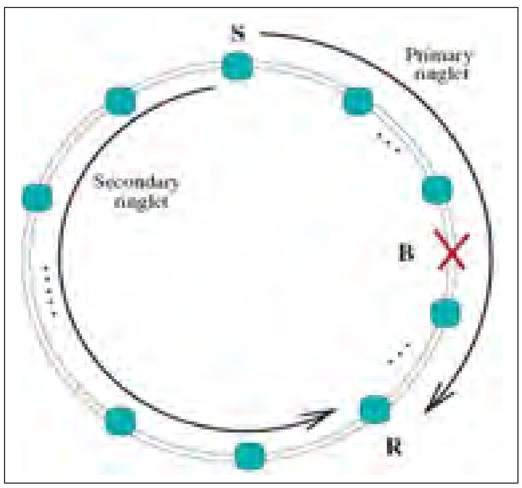

Figure 1.7 RPR network with source S, receiver R, and a link failure B
Taken from Kvalbein and Gjessing (2005)

1.4.4 Strengths and weaknesses of RPR

RPR technology has attracted considerable interest in the last years. Important issues related to the use of RPR technology are discussed in the following, to point out its advantages and review its disadvantages.

The protection mechanisms implemented in RPR are fast, they aim to achieve recovery times of approximately 50 ms and to protect against any single failure in the ring. No bandwidth is dedicated for recovery purposes; therefore, in a failure-less state resource utilization is high. However, in failure, the bandwidth available is substantially reduced. The reduction factor depends on the actual load and distribution of traffic.

If high-priority traffic is used in an RPR ring, the traffic must be shaped at ingress, and the service that uses this type of traffic must be carefully engineered. No mechanisms are provided to solve contention among high-priority traffic streams. If the high-priority traffic admitted exceeds the capacity of a given span, low-priority traffic is blocked. Thus, if problems are to be avoided, the amount of high-priority traffic injected into the ring must be controlled and limited by higher layers, especially in the case of failure. We suggest that each failure scenario be investigated in turn to determine whether a given load is handled properly.

RPR would seem to be a wise choice for efficient and reliable transport of best effort traffic. It may be used to transport traffic with strict bandwidth and delay requirements, although in this case one would need to verify whether RPR would satisfy the necessary parameters for all conceivable traffic flow patterns. With regard to the use of different classes of traffic, RPR requires external measures to prevent congestion. These measures are not standardized or otherwise defined at present, so it is up to the user to provide them. However, it is possible that such measures will be defined as RPR technology matures and its use becomes widespread. An important issue in modern telecommunications networks is interoperability among different layers. A new protocol should interwork smoothly with existing protocols. Interoperability with several physical layer techniques was explicitly considered during the standardization process of the IEEE 802.17 RPR. From the upper layer point of view RPR may be seen as a shared medium technology, and as such the problem was not widely studied

1.5 Synchronous Optical NEtwork (SONET) [IEC]

1.5.1 Introduction to SONET

Synchronous Optical NETwork (SONET) and Synchronous Digital Hierarchy (SDH) are equivalent standards with minor differences. SONET is used widely in North American, and SDH is used in Europe and the rest of the world. For the purpose of this dissertation only SONET terminology is used and discussed. The overhead insertion mechanism, however, can be applied to both.

SONET was originally developed for the telephone network as a long-term solution for a mid-span-meet between vendors. The standard was proposed by Bellcore and was established in 1984. SONET defines the rates and formats, the physical layer, network element architectural features, and network operational criteria for a fiber optic network. The standard soon becomes an excellent way for data communication as well, because it fits well in the physical layer of the OSI data network model.

1.5.2 Rates and formats

1.5.2.1 Typical End-to-End Connection

Because many existing networks use communication schemes of different digital signal hierarchies, encoding techniques, and multiplexing strategies, the complexity and cost to interconnect these networks are high. To reduce this complexity and cost, SONET was defined to standardized rates and formats for interoperability.

SONET systems are synchronous because all system elements use similar clocks rated at a grade of Stratum 3 or higher. The Optical carrier (OC) level and the electrical equivalent, Synchronous Transport Signal (STS), are the building blocks used in SONET. A STS consists of two parts: the STS payload and the STS overhead. The STS payload carries the communicated information, while the STS overhead carries signaling and protocol information.

For two user networks to communicate, the signals are converted to a STS, carried through various SONET networks before the SONET terminating equipment converts the STS back to the user network format. As illustrated in Figure 1.8, four layers exist for the typical SONET end-to-end connection: the path layer, line layer, section layer and photonic layer.

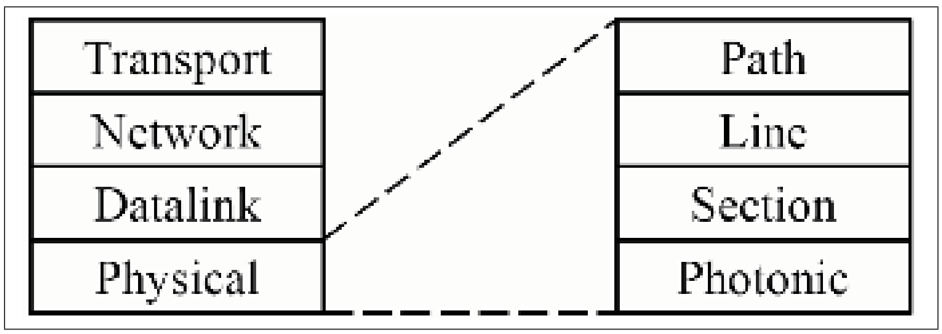

Figure 1.8 SONET Layers
Taken from Prakash

Information from each layer is communicated to and processed by the same layer in the terminating equipment and this processed information is passed up and down the layers. Each layer is responsible for specified aspects of the physical interface. The path is responsible for monitoring; the line is responsible for synchronization, multiplexing, and protection switching; the section, for framing, scrambling, and error monitoring; and the photonic layer, for setting the pulse shape, power level, and wavelength.

1.5.3 Frame Structure

The basic SONET frame is as shown in Figure 1.9. This signal is known as Synchronous Transport Signal Level-1 (STS-1). It consists of 9 rows of 90 bytes *i.e.,* a total of 810 bytes. It is transmitted from left to right and top to bottom. The two dimensional figure is just for convenience. Actual transmission takes place serially, *i.e.,* the left most byte in the top row is transmitted, then the second byte in the first row and so on. After the 90th byte in the first row the left most byte in the second row is transmitted and it goes on. One more point to be noted is that msb is transmitted first and the numbering of bits in a byte is as shown in Figure 1.10. The frame length is $125\mu s$ (*i.e.,* 8000 frames per second). The STS-1 has a bit rate of 51.84 Mbps. The frame for the lowest SDH rate STM-1 contains 270 columns by 9 rows. We will learn more about it later.

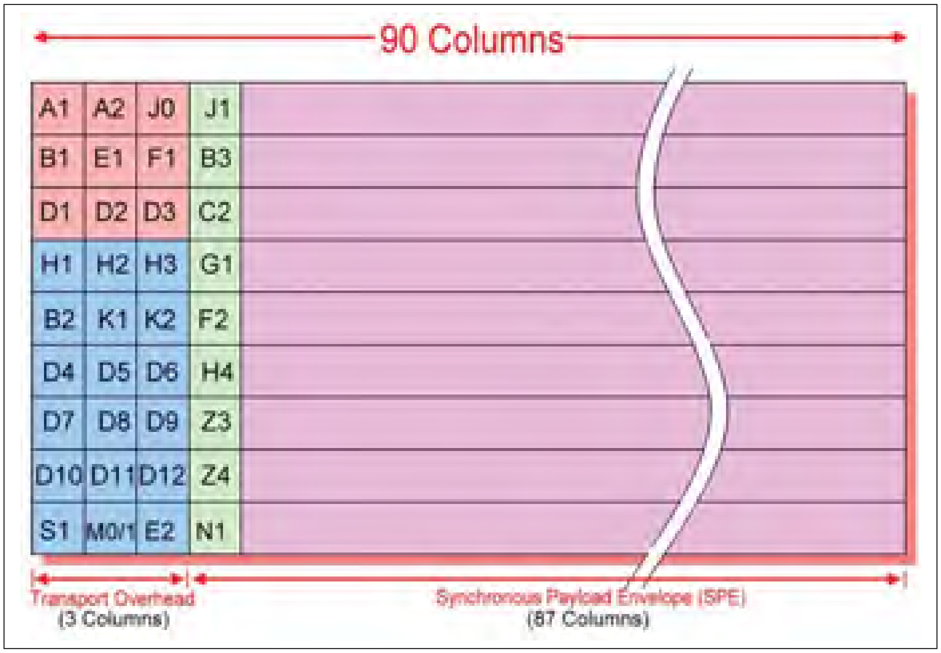

Figure 1.9 SONET Frame
Taken from Prakash

The first 3 columns of SONET frame are called Transport Overhead (TOH). The remaining 87 columns are called Synchronous Payload Envelope (SPE). The first column of SPE is called Payload Overhead (POH). A point to be noted here is that every SONET frame repeats every $125\mu s$ no matter how fast the line speed gets. As line rate goes up SONET frame gets bigger, just sufficient to keep the frame rate at 8000 frames per second.

1.5.4 Overheads

SONET provides substantial overhead information, allowing simpler multiplexing and greatly expanded OAM&P (Operations, Administration, Maintenance, and Provisioning) capabilities. The overhead information has several layers, which are shown in Figure 1.10. Path-level overhead is carried from end-to-end; it's added to DS1 signals when they are mapped into virtual tributaries and for STS-1 payloads that travel end-to-end.

Line overhead is for the STS-N signal between STS-N multiplexers. Section overhead is used for communications between adjacent network elements, such as regenerators.

Enough information is contained in the overhead to allow the network to operate and allow OAM&P communications between an intelligent network controller and the individual nodes. The following sections detail the different SONET overhead information:

- Section Overhead;
- Line Overhead;
- STS Path Overhead;
- VT Path Overhead.

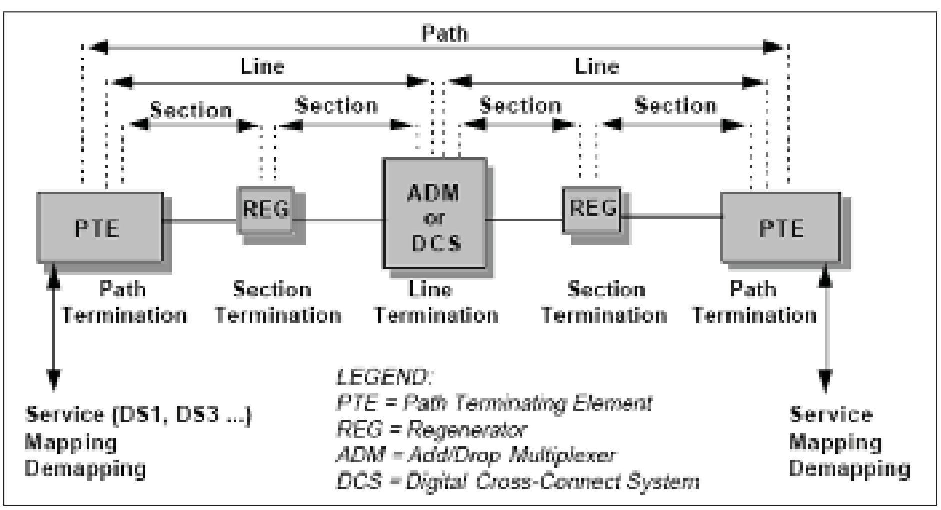

Figure 1.10 Overhead layers
Taken from IEC

1.5.5 SONET Multiplexing

The multiplexing principles of SONET are:

Mapping
A process used when tributaries are adapted into Virtual Tributaries (VTs) by adding justification bits and Path Overhead (POH) information;

Aligning
This process takes place when a pointer is included in the STS Path or VT Path Overhead, to allow the first byte of the Virtual Tributary to be located;

Multiplexing
This process is used when multiple lower-order path- layer signals are adapted into a higher-order path signal, or when the higher-order path signals are adapted into the Line Overhead;

Stuffing
SONET has the ability to handle various input tributary rates from asynchronous signals. As the tributary signals are multiplexed and aligned, some spare capacity has been designed into the SONET frame to provide enough space for all these various tributary rates. One of the benefits of SONET is that it can carry large payloads (above 50 $^{Mb}/_{s}$).

To achieve this capability, the STS Synchronous Payload Envelope can be sub-divided into smaller components or structures, known as Virtual Tributaries (VTs), for the purpose of transporting and switching payloads smaller than the STS-1 rate. All services below DS3 rate are transported in the VT structure.

Figure 1.11 illustrates the basic multiplexing structure of SONET. Any type of service, ranging from voice to high-speed data and video, can be accepted by various types of service adapters. New services and signals can be transported by adding new service adapters at the edge of the SONET network. Except for concatenated signals, all inputs are eventually converted to a base format of a synchronous STS-1 signal (51.84 $^{Mb}/_{s}$ or higher). Lower speed inputs such as DS1s are first bit- or byte-multiplexed into virtual tributaries. Several synchronous STS-1s are then multiplexed together in either a single- or two-stage process to form an electrical STS-N signal (N = 1 or more). STS multiplexing is performed at the Byte Interleave Synchronous Multiplexer. Basically, the bytes are interleaved together in a format such that the low-speed signals are visible. No additional signal processing occurs except a direct conversion from electrical to optical to form an OC-N signal.

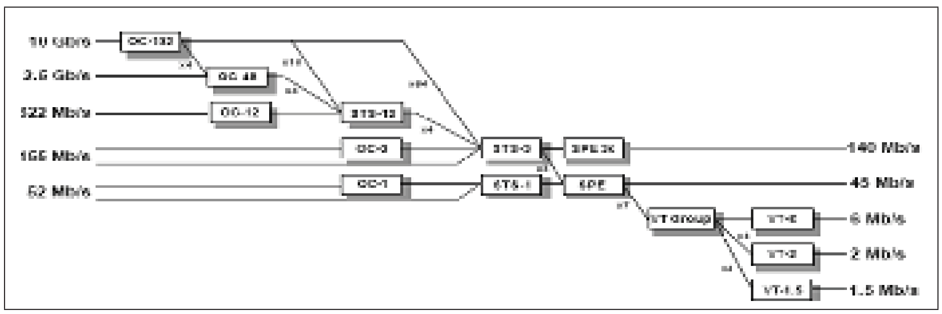

Figure 1.11 SONET multiplexing hierarchy
Taken from IEC

1.5.6 Ring Architecture

The SONET building block for ring architecture is the ADM. Multiple ADMs can be put into a ring configuration for either bi-directional or uni-directional traffic (see Figure 1.12). The main advantage of the ring topology is its survivability; if a fiber cable is cut, the multiplexers have the intelligence to send the services affected via an alternate path through the ring without interruption. The demand for survivable services, diverse routing of fiber facilities, flexibility to rearrange services to alternate serving nodes, as well as automatic restoration within seconds, have made rings a popular SONET topology.

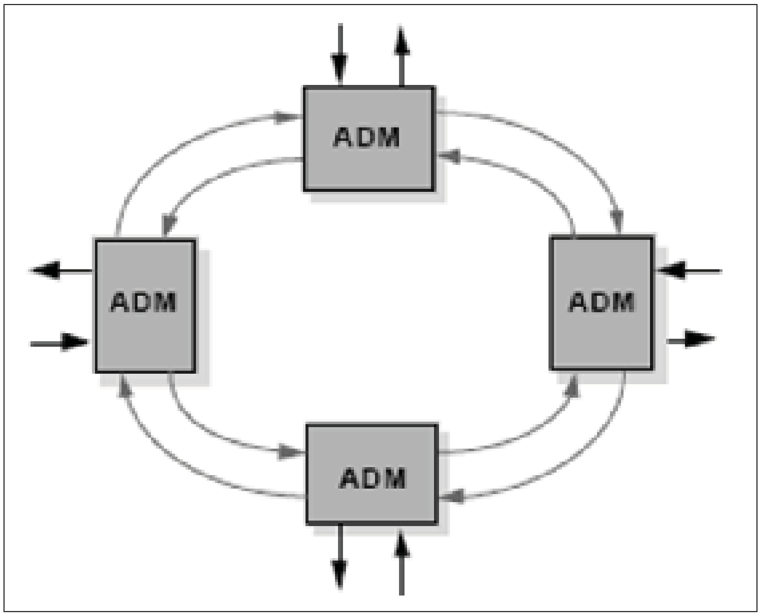

Figure 1.12 Ring architecture
Taken from IEC

1.6 Gigabyte Ethernet (GE) [CIS, Chitti *et al.* (2015)]

1.6.1 Introduction

Invented by Dr. Robert Metcalf and pioneered by Intel, Digital and Xerox, Ethernet has become the most commonly used LAN technology worldwide. More than 85% of all installed network connections are Ethernet, according to International Data Corporation (IDC, 2000). As a transport protocol, Ethernet operates at Layers 1 and 2 of the 7-layer OSI networking model, delivering its data packets to any device connected to the network cable. IT managers have found that Ethernet is simple, easy to use and readily upgradeable. An organization can scale from 10 to 100 or 1000 Mbps Ethernet, either network-wide or a segment at a time, knowing that the new equipment will be backwards compatible with legacy equipment. This reduces the infrastructure investment that an organization must make. Ethernet is also a reliable technology. Experience shows that it can be deployed with confidence for mission-critical applications.

1.6.2 Standards Evolution

In the last several years, the demand on the network has increased drastically. The old 10BASE5 and 10BASE2 Ethernet networks were replaced by 10BASE-T hubs, allowing for greater manageability of the network and the cable plant. As applications increased the demand on the network, newer, high-speed protocols such as FDDI and ATM became available. However, Fast Ethernet became the backbone of choice because its simplicity and its reliance on Ethernet. The primary goal of Gigabit Ethernet was to build on that topology and knowledge base in order to build a higher-speed protocol without forcing customers to throw away existing networking equipment. The standards body that worked on Gigabit Ethernet was the IEEE 803.2z Task Force. The possibility of a Gigabit Ethernet Standard was raised in mid-1995 after the final ratification of the Fast Ethernet Standard. By November 1995 there was enough interest to form a high-speed study group. This group met at the end of 1995 and several times during early 1996 to study the feasibility of Gigabit Ethernet.

The meetings grew in attendance, reaching 150 to 200 individuals. Numerous technical contributions were offered and evaluated. In July 1996, the 802.3z Task Force was established with the charter to develop a standard for Gigabit Ethernet. Basic concept agreement on technical contributions for the standard was achieved at the November 1996 IEEE meeting. The first draft of the standard was produced and reviewed in January 1997; the final standard was approved in June 1998.

1.6.3 Gigabit Ethernet Protocol Architecture

In order to accelerate speeds from 100 Mbps Fast Ethernet up to 1 Gbps, several changes need to be made to the physical interface. It has been decided that Gigabit Ethernet will look identical to Ethernet from the data link layer upward. The challenges involved in accelerating to 1 Gbps have been resolved by merging two technologies together: IEEE 802.3 Ethernet and ANSI X3T11 Fibre Channel. Figure 1.13 shows how key components from each technology have been leveraged to form Gigabit Ethernet.

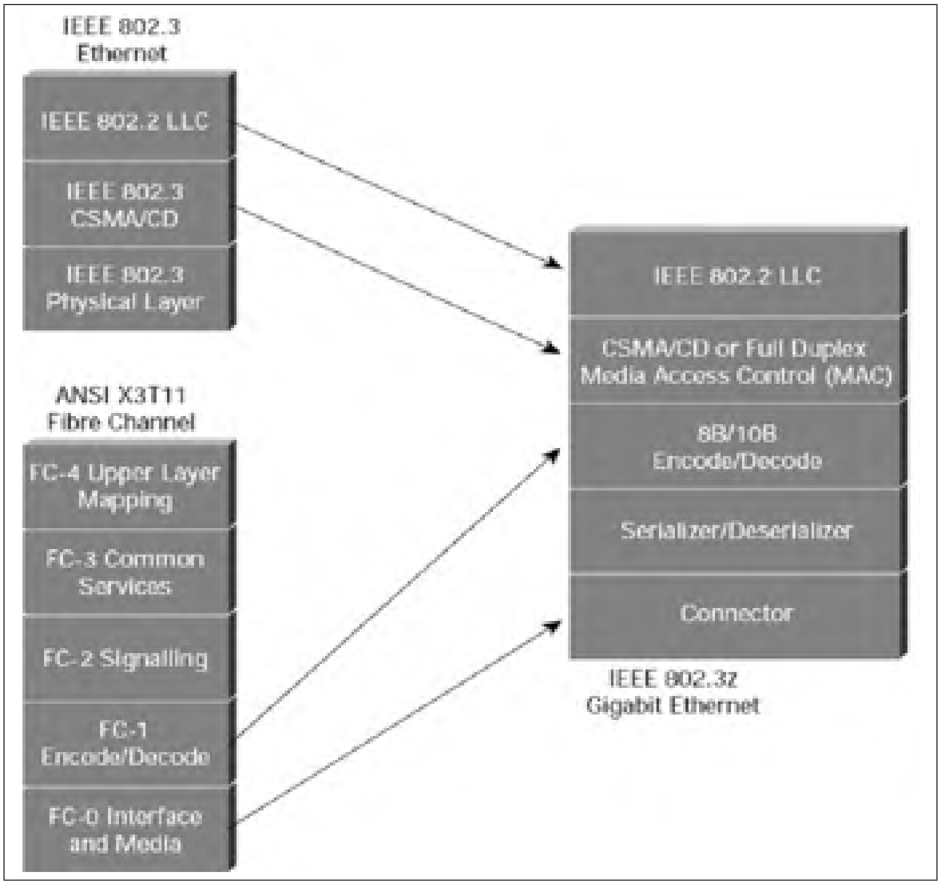

Figure 1.13 Gigabit Ethernet Protocol Stack
Taken from CIS

Leveraging these two technologies means that the standard can take advantage of the existing high-speed physical interface technology of Fibre Channel while maintaining the IEEE 802.3 Ethernet frame format, backward compatibility for installed media, and use of full- or half-duplex carrier sense multiple access collision detect (CSMA/CD). This scenario helps minimize the technology complexity, resulting in a stable technology that can be quickly developed. The actual model of Gigabit Ethernet is shown in Figure 1.14. Each of the layers will be discussed in detail.

1.6.4 Physical Interface

Figure 1.15 depicts the physical layers of these networks.

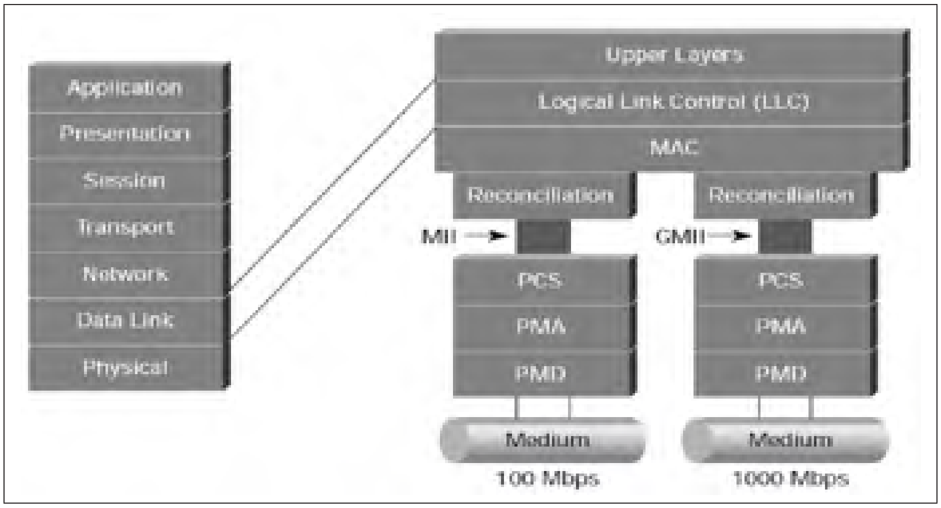

Figure 1.14 Architectural Model of IEEE 802.3z Gigabit Ethernet
Taken from CIS

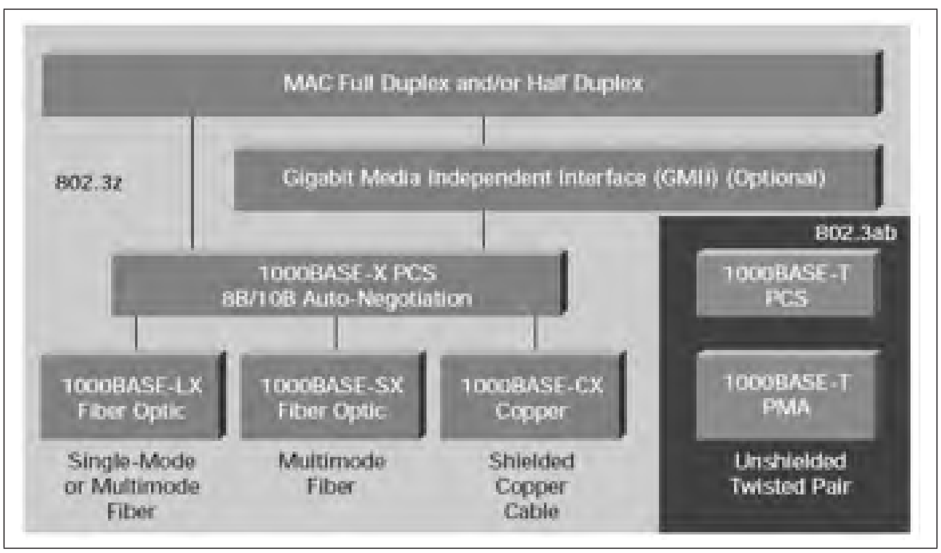

Figure 1.15 802.3z and 802.3ab Physical Layers
Taken from CIS

1.6.5 Media Access Control Layer

Gigabit Ethernet has been designed to adhere to the standard Ethernet frame format. This setup maintains compatibility with the installed base of Ethernet and Fast Ethernet products, requiring no frame translation. Figure 1.16 describes the IEEE 802.3 Ethernet frame format.

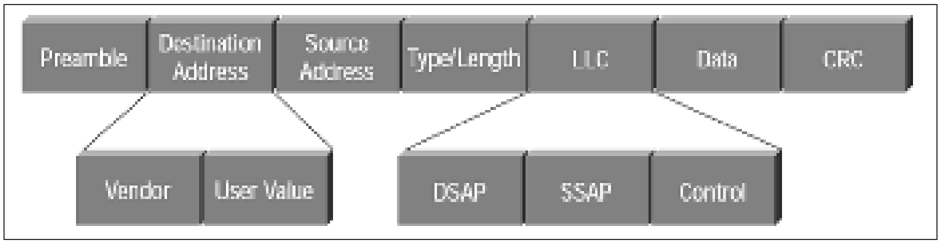

Figure 1.16 Ethernet Frame Format
Taken from CIS, Tao *et al.* (2014)

The original Xerox specification identified a type field, which was utilized for protocol identification. The IEEE 802.3 specification eliminated the type field, replacing it with the length field. The length field is used to identify the length in bytes of the data field. The protocol type in 802.3 frames is left to the data portion of the packet. The Logical Link Control (LLC) is responsible for providing services to the network layer regardless of media type, such as FDDI, Ethernet, Token Ring, and so on. The LLC layer makes use of LLC protocol data units (PDUs) in order to communicate between the Media Access Control (MAC) layer and the upper layers of the protocol stack. The LLC layer uses three variables to determine access into the upper layers via the LLC-PDU. Those addresses are the destination service access point (DSAP), source service access point (SSAP), and control variable. The DSAP address specifies a unique identifier within the station providing protocol information for the upper layer; the SSAP provides the same information for the source address.

The LLC defines service access for protocols that conform to the Open System Interconnection (OSI) model for network protocols.

1.6.6 Example of Implementation

Let's see an example in a corporate campus setting Figure 1.17. In this kind of environment we find a large number of users, servers and multiple network segments, resulting in complex needs. Cat-5 copper cabling is likely to be in place within the data center, while fiber is typically used for connections between buildings, to link segment switches to the data center, and to connect servers outside the enterprise. Gradual migration to Gigabit Ethernet will provide more bandwidth for high-performance desktops, server connections, and switch-to-switch connections.

Deployment steps include:

- For high-demand servers, replace 10/100Mbps adapters with multiple auto-negotiating 10/100/1000Mbps adapters for copper, 1000Mbps for fiber;
- In the R&D department, replace 10/100 desktop adapters with Gigabit adapters and replace the 10/100Mbps segment switch with a Layer 2 Gigabit switch;
- Install Gigabit up-links from 10/100 switch stacks to the data center;
- Replace the 10/100Mbps backbone switch with a high-performance, Layer 3 Gigabit switch – at this point, the legacy Cat-5 cabling within the data center and existing fiber cabling to segment switches will begin running at Gigabit speed;
- Begin replacing 10/100 desktop adapters with Gigabit adapters in other departments besides R&D.

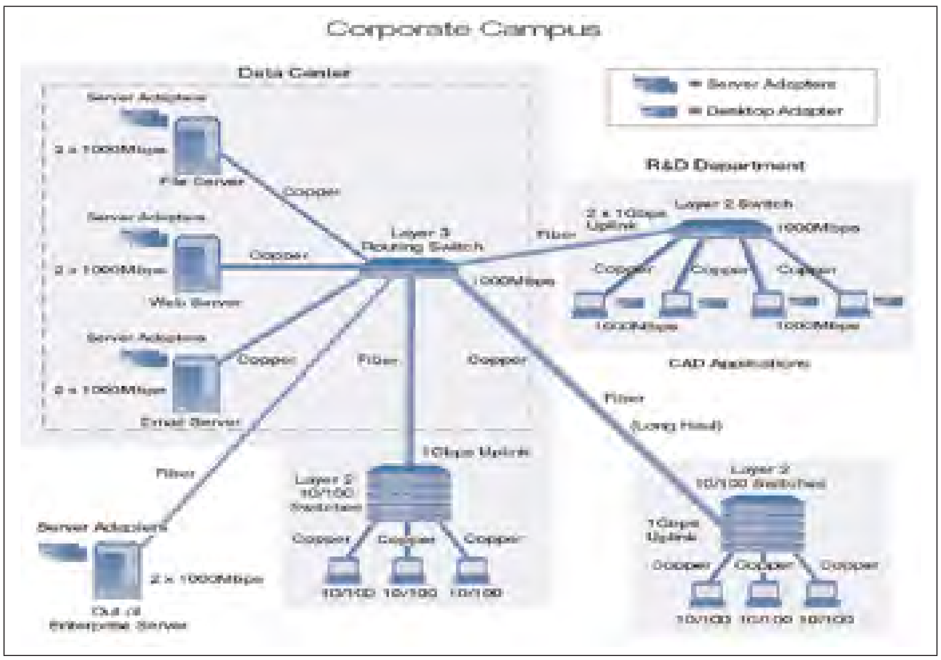

Figure 1.17   Corporate Campus
Taken from CIS

CHAPTER 2

OBJECTIVES OF RESEARCH AND ORIGINALITY

2.1 Objectives of Research

2.1.1 Problem Statement

The recently approved IEEE standard 802.17 Resilient Packet Ring (RPR) aims at combining SONET/SDH's carrier-class functionalities of high availability, reliability, and profitable TDM service support and Ethernet's high bandwidth utilization, low equipment cost, and simplicity. RPR is a ring-based architecture consisting of two counter directional optical fiber rings. Similar to SONET/SDH, RPR is able to provide fast recovery from a single link or node failure and to carry legacy TDM traffic with a high level of quality of service (QoS). Similar to Ethernet, RPR provides the advantages of low equipment cost and simplicity and exhibits improved bandwidth utilization due to statistical multiplexing. Since RPR belongs to the IEEE 802 LAN/MAN families of network protocols, it can inherently bridge to other IEEE 802 networks (e.g., GbE, SONET/SDH, etc.) and mimic a broadcast medium. RPR implements a MAC protocol for access to the shared ring communication medium that has a client interface similar to that of Ethernet's. Since networks deployed by service providers in LAN, MANs or wide area networks (WANs) are often based on Ethernet, SONET/SDH rings. In our study, we want to attach RPR rings to these L2 networks and we will analyze the performance and the management of this Large New L2 Network (NLL2N). Furthermore, we will analyze the performance and the benefits in the NLL2N. Specifically, it is important to investigate the feasibility of the integration of all these protocols and make them work together.

2.1.2 Objectives

The objectives of the research project are as follows:

- Identification of problems encountered to investigate the integration and the performance of RPR over Ethernet, RPR over SONET, SONET over Ethernet and finally merge all these protocols and investigate their management, performance and integration as a New Large Layer 2 Network;
- Solutions to the identified performance and management improvement problems in the NLL2N must be found, developed, and assessed;
- Evaluation of the proposed solutions will be provided by means of verifying simulation and experimental implementation and investigation. The impact of the various network parameters and traffic conditions on the network performance will be studied for different node and/or link failure scenarios and network configurations;
- Experimental investigation of performance, latency, and benefits in the NLL2N.

2.2 Methodology

The methodology of the research project is as follows:

- To acquire the required knowledge of the considered network architectures, protocols, and standards and enable the finding of appropriate solutions a major part of the work will involve extensive literature study of existing research results, e.g., journals, conference proceedings, tutorials, surveys, standards, books;
- To enable the evaluation and comparison of proposed solutions, appropriate simulation, implementation, and experimental validation tools will be used;

- The impact of various network and traffic parameters on the throughput-delay performance and management of the NLL2N will be investigated by means of simulation and experiment;
- Via simulation and experiment, RPR's access, bandwidth management, performance, latency and possible extensions required for their use in the NLL2N will be examined;
- A proof-of-concept experimental demonstration the improvement of the performance and management used in the NLL2N will be provided.

Goals and Innovations of the Thesis

The goal of our research is to investigate and analyze the performance and management when RPR rings are attached to a large L2 network. We will demonstrate that RPR, Ethernet and SONET could be integrated in the same Large Layer 2 Network by the simulation of RPR over Ethernet (RPRoE), RPR over SONET (RPRoSONET), SONET over Ethernet (SONEToE) and the New Large Layer 2 Network (NLL2N). During our research we investigate and analyze, specifically, the performance and the benefits of it.

CHAPTER 3

RPR OVER ETHERNET

Ammar Hamad[1], Michel Kadoch[1]

[1] Department of Electrical Engineering, École de Technologie Supérieure
1100 Notre-Dame Ouest, Montreal, Québec, Canada H3C 1K3

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This chapter deals with the Resilient Packet Ring (RPR) and Ethernet. The two protocols are implemented in the layer 2 (OSI Model) and often are used separately. In this chapter, we will demonstrate that RPR and Ethernet could be integrated together in the same Layer 2 (MAC layer) Network. We will explain and detail the use of RPR over Ethernet (RPRoE) with a simulation that shows a better performance using RPRoE than Ethernet and RPR by themselves.

3.1 Introduction

RPR is among the standards the IEEE has defined to enable carrier-class Ethernet. RPR was standardized by the IEEE 802.17 Working Group in 2004. The primary focus of IEEE 802.17 IEE (2004) has been to standardize the media access control (MAC) layer technology for enabling carrier-class RPR over SONET/SDH or Ethernet physical layer transceivers (PHYs). Currently, the IEEE 802.17 Working Group is in the process of standardizing 802.17b, which enhances the RPR bridging methodology for Ethernet packets sourced and/or destined to stations off the ring.

RPR has been implemented in LAN and MAN network and works adequately by itself. Our challenge in this chapter is merge the two protocols (RPR and Ethernet) and make them work as a one layer 2 protocol. The methodology that we will be using is to encapsulate RPR frame in Ethernet data frame. Our method will be simulated and tested in a laboratory. We analyze the load of the link and the Input/Output of the data transmitted. Having RPR rings attached directly to a large L2 networks, as SONET/SDH, Ethernet, GbE, will be an interesting way to help business to set their layer 2 environments adequately and reduce their daily load.

3.2 Fundamentals of RPR

Resilient Packet Ring (RPR), which was standardized in 2004 as IEEE 802.17 RPR, is based on two counter-rotating fiber rings that carry data and control information [Davik *et al.* (2004), and Spadaro *et al.* (2004)]. Packet ring-based data networks were pioneered by the Cambridge Ring [Needham and Herbert (1982)], and followed by other important network architectures. Rings are built using several point-to-point connections. When the connections between the stations are bidirectional, rings allow for resilience (a frame can reach its destination even in the presence of a link failure). Since RPR is being standardized in the IEEE 802 LAN/MAN families of network protocols, it can inherently bridge to other IEEE 802 networks and mimic a broadcast medium. RPR implements a MAC protocol for access to the shared ring communication medium that has a client interface similar to that of Ethernet's.

Furthermore, RPR uses the available ring bandwidth more efficiently than SONET/SDH by making use of destination stripping and shortest path routing both enabling spatial bandwidth reuse. With destination stripping, a packet sent along the ring from source node A to destination node B is removed from the ring by node B. The transmission of the packet only consumes bandwidth on the ring segment between node A and B as opposed to legacy ring systems that use source stripping where after passing its destination B the packet continues its travel around the ring until it reaches the source node A. Destination stripping has the advantage over source stripping that bandwidth is only consumed on the ring links between A and B so that other simultaneous transmissions can take place on the remaining links. In other words, destination stripping enables spatial reuse of the ring bandwidth by transmitting multiple packets simultaneously on different ring segments.

For uniform traffic destination stripping doubles the ring capacity compared to source stripping. The spatial reuse of the ring bandwidth is further increased by making use of shortest path routing. Since RPR is based on a bi-directional fiber ring a source node can choose the ring direction with the smallest hop distance to the destination node. Shortest path routing further reduces the average number of links used for a transmission between two nodes enabling even larger spatial reuse. For uniform traffic, shortest path routing doubles the capacity of a destination stripping ring compared to sending each packet randomly in either or all packets in the same direction. Figure 3.1 shows an example scenario where spatial reuse is obtained on the outer RPR fiber ring, whereby station 2 transmits to station 4 at the same time as station 6 transmits to station 9. Every station on the ring has a buffer, called transit queue (see Figure 3.1) [Needham and Herbert (1982)], in which frames transiting the station may be temporarily queued. Each station acts according to two basic rules. The first rule is that the station may only start to add a packet if the transit queue is empty and there are no frames in transit. Second, if a transiting frame arrives after the station has started to add a frame, this transiting frame is temporarily stored (for as long as it takes to send the added frame) in the transit queue. Obviously, these two simple principles need some improvement to make up a full working protocol that distributes bandwidth fairly.

3.3 Station Design and Packet Priority

The stations on the RPR ring implement a MAC protocol that controls the stations' access to the ring communication medium. The MAC entity also implements access points which clients can call in order to send and receive frames and status information. RPR provides a three-level class-based traffic priority scheme. The objectives of the class based scheme are to let class A be a low-latency low-jitter class, class B be a class with predictable latency and jitter, and class C be a best effort transport class. It is worthwhile to note that the RPR ring does not discard frames to resolve congestion. Hence, when a frame has been added onto the ring, even if it is a class C frame, it will eventually arrive at its destination. Class A traffic is divided into classes A0 and A1, and class B traffic is divided into classes B-CIR (committed information rate)

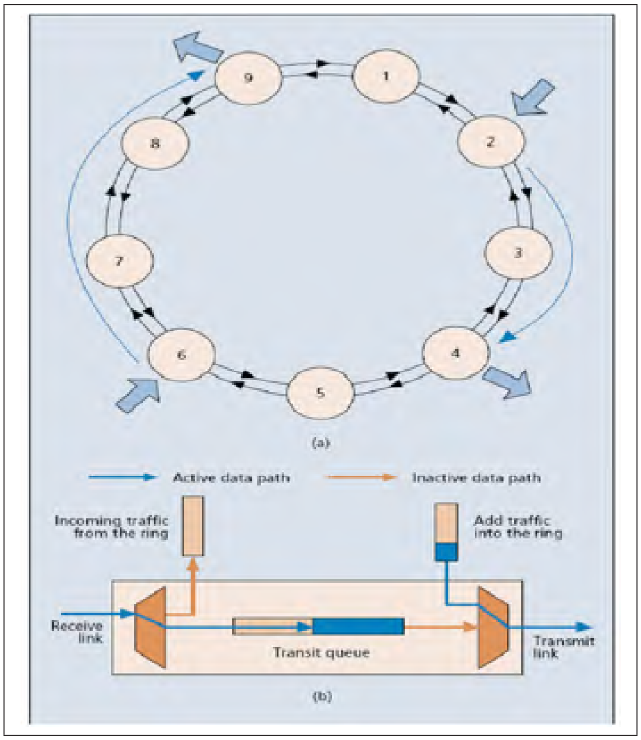

Figure 3.1 RPR network: a) destination stripping and spatial reuse; b) station's attachment to only one ringlet, showing the transit queue
Taken from Needham and Herbert (1982)

and B-EIR (excess information rate). The two traffic classes C and B-EIR are called fairness eligible (FE), because such traffic is controlled by the fairness algorithm described in the next section. In order to fulfill the service guarantees for class A0, A1, and B-CIR traffic, bandwidth needed for these traffic classes is pre-allocated. Bandwidth pre-allocated for class A0 traffic is called reserved and can only be utilized by the station holding the reservation. Bandwidth pre-allocated for class A1 and B-CIR traffic is called reclaimable. Reserved bandwidth not in use is wasted. Bandwidth not pre-allocated and reclaimable bandwidth not in use may be used to send FE traffic.

A station's reservation of class A0 bandwidth is broadcast on the ring using topology messages (topology discovery is discussed later). Having received such topology messages from all other stations on the ring, every station calculates how much bandwidth to reserve for class

A0 traffic. The remaining bandwidth, called unreserved rate, can be used for all other traffic classes. An RPR station implements several traffic shapers (for each ringlet) that limit and smooth add and transit traffic. There is one shaper for each of A0, A1, and B-CIR as well as one for FE traffic. There is also a shaper for all transmit traffic other than class A0 traffic, called the downstream shaper. The downstream shaper ensures that the total transmit traffic from a station, other than class A0 traffic, does not exceed the unreserved rate. The other shapers are used to limit the station's add traffic for the respective traffic classes. The shapers for classes A0, A1, and B-CIR are preconfigured; the downstream shaper is set to the unreserved rate, while the FE shaper is dynamically adjusted by the fairness algorithm. While a transit queue of one maximum transmission unit (MTU) is enough for buffering of frames in transit when the station adds a new frame into the ring, some flexibility for scheduling of frames from the add and transit paths can be obtained by increasing the size of the transit queue. For example, a station may add a frame even if the transit queue is not completely empty. Also, a larger queue may store lower-priority transit frames while the station is adding high priority frames. The transit queue could have been specified as a priority queue, where frames with the highest priority are dispatched first. A simpler solution, adopted by RPR, is to optionally have two transit queues. Then high-priority transit frames (class A) are queued in the primary transit queue (PTQ), while class B and C frames are queued in the secondary transit queue (STQ). Forwarding from the PTQ has priority over the STQ and most types of add traffic. Hence, a class A frame traveling the ring will usually experience not much more than the propagation delay and some occasional transit delays waiting for outgoing packets to completely leave the station (RPR does not support preemption of packets). Figure 3.2 [Needham and Herbert (1982)] shows one ring interface with three add queues and two transit queues. The numbers in the circles indicate a crude priority on the transmit link. An RPR ring may consist of both one- and two-transit-queue stations. The rules for adding and scheduling traffic are local to the station, and the fairness algorithm described below works for both station designs.

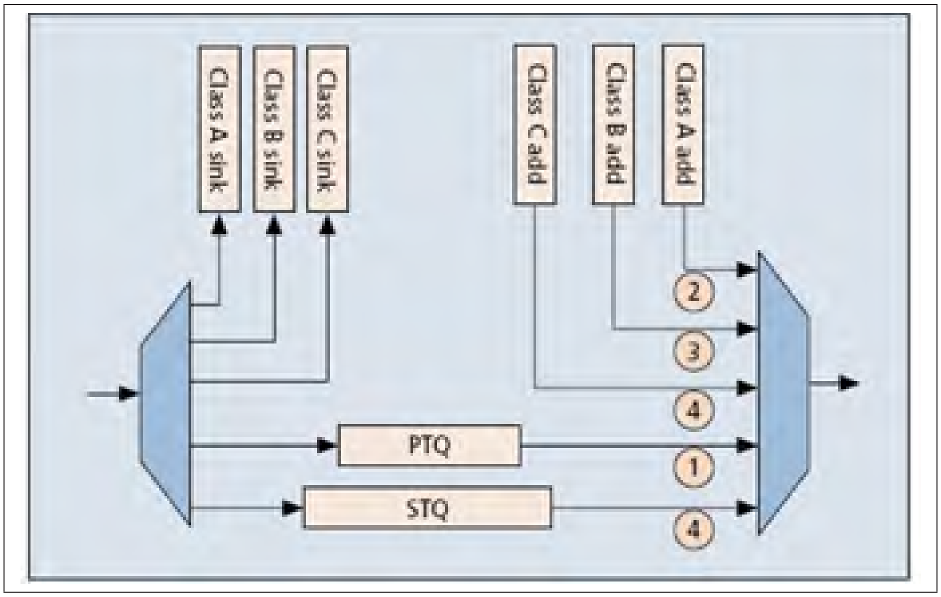

Figure 3.2 The attachment to one ring by a dual-transit-queue station. The numbers in the circles give a very crude indication of transmit link priority
Taken from Needham and Herbert (1982)

3.4 Fundamentals of Gigabyte Ethernet

Invented by Dr. Robert Metcalf and pioneered by Intel, Digital and Xerox, Ethernet has become the most commonly used LAN technology worldwide. More than 85% of all installed network connections are Ethernet, according to International Data Corporation (IDC, 2000). As a transport protocol, Ethernet operates at Layers 1 and 2 of the 7-layer OSI networking model, delivering its data packets to any device connected to the network cable. IT managers have found that Ethernet is simple, easy to use and readily upgradeable. An organization can scale from 10 to 100 or 1000Mbps Ethernet, either network-wide or a segment at a time, knowing that the new equipment will be backwards compatible with legacy equipment. This reduces the infrastructure investment that an organization must make. Ethernet is also a reliable technology. Experience shows that it can be deployed with confidence for mission-critical applications.

3.4.1 Standard evolution

In the last several years, the demand on the network has increased drastically. The old 10BASE5 and 10BASE2 Ethernet networks were replaced by 10BASE-T hubs, allowing for greater manageability of the network and the cable plant. As applications increased the demand on the network, newer, high-speed protocols such as FDDI and ATM became available. However, Fast Ethernet became the backbone of choice because its simplicity and its reliance on Ethernet. The primary goal of Gigabit Ethernet was to build on that topology and knowledge base in order to build a higher-speed protocol without forcing customers to throw away existing networking equipment. The standards body that worked on Gigabit Ethernet was the IEEE 803.2z Task Force. The possibility of a Gigabit Ethernet Standard was raised in mid-1995 after the final ratification of the Fast Ethernet Standard. By November 1995 there was enough interest to form a high-speed study group. This group met at the end of 1995 and several times during early 1996 to study the feasibility of Gigabit Ethernet.

The meetings grew in attendance, reaching 150 to 200 individuals. Numerous technical contributions were offered and evaluated. In July 1996, the 802.3z Task Force was established with the charter to develop a standard for Gigabit Ethernet. Basic concept agreement on technical contributions for the standard was achieved at the November 1996 IEEE meeting. The first draft of the standard was produced and reviewed in January 1997; the final standard was approved in June 1998.

3.4.2 Gigabit Ethernet Protocol Architecture

In order to accelerate speeds from 100 Mbps Fast Ethernet up to 1 Gbps, several changes need to be made to the physical interface. It has been decided that Gigabit Ethernet will look identical to Ethernet from the data link layer upward. The challenges involved in accelerating to 1 Gbps have been resolved by merging two technologies together: IEEE 802.3 Ethernet and ANSI X3T11 Fibre Channel. Figure 3.3 shows how key components from each technology have been leveraged to form Gigabit Ethernet.

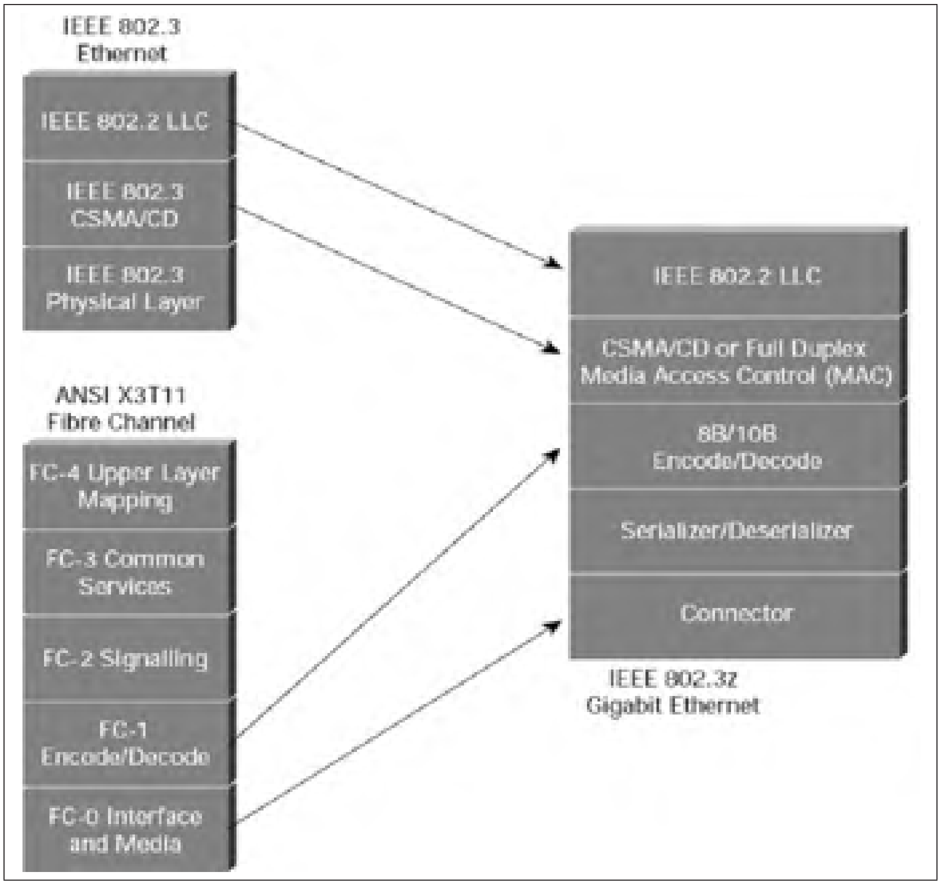

Figure 3.3 Gigabit Ethernet Protocol Stack
Taken from CIS

Leveraging these two technologies means that the standard can take advantage of the existing high-speed physical interface technology of Fibre Channel while maintaining the IEEE 802.3 Ethernet frame format, backward compatibility for installed media, and use of full- or half-duplex carrier sense multiple access collision detect (CSMA/CD). This scenario helps minimize the technology complexity, resulting in a stable technology that can be quickly developed.

3.5 Basic Principles of RPR Over Ethernet

RPR over Ethernet (RPRoE) is an RPR transmission technology that carries RPR frames directly on the Ethernet link layer. This solution complies with the Ethernet specification frame by IEEE 802.3. Figure 3.4 shows the RPRoE encapsulation format.

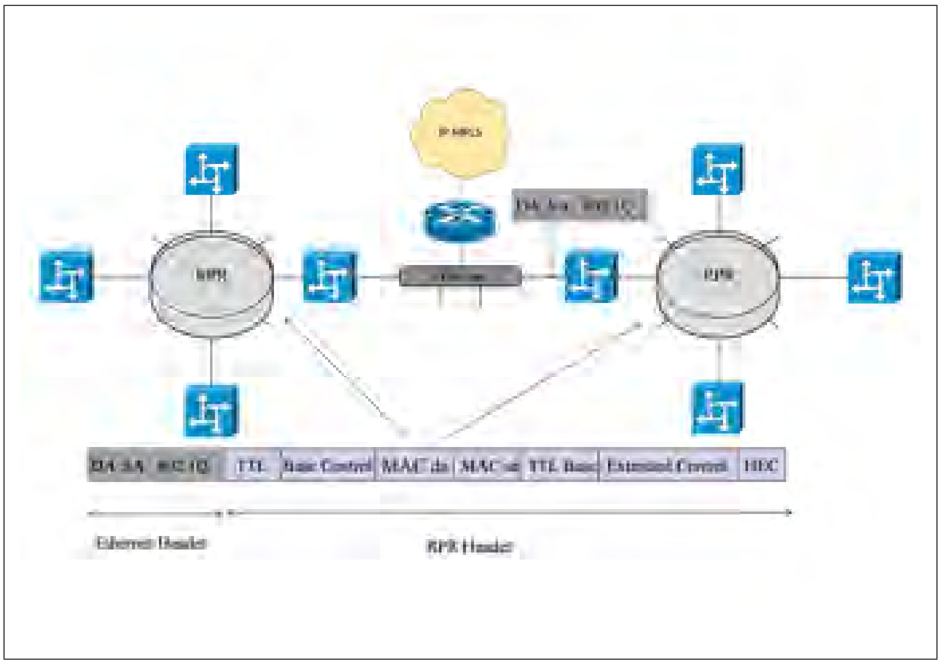

Figure 3.4 RPRoE frame format

a. All the devices on the ring or on the Ethernet segment are plug-and play nature;

b. New stations added to the ring or to the Ethernet do not affect the existing traffic;

c. With RPR over Ethernet technology, all the transit packets are forwarded according to Ethernet header;

d. Transit stations do not learn any RPR MAC.

When a frame is inserted to Ethernet, RPR frames are encapsulated in Ethernet data frame to then be forwarded on the Ethernet segment. In a copy operation, the Ethernet headers are stripped off and only RPR frames are forwarded.

3.5.1 Address learning of RPR over Ethernet

A device is logically divided into two parts. One part is at the RPR side to deal with RPR switching. The other part is at the Ethernet side to process RPRoE. When the RPR part receives a frame, it determines, according to the destination RPR MAC address, the Ethernet segment that the frame will send to. The RPRoE part finds the destination Ethernet MAC address, and the number of hops based on the user MAC address. It encapsulates the Ethernet frame header and then sends the frame to the Ethernet interface. When receiving an RPRoE data frame from Ethernet interface, the device will learn the source RPR MAC address and the Ethernet MAC address of the source Ethernet station. Ethernet station keeps two MAC tables. One is at the RPR side recording the mapping between user MAC addresses and RPR egress ports. The other is at the Ethernet side for recording the mapping between user MAC addresses and destination Ethernet stations. See the Figure 3.5 to follow the forwarding process.

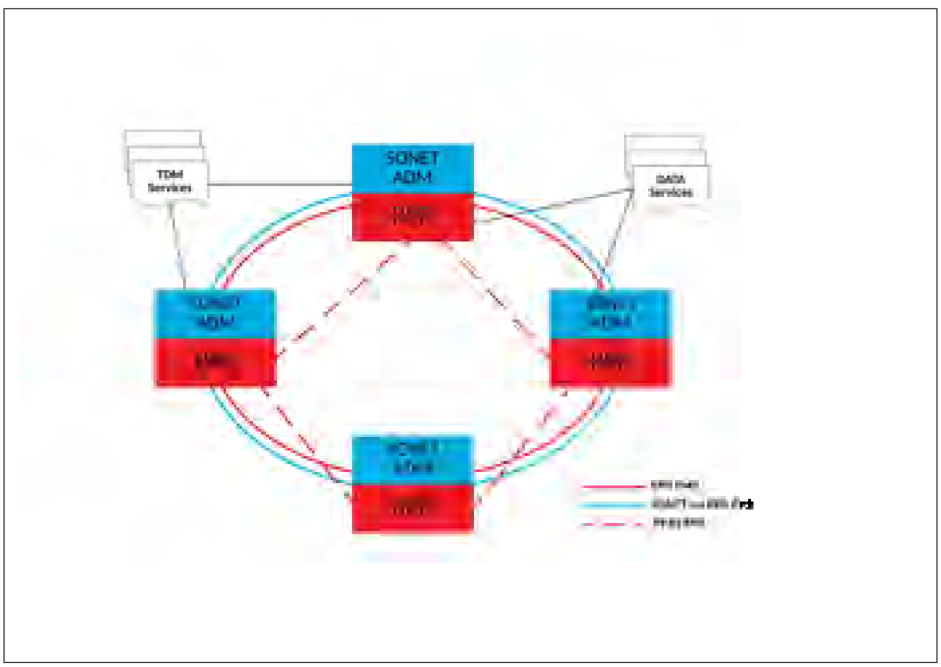

Figure 3.5 RPRoE frame format

As shown in Figure 3.6, when the first RPR frame at the user's side is sent to Ethernet E1 from device 3, the user's source MAC address R1 is learned from the RPR MAC address table of device 3. See Table 3.1.

Table 3.1 RPR MAC address

RPR MAC	**User VLAN**	**MAC address of destination**	**No. of hops to destination**
R1	1	Station device 1 (R1-MAC 1)	2
R2	1	Station device 2 (R1-MAC 2)	2
R3	1	Station device 6 (R2-MAC 1)	2
R4	1	Station device 5 (R2-MAC 3)	3
E1	1	Station device 3 (E1-MAC 1)	2
E2	1	Station device 4 (E1-MAC 2)	2

After the first frame of the user is send to the segment, it passes device 4 and then arrives at device 6. The user's source MAC address R1 is learned from the Ethernet MAC table of device 4. See Table 3.2.

Table 3.2 Ethernet MAC address

Ethernet MAC	**User VLAN**	**Egress port**
R1	1	Insert on RPR 1
R2	1	Insert on RPR 1
R3	1	Insert on RPR 2
R4	1	Insert on RPR 2
E1	1	Insert on E-MAC 3
E2	1	Insert on E-MAC 3

3.5.2 RPRoE Simulation

The Figure 3.6 shows how all the stations on the two irrelevant RPRoE segment learn MAC addresses. When a device accesses multiple Ethernet segments, the device must learn from its RPR MAC address table which Ethernet segment has the insert port that is mapped to the MAC address of user.

In the RPRoE network, the RPR MAC table of any transit station does not learn the user MAC address of traffic between other stations.

In this simulation, we attached almost the entire online workstations and servers to the RPR rings and we kept the batch servers, the file servers, and the reporting servers in the Ethernet segment. Doing that; we divided the load in two categories: the heavy load and the light load. Normally the heavy loads (batch process, reporting, and the file transfer) are used during the night so there is no major impact on the users. The light loads are all the servers and workstations used during the day time. So, the users need speed, bandwidth, and fast recovery.

This kind of topology (RPRoE) gives the customer the possibility to create a NLL2N, and to have a huge layer two network, with no impact on the performance. Figure 3.6 clearly shows that we have a better performance with this topology configuration. Figure 3.7 shows the performance of the end to end link without splitting the load. We see that we have the maximum output higher than the maximum input. The same goes with the average maximum output and maximum input. This behavior is due to the fact that all the servers and workstations were attached without any consideration of their load and their utilities. However, in the Figure 3.8, we have the opposite effect and this is due to the fact that having the load divided and using NLL2N, we can have that behavior with a better performance. The maximum input was higher and the maximum output is smaller. This behavior is due to the fact that splitting the load in two categories (heavy and light load) maximizes the maximum input load and minimizes the output load.

RPRoE scales as RPR and Ethernet and we can have the benefit of both. In addition, we proved that setting the layer 2 environments by load will help the business and ensure a better use of their bandwidth.

3.5.3 Advantages of RPRoE

According to our simulation and analysis, we understand that the RPRoE technique in a NLL2N has many advantages:

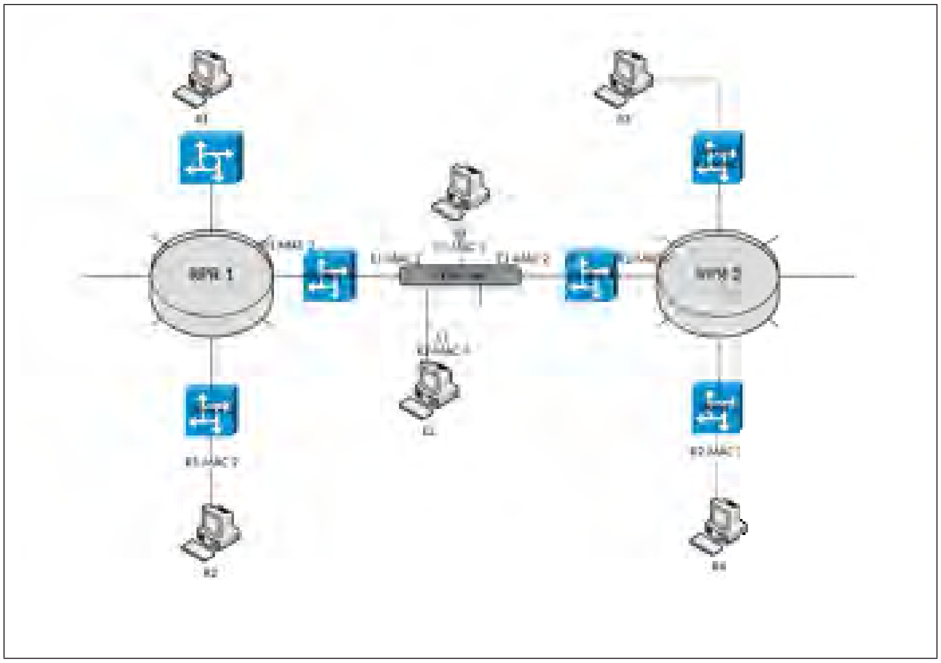

Figure 3.6 RPRoE simulation

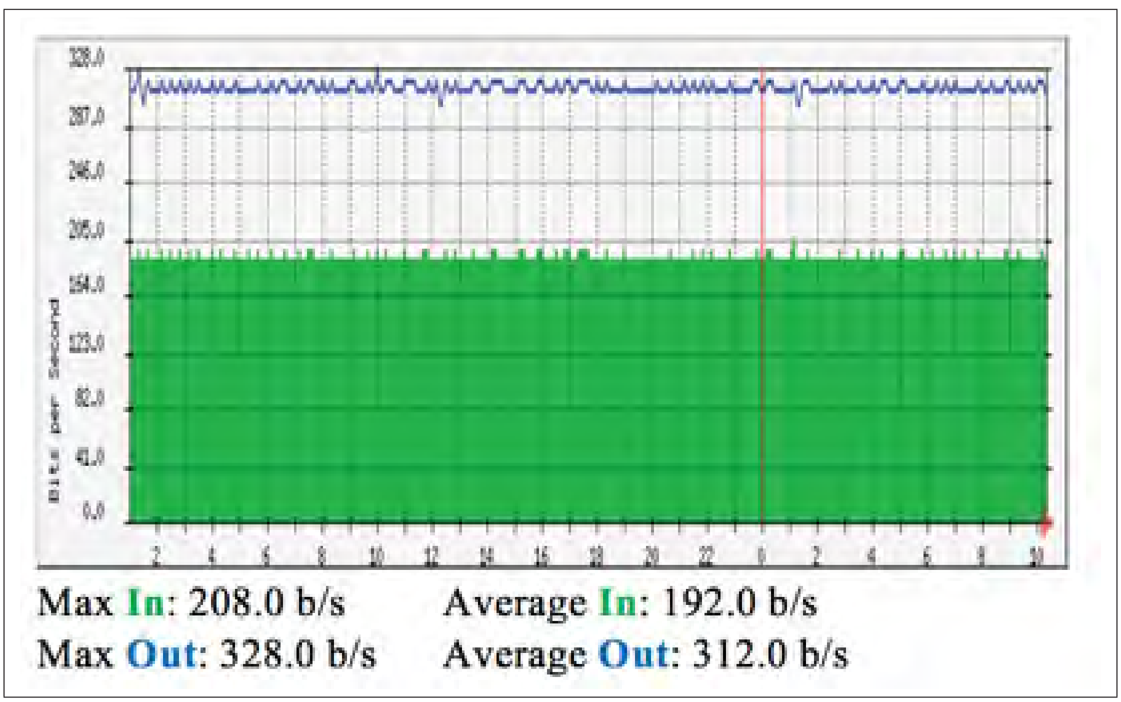

Figure 3.7 In/Out without using NLL2N

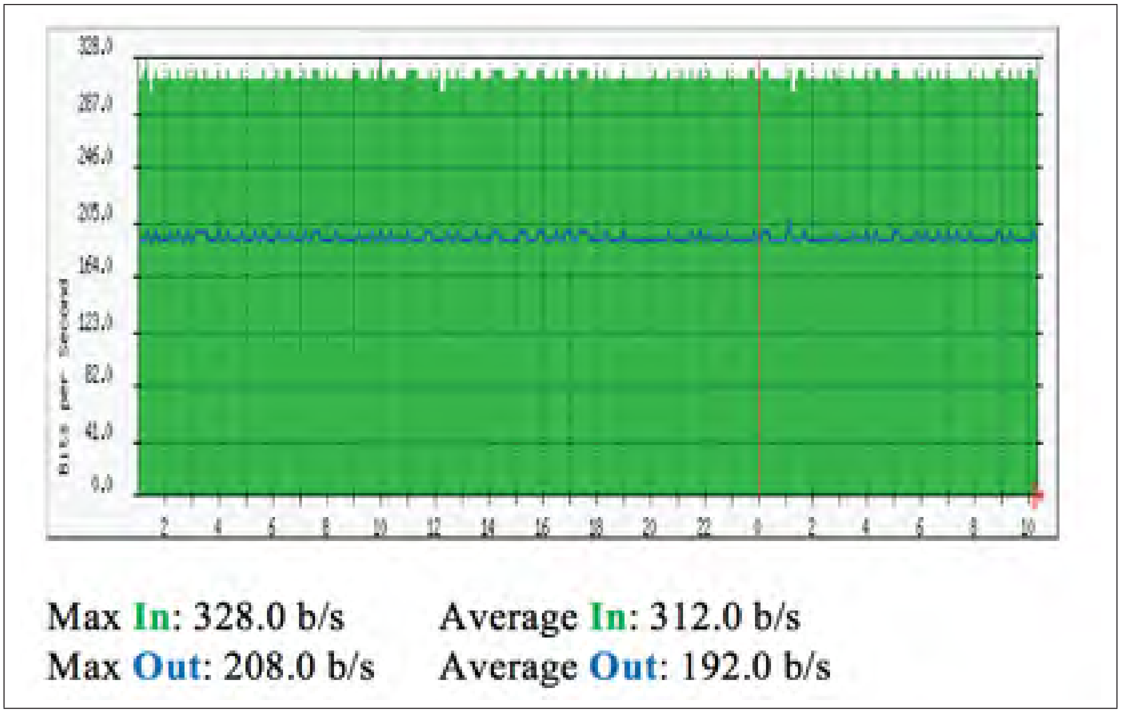

Figure 3.8 In/Out with NLL2N

a. Using the steering and the wrapping, RPRoE is still able to complete the protection switching less than 50 ms and make use of the full bandwidth;

b. Plug and play: In RPRoE solution, transit traffic is used as usual; RPR frame is transmitted transparently as an Ethernet frame. When we insert any new device to the Ethernet segment, there is no need to do anything. The same goes when we insert in RPR ring;

c. The two technologies use almost the same MAC address to identify the destination device. The transmission can bridge to any other Ethernet;

d. We had a good performance; our monitoring static shows that there is sometimes some latency, but this problem could be resolved by adding the Quality of Service (QoS);

e. Our Local Area Network (LAN) will be extended to a New Large Layer 2 Network (NLL2N).

3.6 Conclusion

This chapter shows us that we are able to create a NLL2N by combining different Layer 2 protocols, like RPR, Ethernet, and SONET. In this chapter, we focussed on RPRoE. By setting the server separations by functionalities in the company, we successfully identified and divided the load in two categories: Heavy and Light load. Doing that, we increase the Input speed and we decrease the output speed. We showed that we are able to combine RPR and Ethernet and create a New Large Layer 2 Network and made possible for a company to manage their infrastructure in a better way by implementing this kind of architecture. In our next chapter, we will investigate SONEToRPR.

CHAPTER 4

SONET OVER RPR

Ammar Hamad[1], Michel Kadoch[1]

[1] Department of Electrical Engineering, École de Technologie Supérieure
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K

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This chapter deals with the Synchronous Optical NETwork (SONET) and Resilient Packet Ring (RPR). The two protocols used the same layer (OSI Model) and often are used separately. In this chapter, we will demonstrate that SONET and RPR could be integrated together; we will explain and detail the use of SONET over RPR (SONEToRPR) with a simulation that shows the possibility to create a New Large Layer 2 Network and to point the benefits of it with a better performance.

4.1 Introduction

SONET over RPR (SONEToRPR) is an SONET transmission technology that carries SONET frames directly on the RPR link layer. This solution complies with the RPR specification frame by IEEE 802.17 [Needham and Herbert (1982)].

SONET has been implemented in LAN and MAN network and works adequately but, it has not been implemented or tested with a large Layer 2 (L2) network. The SONET rings (UPSR, BLSR) and RPR have few important similitudes:

- Support all SONET and RPR rates, and full concatenated payloads (*ie.g.,* OC48c) for data traffic and channelization for mixed data and TDM traffic;
- Protection switching at Layer 1 (Physical layer) or 2 (MAC layer);

- Co-existence of UPSR and RPR on the same ring;
- UPSR and BLSR interwork with RPR;
- To gain efficiency, SONET allows sharing paths for data among multiple nodes.

Our main objective of this chapter is to simulate SONEToRPR, point the benefits, and analyze the performance.

4.2 Fundamentals of SONET

4.2.1 Introduction to SONET

Synchronous Optical NETwork (SONET) and Synchronous Digital Hierarchy (SDH) are equivalent standards with minor differences. SONET is used widely in North American, and SDH is used in Europe and the rest of the world. For the purpose of this dissertation only SONET terminology is used and discussed. The overhead insertion mechanism, however, can be applied to both.

SONET was originally developed for the telephone network as a long-term solution for a mid-span-meet between vendors. The standard was proposed by Bell core and was established in 1984. SONET defines the rates and formats, the physical layer, network element architectural features, and network operational criteria for a fiber optic network. The standard soon becomes an excellent way for data communication as well, because it fits well in the physical layer of the OSI data network model.

4.2.2 Frame Structure

The basic SONET frame is as shown in Figure 4.1. This signal is known as Synchronous Transport Signal Level-1 (STS-1). It consists of 9 rows of 90 bytes *i.e.,* a total of 810 bytes. It is transmitted from left to right and top to bottom. The two dimensional figure is just for convenience. Actual transmission takes place serially *i.e.,* the left most byte in the top row is transmitted, then the second byte in the first row and so on. After the 90^{th} byte in the first row the left most byte in the second row is transmitted and it goes on. One more point to be noted is that msb is transmitted first and the numbering of bits in a byte is as shown in figure 4.2. The frame length is $125\mu s$ (*i.e.,* 8000 frames per second). The STS-1 has a bit rate of 51.84Mbps. The frame for the lowest SDH rate STM-1 contains 270 columns by 9 rows.

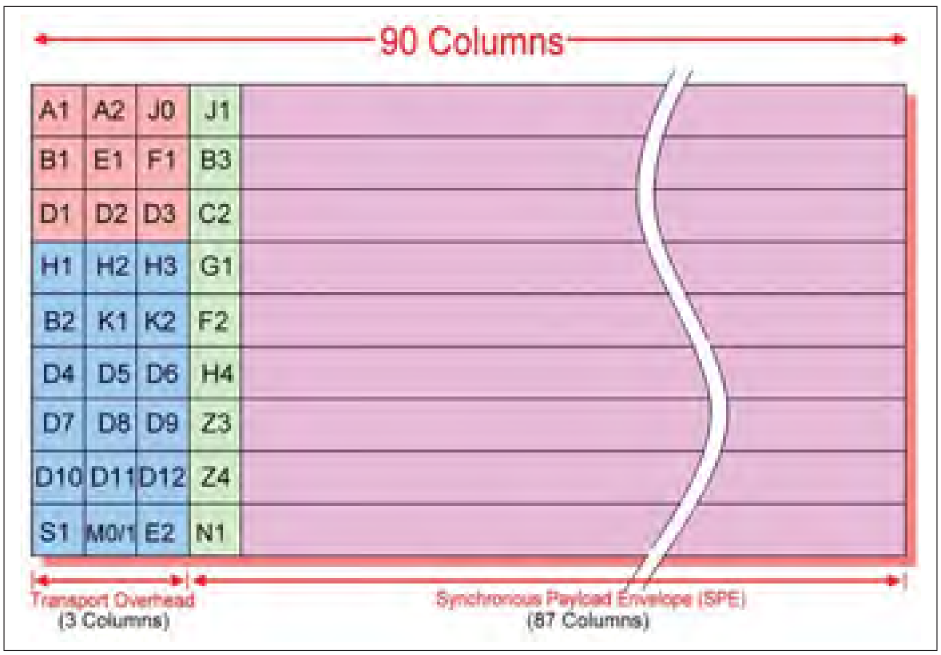


Figure 4.1 SONET frame
Taken from IEC, Prakash

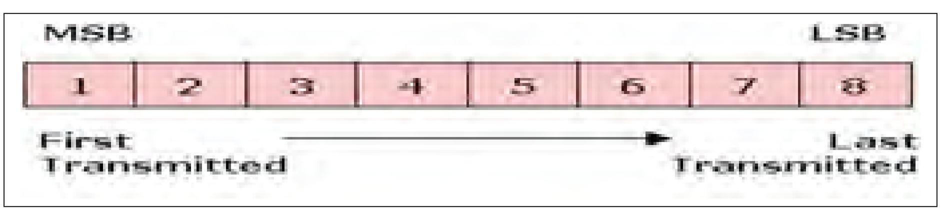


Figure 4.2 Order of byte transmission
Taken from IEC, Prakash

4.3 FUNDAMENTALS OF RPR

Resilient Packet Ring (RPR), which was standardized in 2004 as IEEE 802.17 RPR, is based on two counter-rotating fiber rings that carry data and control information [Davik *et al.* (2004), Spadaro *et al.* (2004)]. Packet ring-based data networks were pioneered by the Cambridge Ring [Needham and Herbert (1982)], and followed by other important network architectures. Rings are built using several point-to-point connections. When the connections between the stations are bidirectional, rings allow for resilience (a frame can reach its destination even in the presence of a link failure). Since RPR is being standardized in the IEEE 802 LAN/MAN families of network protocols, it can inherently bridge to other IEEE 802 networks and mimic a broadcast medium. RPR implements a MAC protocol for access to the shared ring communication medium that has a client interface similar to that of Ethernet's.

Furthermore, RPR uses the available ring bandwidth more efficiently than SONET/SDH by making use of destination stripping and shortest path routing both enabling spatial bandwidth reuse. With destination stripping, a packet sent along the ring from source node A to destination node B is removed from the ring by node B. The transmission of the packet only consumes bandwidth on the ring segment between node A and B as opposed to legacy ring systems that use source stripping where after passing its destination B the packet continues its travel around the ring until it reaches the source node A. Destination stripping has the advantage over source stripping that bandwidth is only consumed on the ring links between A and B so that other simultaneous transmissions can take place on the remaining links. In other words, destination stripping enables spatial reuse of the ring bandwidth by transmitting multiple packets simultaneously on different ring segments.

For uniform traffic destination stripping doubles the ring capacity compared to source stripping. The spatial reuse of the ring bandwidth is further increased by making use of shortest path routing. Since RPR is based on a bi-directional fiber ring a source node can choose the ring direction with the smallest hop distance to the destination node. Shortest path routing further reduces the average number of links used for a transmission between two nodes enabling even larger spatial reuse. For uniform traffic, shortest path routing doubles the capacity of a destination stripping ring compared to sending each packet randomly in either or all packets in the same direction. Figure 4.3 shows an example scenario where spatial reuse is obtained on the outer RPR fiber ring, whereby station 2 transmits to station 4 at the same time as station 6 transmits to station 9.

Every station on the ring has a buffer, called transit queue [Davik *et al.* (2004)], in which frames transiting the station may be temporarily queued. Each station acts according to two basic rules. The first rule is that the station may only start to add a packet if the transit queue is empty and there are no frames in transit. Second, if a transiting frame arrives after the station has started to add a frame, this transiting frame is temporarily stored (for as long as it takes to send the added frame) in the transit queue. Obviously, these two simple principles need some improvement to make up a full working protocol that distributes bandwidth fairly.

4.4 Station Design and Packet Priority

The stations on the RPR ring implement a MAC protocol that controls the stations' access to the ring communication medium. The MAC entity also implements access points which clients can call in order to send and receive frames and status information. RPR provides a three-level class-based traffic priority scheme. The objectives of the class based scheme are to let class A be a low-latency low-jitter class, class B be a class with predictable latency and jitter, and class C be a best effort transport class. It is worthwhile to note that the RPR ring does not discard frames to resolve congestion. Hence, when a frame has been added onto the ring, even if it is a class C frame, it will eventually arrive at its destination.

Class A traffic is divided into classes A0 and A1, and class B traffic is divided into classes B-CIR (committed information rate) and B-EIR (excess information rate). The two traffic classes C and B-EIR are called fairness eligible (FE), because such traffic is controlled by the fairness algorithm described in the next section. In order to fulfill the service guarantees for class A0, A1, and B-CIR traffic, bandwidth needed for these traffic classes is pre-allocated.

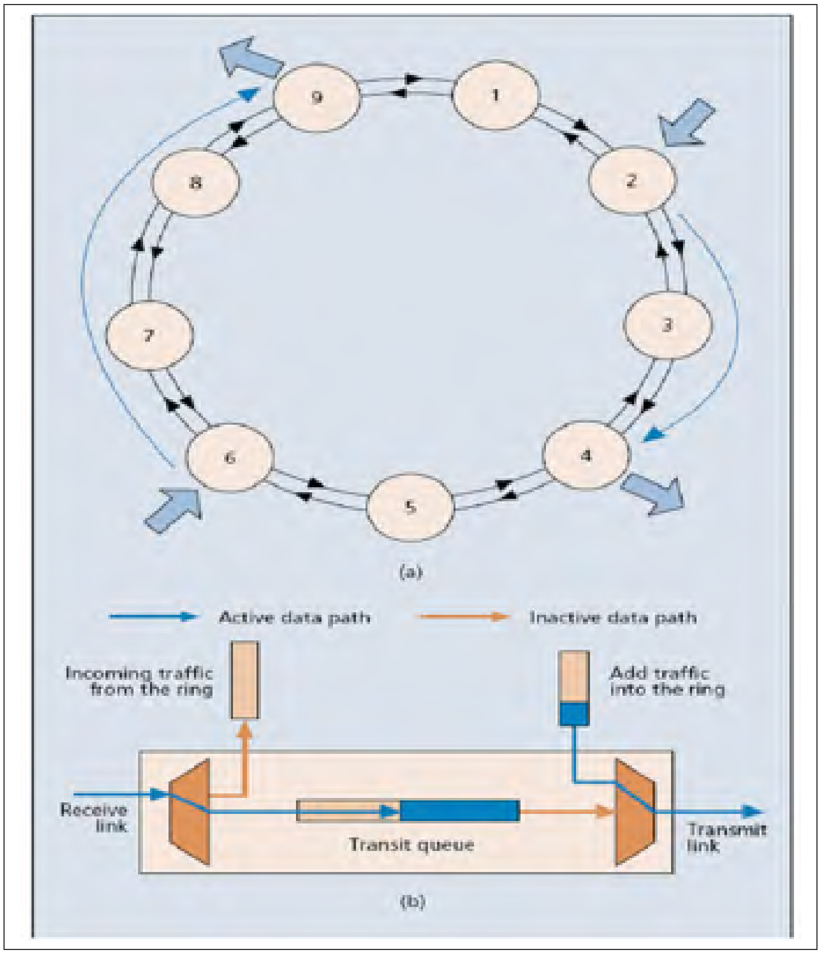


Figure 4.3 RPR network: a) destination stripping and spatial reuse; b) station's attachment to only one ringlet, showing the transit queue
Taken from Davik *et al.* (2004)

Bandwidth pre-allocated for class A0 traffic is called reserved and can only be utilized by the station holding the reservation. Bandwidth pre-allocated for class A1 and B-CIR traffic is called reclaimable. Reserved bandwidth not in use is wasted. Bandwidth not pre-allocated and reclaimable bandwidth not in use may be used to send FE traffic. A station's reservation of class A0 bandwidth is broadcast on the ring using topology messages (topology discovery is discussed later). Having received such topology messages from all other stations on the ring, every station calculates how much bandwidth to reserve for class A0 traffic. The remaining bandwidth, called unreserved rate, can be used for all other traffic classes. An RPR station implements several traffic shapers (for each ringlet) that limit and smooth add and transit traffic. There is one shaper for each of A0, A1, and B-CIR as well as one for FE traffic. There is also a shaper for all transmit traffic other than class A0 traffic, called the downstream shaper. The downstream shaper ensures that the total transmit traffic from a station, other than class A0 traffic, does not exceed the unreserved rate. The other shapers are used to limit the station's add traffic for the respective traffic classes. The shapers for classes A0, A1, and B-CIR are preconfigured; the downstream shaper is set to the unreserved rate, while the FE shaper is dynamically adjusted by the fairness algorithm. While a transit queue of one maximum transmission unit (MTU) is enough for buffering of frames in transit when the station adds a new frame into the ring, some flexibility for scheduling of frames from the add and transit paths can be obtained by increasing the size of the transit queue. For example, a station may add a frame even if the transit queue is not completely empty.

Also, a larger queue may store lower-priority transit frames while the station is adding high priority frames. The transit queue could have been specified as a priority queue, where frames with the highest priority are dispatched first. A simpler solution, adopted by RPR, is to optionally have two transit queues. Then high-priority transit frames (class A) are queued in the primary transit queue (PTQ), while class B and C frames are queued in the secondary transit queue (STQ). Forwarding from the PTQ has priority over the STQ and most types of add traffic. Hence, a class A frame traveling the ring will usually experience not much more than the propagation delay and some occasional transit delays waiting for outgoing packets to completely leave the station (RPR does not support preemption of packets). Figure 4.4 [Davik *et al.* (2004)] shows one ring interface with three add queues and two transit queues. The numbers in the circles indicate a crude priority on the transmit link. An RPR ring may consist of both one- and two-transit-queue stations. The rules for adding and scheduling traffic are local to the station, and the fairness algorithm described below works for both station designs.

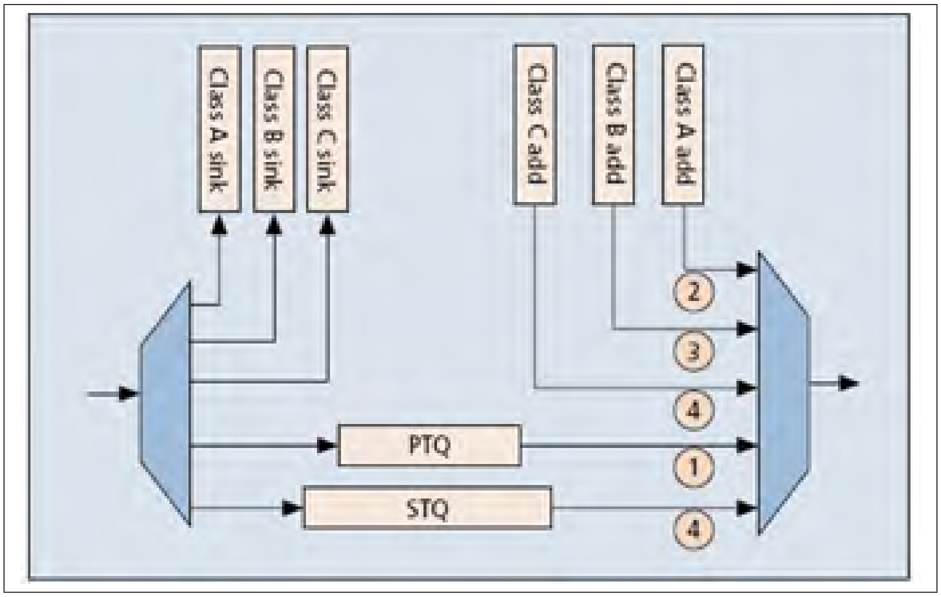


Figure 4.4 The attachment to one ring by a dual-transit-station
Taken from Davik *et al.* (2004)

4.5 Basic Principles of SONET Over RPR

SONET over RPR (SONEToRPR) is an SONET transmission technology that carries SONET frames directly on the RPR link layer. The physical path SONET connections are used by RPR boxes. This solution complies with the RPR specification frame by IEEE 802.17. Figure 4.5 shows the SONEToRPR encapsulation format.

a. All the devices on the SONET ring or on the RPR ring are plug-and play nature;

b. New stations added to the SONET ring or on the RPR ring do not affect the existing traffic;

c. With SONET over RPR technology, all the transit packets are forwarded according to SONET header;

d. Transit stations do not learn any RPR MAC;

e. Co-exiting of SONET rings, UPSR and BLSR, and RPR;

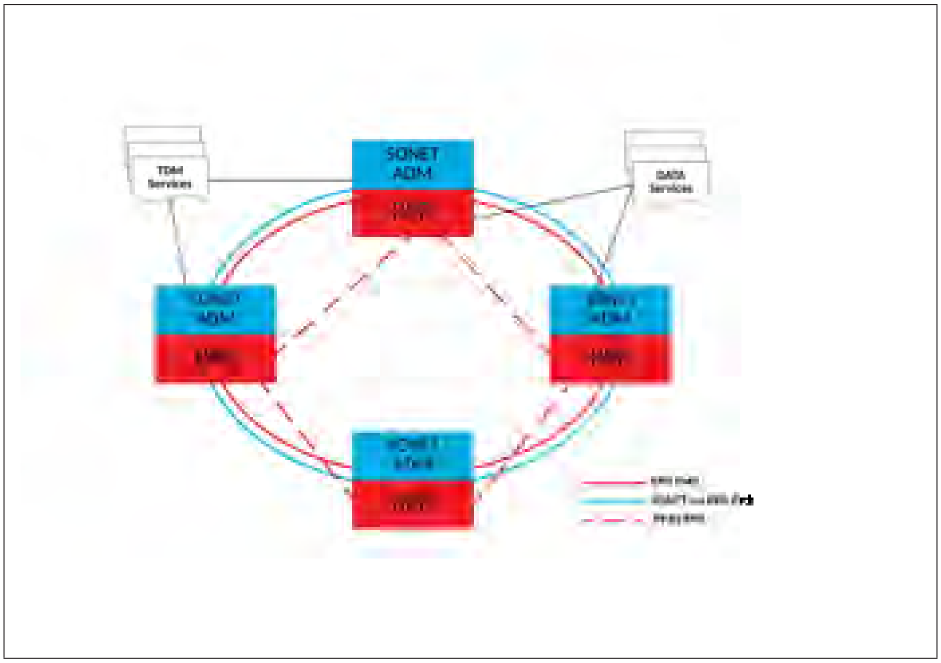


Figure 4.5   SONEToRPR frame format

f. UPSR and BLSR interwork with RPR;

g. To gain efficiency, SONET allows sharing paths for data among multiple nodes.

When a frame is inserted to SONET, RPR frames are encapsulated in SONET data frame for forwarding on the SONET segment. In a copy operation, the RPR headers are stripped off and only SONET frames are forwarded. By disabling the SONET ring protection, we can interperate SONET and RPR and resiliency becomes a suitable solution. But, the SONET and RPR protection will not work together.

4.5.1 Goals for SONET over RPR

Having SONEToRPR, we support TDM traffic and we are still supporting packet optimization. SONEToRPR supports all RPR rates: STM-1/OC-3, STM-4/OC-12, STM-16/OC-48, and STM-64/OC-192. It also supports full concatenated payloads (*ie.g.,* STM-16) for channelization for mixed data and TDM traffic and data traffic.

The protection switching is at MAC layer or Layer 1. Figure 4.6 shows SONET and RPR using the same ring. Like we said before by disabling the SONET ring protection, we can interperate SONEToRPR using the RPR resiliency. But, SONET and RPR protection will not work together.

So, SONEToRPR helps to share and use the same paths for data traffic among multiple nodes on a ring to gain efficiency.

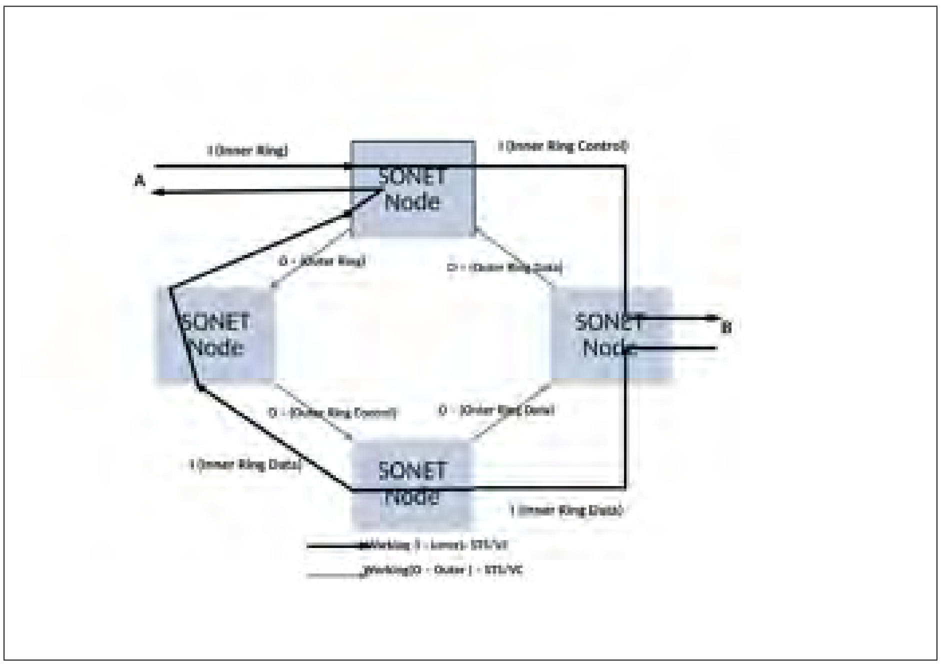


Figure 4.6 SONEToRPR frame format

4.5.2 SONEToRPR Simulation

Figure 4.7 shows how all the nodes on the SONEToRPR set and work. Two categories of node are used: one was set to receive and send TDM and Data traffic; the other was set receive and send TDM traffic only.

The first category of node has two switches: a TDM switch manages the entire SONET traffic and the RPR switch manages RPR Data traffic. The second category node is used to receive or drop only TDM traffic.

In this simulation, we are using the two RPR rings (Outer ring and Inner ring). The network transport will be under RPR which makes the transport more efficient than TDM transport such as SONET. With this unique advantage delivery efficient data transport and resiliency, SONEToRPR becomes a suitable solution to build a New Large Layer 2 Network (NLL2N).

This kind of topology (SONEToRPR) gives to the customer the possibility to create a NLL2N. We got a better use of the bandwidth with less latency and no impact on performance (See Figure 4.10). Figure 4.9 shows that SONET without RPR perform a little less with a high latency.

This behavior is due to the fact that the layer two back-end is RPR, so all the bandwidth in the two rings are used. If we analyze our load and adequately set the different nodes while taking into consideration the quality of service, the outcome is a better performance.

SONEToRPR has the ability to protect the network from single span failures. Figure 4.8 shows who the ring protection works when a failure occurs. As soon as the failure happen a protection messages are sent and RPR use his two mechanisms:

- Wrapping – Nodes neighboring the failed span will direct packets away from the failure by wrapping traffic around the other fiber (ringlet).
- Steering – The protection mechanism notifies all nodes on the ring of the failure span. Every node on the ring will adjust their topology maps to avoid this span. Regardless of the protection used, the ring will be protected within 50ms.

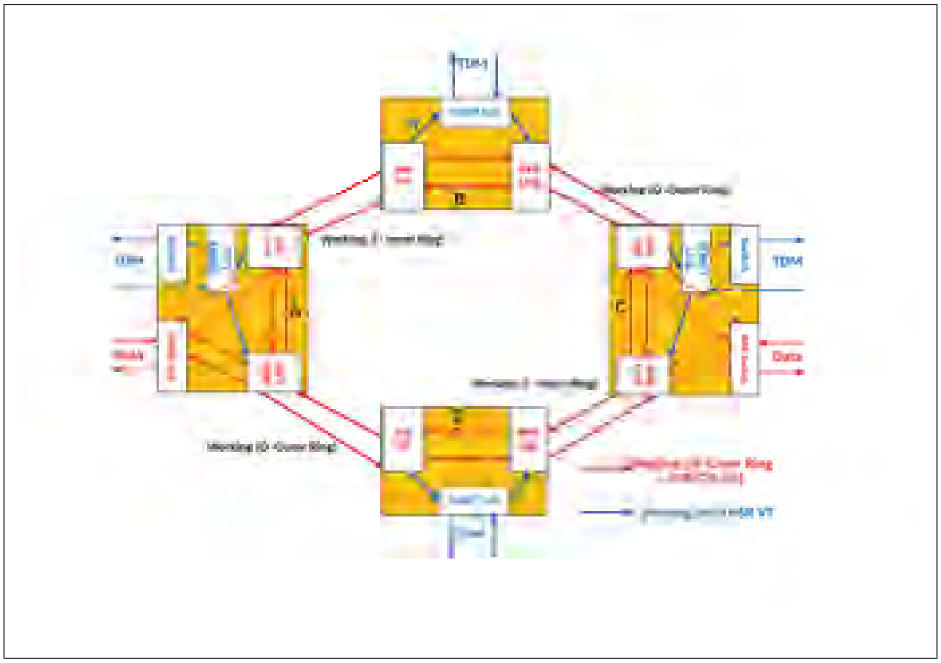


Figure 4.7   SONEToRPR simulations

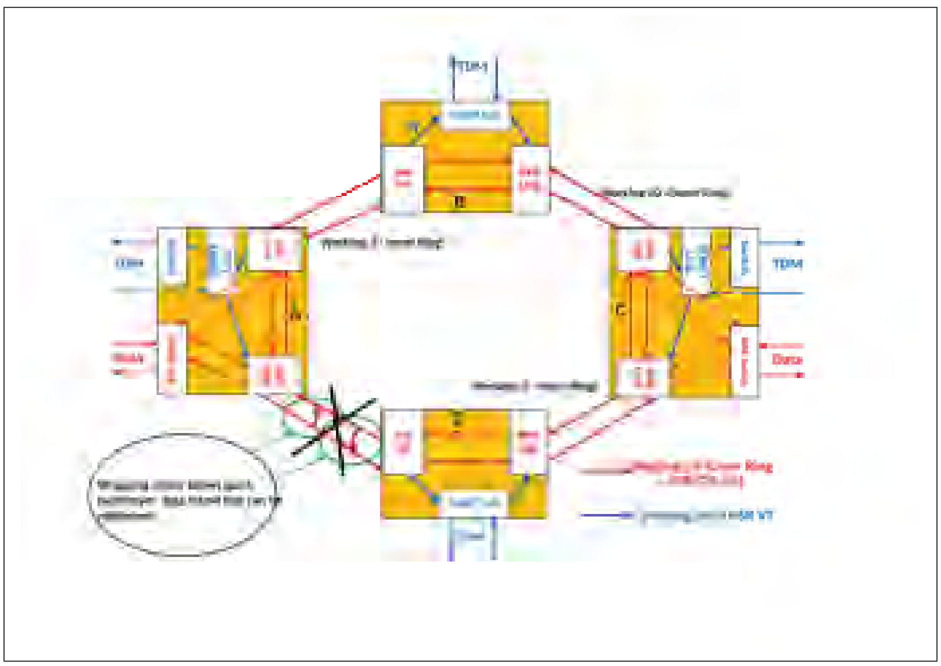
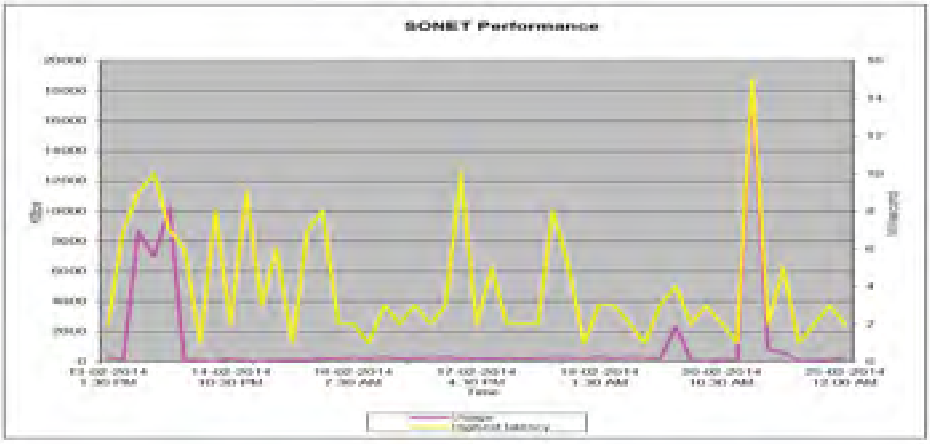
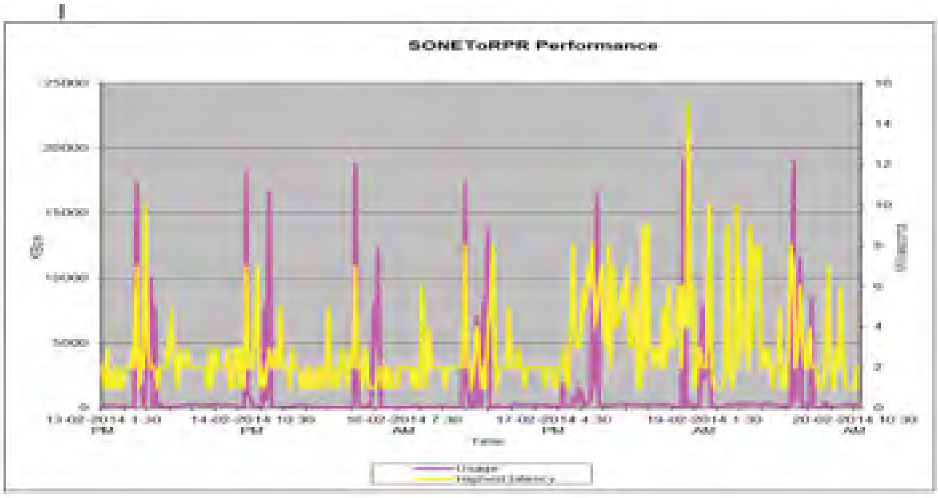


Figure 4.8   SONEToRPR simulations



	Maximum	Minimum	Average
Usage (KBps)	18393	50	1139.551
Highest Latency (ms)	15	1	3.980

Figure 4.9 In/Out without NLL2N



	Maximum	Minimum	Average
Usage (KBps)	19104	55	1113.643
Highest Latency (ms)	15	1	2.793

Figure 4.10 In/Out using NLL2N

4.5.3 Advantages of SONEToRPR

According to our simulation and analysis, we understand that the SONEToRPR technique in a NLL2N has many advantages:

a. Using the steering and the wrapping, SONEToRPR is still able to complete the protection, switching less than 50ms and making use of the full bandwidth;

b. Plug and play: In SONEToRPR solution, transit traffic is used as usual; SONET frame is transmitted transparently as an RPR frame. When we insert any new device to the SONET segment, there is no need to do anything. The same is true when we insert in RPR ring;

c. SONEToRPR uses the available ring bandwidth more efficiently than SONET alone;

d. Due that the two technologies that used almost the same MAC address to identify the destination device. The transmission can bridge to any other RPR;

e. We had a good performance; our monitoring static shows that sometimes there is some latency. But this problem could be resolved by adding the Quality of Service (QoS);

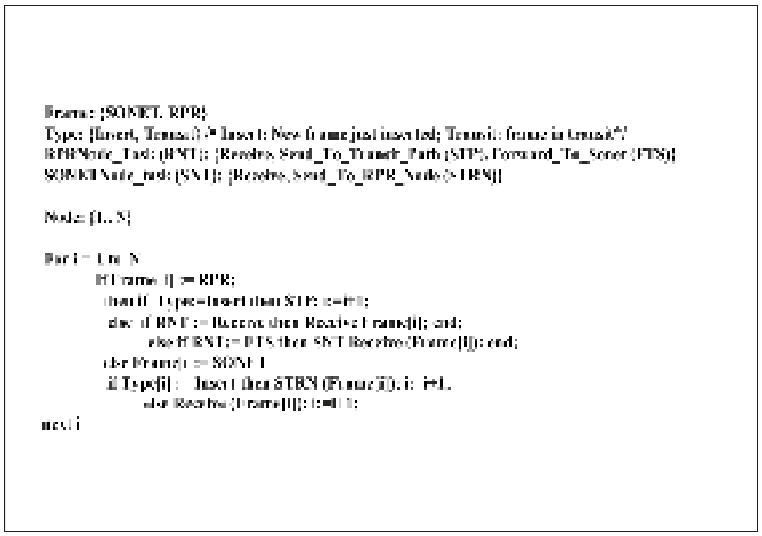
f. SONEToRPR uses destination stripping, which double the ring capacity compared to source stripping;

g. Having put in place this kind of topology, we extended our Local Area Network (LAN) to a large layer 2 network that we named: New Large Layer 2 Network (NLL2N).

4.5.4 Performance analysis of SONEToRPR

In our research, we used RPR as a transporter; however the destination stripping was used. We demonstrated, mathematically, that serving the entire ring in a linear manner gave a better performance; however, the time complexity is O(n). Let's see how SONEToRPR algorithm works.

- Each frame is SONET or RPR;
- We have two types of frame: in inserted mode and in transit mode;
- SONET node has two functionalities: Receive and/or send the frame from the user or from RPR node.



```
Frame: {SONET, RPR}
Type: {Insert, Transit} /* Insert: New frame just inserted; Transit: frame in transit*/
RPRNode_Task: (RNT): {Receive, Send_To_Transit_Path (STP), Forward_To_Sonet (FTS)}
SONETNode_task: (SNT): {Receive, Send_To_RPR_Node (STRN)}

Node: {1..N}

For i = 1 to N
        If Frame[i] := RPR;
          then if Type=Insert then STP; i=i+1;
           else if RNT := Receive then Receive Frame[i]; end;
                 else if RNT := FTS then SNT Receive(Frame[i]); end;
          else Frame[i] := SONET
           if Type[i] := Insert then STRN (Frame[i]); i := i+1;
                else Receive (Frame[i]); i:=i+1;
next i
```

Figure 4.11   How SONEToRPR algorithm works

4.6 Conclusion

This chapter shows us that we are able to create a New Large Layer 2 Network (NLL2N) by the combination of different Layer 2 protocols, as SONET, RPR, and Ethernet. In this chapter we did focus on SONEToRPR; by using RPR rings as a transporter we automatically used the destination stripping and we did gain efficiency. We reduced the latency and we increased the bandwidth usage. We did show that we are able to combine SONET and RPR to create a New Large Layer 2 Network and give the possibility to a company to manage their infrastructure in a better way by implementing this kind of architecture. In our next chapter, we will investigate the combination of SONET, RPR, and Ethernet.

CHAPTER 5

SONET OVER ETHERNET

Ammar Hamad[1], Michel Kadoch[1]

[1] Department of Electrical Engineering, École de Technologie Supérieure
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

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Today's common and extensively used MAC layers are SONET and Ethernet. They serve different networks and are incompatible. It is however necessary to interface the two networks since they may be part of the route used by data. This chapter integrates SONET over Ethernet creating thus compatibility between these two protocols without going through unnecessary conversions. Through simulation it is shown that this New Layer 2 Network improves the performance and brings added benefits.

5.1 Introduction

SONET over Ethernet (SONEToE) is an SONET transmission technology that carries SONET frames directly on the Ethernet link layer. This solution complies with the Ethernet specification frame by IEEE 802.3 [Davik *et al.* (2004)].

SONET has been implemented in LAN and MAN network and works adequately but, it has not been implemented or tested with a large Layer 2 (L2) network. The challenge in this chapter is to merge the two protocols (SONET and Ethernet) and make them work as a one layer 2 protocol. The methodology that will be used is to encapsulate SONET frame in Ethernet data frame. The method will be simulated and tested in a laboratory. The load of the link and the Input/Output of the data transmitted will be analyzed. Having SONET rings attached directly to Ethernet will be an interesting way to help business to set their layer 2 environments adequately and reduce their daily load and cost.

5.2 Fundamentals of SONET

5.2.1 Introduction to SONET

Synchronous Optical NETwork (SONET) and Synchronous Digital Hierarchy (SDH) are equivalent standards with minor differences [IEC]. SONET is used widely in North American, and SDH is used in Europe and the rest of the world. For the purpose of this dissertation only SONET terminology is used and discussed. The overhead insertion mechanism, however, can be applied to both. SONET was originally developed for the telephone network as a long-term solution for a mid-span-meet between vendors. The standard was proposed by Bell core and was established in 1984. SONET defines the rates and formats, the physical layer, network element architectural features, and network operational criteria for a fiber optic network. The standard soon becomes an excellent way for data communication as well, because it fits well in the physical layer of the OSI data network model.

5.2.2 Frame Structure

The basic SONET frame is as shown in Figure 5.1 [Prakash]. This signal is known as Synchronous Transport Signal Level-1 (STS-1). It consists of 9 rows of 90 bytes *i.e.,* a total of 810 bytes. It is transmitted from left to right and top to bottom. The two dimensional figure is just for convenience. Actual transmission takes place serially *i.e.,* the left most byte in the top row is transmitted, then the second byte in the first row and so on. After the 90$^{\text{th}}$ byte in the first row the left most byte in the second row is transmitted and it goes on. One more point to be noted is that msb is transmitted first and the numbering of bits in a byte is as shown in Figure 5.2. The frame length is 125μs (*i.e.,* 8000 frames per second). The STS-1 has a bit rate of 51.84Mbps. The frame for the lowest SDH rate STM-1 contains 270 columns by 9 rows.

5.2.3 SONET Multiplexing

The multiplexing principles of SONET are as follows:

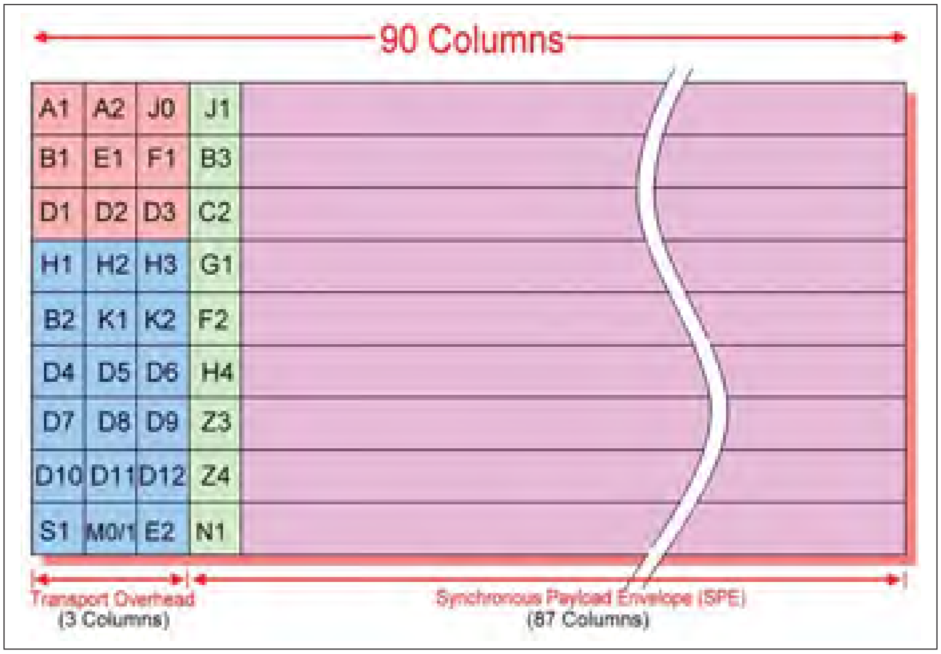


Figure 5.1 SONET frame
Taken from IEC, Prakash

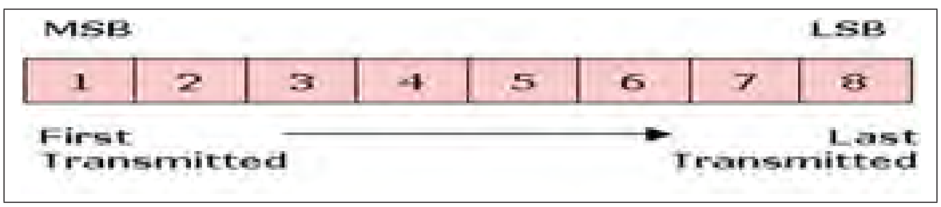


Figure 5.2 Order of byte transmission
Taken from IEC, Prakash

- Mapping – used when tributaries are adopted into virtual tributary (VTs) by adding justification bits and path overhead (POH) information;
- Aligning – takes place when a pointer is included in the (STS) path or VT POH, to allow the first byte of the VT to be located;
- Multiplexing – used when multiple lower order path-layer signals are adapted into higher-order path signals are adapted into the line overhead;

- Stuffing – SONET has the ability to handle various input tributary rates from asynchronous signals; as the tributary signals are multiplexed and aligned; some spare capacity has been designed into the SONET frame to provide enough space for all these various tributary rates.

Figure 4.3 illustrates the basic multiplexing structure of SONET. Any type of service, ranging from voice to high-speed data and video, can be accepted by various types of service adapters. New services and signals can be transported by adding new service adapters at the edge of the SONET network. Except for concatenated signals, all inputs are eventually converted to a base format of a synchronous STS-1 signal (51.84 $^{Mb}/_{s}$ or higher).

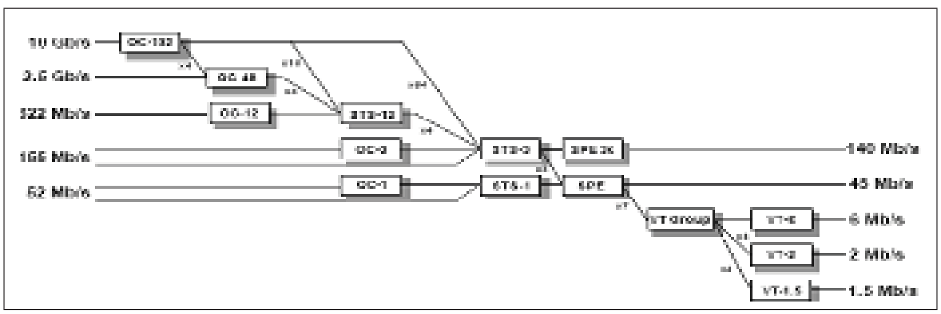


Figure 5.3 SONET multiplexing hierarchy
Taken from IEC

5.3 Fundamentals of Gigabit Ethernet

Invented by Dr. Robert Metcalf and pioneered by Intel, Digital and Xerox, Ethernet has become the most commonly used LAN technology worldwide. More than 85% of all installed network connections are Ethernet, according to International Data Corporation (IDC, 2000). As a transport protocol, Ethernet operates at Layers 1 and 2 of the 7-layer OSI networking model, delivering its data packets to any device connected to the network cable. IT managers have found that Ethernet is simple, easy to use and readily upgradeable. An organization can scale from 10 to 100 or 1000Mbps Ethernet, either network-wide or a segment at a time, knowing that the new equipment will be backwards compatible with legacy equipment. This reduces the infrastructure investment that an organization must make. Ethernet is also a reliable technology. Experience shows that it can be deployed with confidence for mission-critical applications.

5.3.1 Standard evolution

In the last several years, the demand on the network has increased drastically. The old 10BASE5 and 10BASE2 Ethernet networks were replaced by 10BASE-T hubs, allowing for greater manageability of the network and the cable plant. As applications increased the demand on the network, newer, high-speed protocols such as FDDI and ATM became available. However, Fast Ethernet became the backbone of choice because its simplicity and its reliance on Ethernet. The primary goal of Gigabit Ethernet was to build on that topology and knowledge base in order to build a higher-speed protocol without forcing customers to throw away existing networking equipment. The standards body that worked on Gigabit Ethernet was the IEEE 803.2z Task Force. The possibility of a Gigabit Ethernet Standard was raised in mid-1995 after the final ratification of the Fast Ethernet Standard. By November 1995 there was enough interest to form a high-speed study group. This group met at the end of 1995 and several times during early 1996 to study the feasibility of Gigabit Ethernet.

The meetings grew in attendance, reaching 150 to 200 individuals. Numerous technical contributions were offered and evaluated. In July 1996, the 802.3z Task Force was established with the charter to develop a standard for Gigabit Ethernet. Basic concept agreement on technical contributions for the standard was achieved at the November 1996 IEEE meeting. The first draft of the standard was produced and reviewed in January 1997; the final standard was approved in June 1998.

5.3.2 Gigabit Ethernet Protocol Architecture

In order to accelerate speeds from 100 Mbps Fast Ethernet up to 1 Gbps, several changes need to be made to the physical interface. It has been decided that Gigabit Ethernet will look identical to Ethernet from the data link layer upward. The challenges involved in accelerating to 1 Gbps have been resolved by merging two technologies together: IEEE 802.3 Ethernet and ANSI X3T11 Fibre Channel. Figure 5.4 shows how key components from each technology have been leveraged to form Gigabit Ethernet.

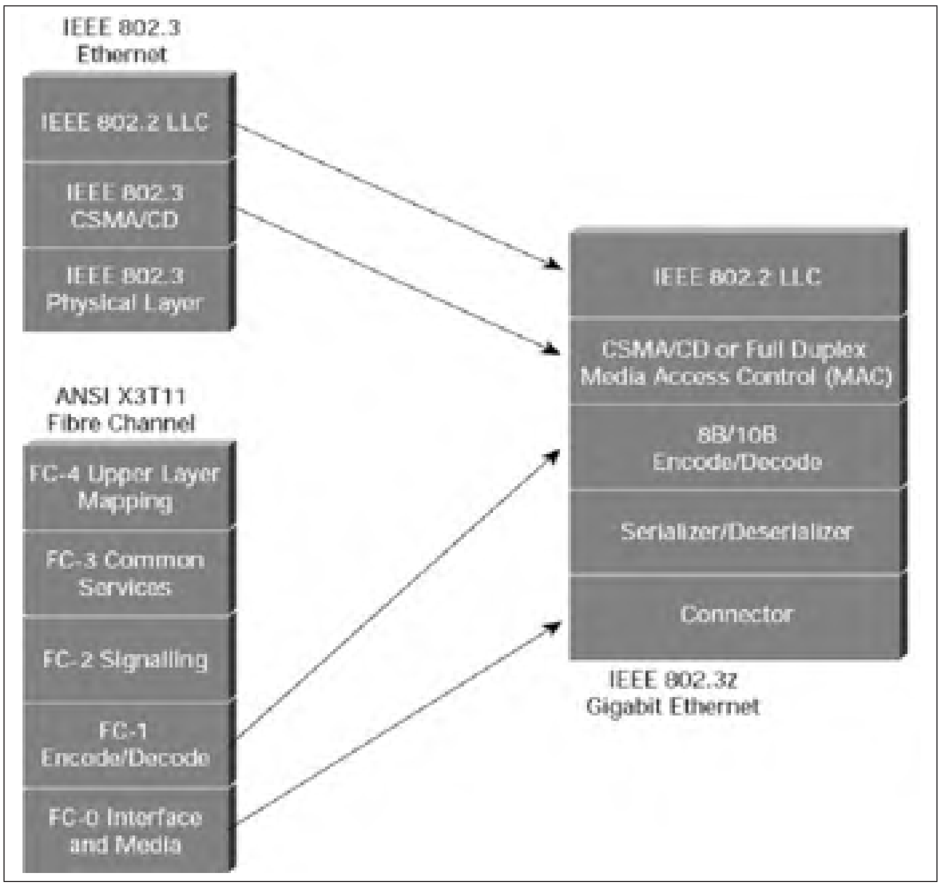


Figure 5.4 Gigabit Ethernet Protocol Stack
Taken from Davik *et al.* (2004)

Leveraging these two technologies means that the standard can take advantage of the existing high-speed physical interface technology of Fibre Channel while maintaining the IEEE 802.3 Ethernet frame format, backward compatibility for installed media, and use of full- or half-duplex carrier sense multiple access collision detect (CSMA/CD). This scenario helps minimize the technology complexity, resulting in a stable technology that can be quickly developed.

5.4 Basic Principles of SONET Over Ethernet

SONET over Ethernet (SONEToE) is a SONET transmission technology that carries SONET frames directly on the Ethernet link layer. This solution complies with the Ethernet specification frame by IEEE 802.3. Figure 5.5 shows the SONEToE encapsulation format.

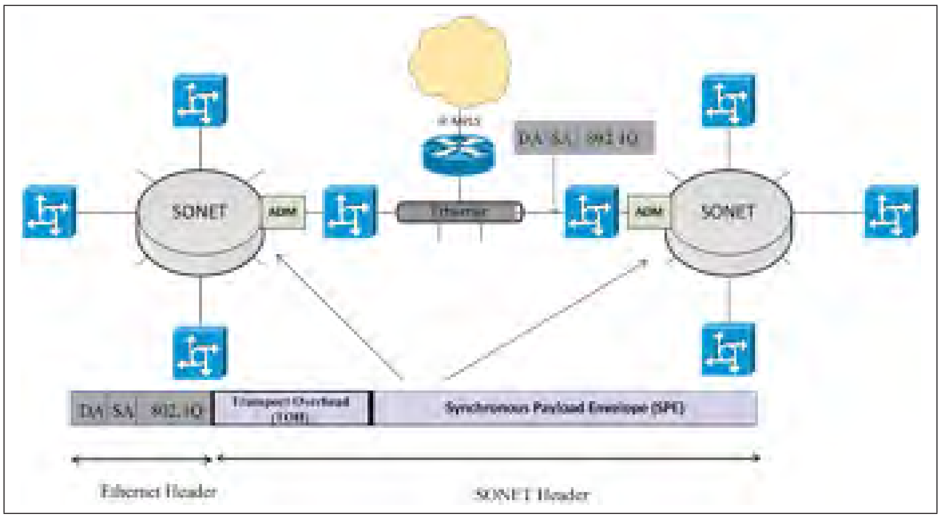


Figure 5.5 SONEToE frame format

a. All the devices on the SONET ring or on the Ethernet segment are plug-and-play nature;

b. New stations added to the SONET ring or on the Ethernet segment do not affect the existing traffic;

c. With SONET over Ethernet technology, all the transit packets are forwarded according to SONET header;

d. Transit stations do not learn any Ethernet MAC;

e. UPSR and BLSR interwork with Ethernet;

f. To gain efficiency, SONET allows sharing paths for data among multiple nodes.

When a frame is inserted to SONET, Ethernet frames are encapsulated in SONET data frame for forwarding on the SONET segment. In a copy operation, the Ethernet headers are stripped off and only SONET frames are forwarded.

5.4.1 Address learning of SONET over Ethernet

A device is logically divided into two parts. One part is at the SONET side to deal with SONET switching. The other part is at the Ethernet side to process SONEToE. When the SONET part receives a frame, it determines, according to the destination MAC address, the Ethernet segment that the frame will send to and use the right circuit STS to insert the packet. The RPRoE part finds the destination Ethernet MAC address and the number of hops based on the user MAC address. It encapsulates the Ethernet frame header and then sends the frame to the Ethernet interface.

When receiving a RPRoE data frame from Ethernet interface, the device will send it to the right circuit. The device will learn the source SONET MAC address and the Ethernet MAC address of the source Ethernet station.

Ethernet station keeps two MAC tables. One is at the SONET side recording the mapping between user MAC addresses and SONET egress paths. The other is at the Ethernet side for recording the mapping between user MAC addresses and destination Ethernet stations. See Figure 5.6 to follow the forwarding process.

5.4.2 SONEToE Simulation

Figure 5.7 shows how all the nodes on the SONEToE set and work. Two categories of node are used: one was set to receive and send TDM and Data traffic; the other was set receive and send TDM traffic only.

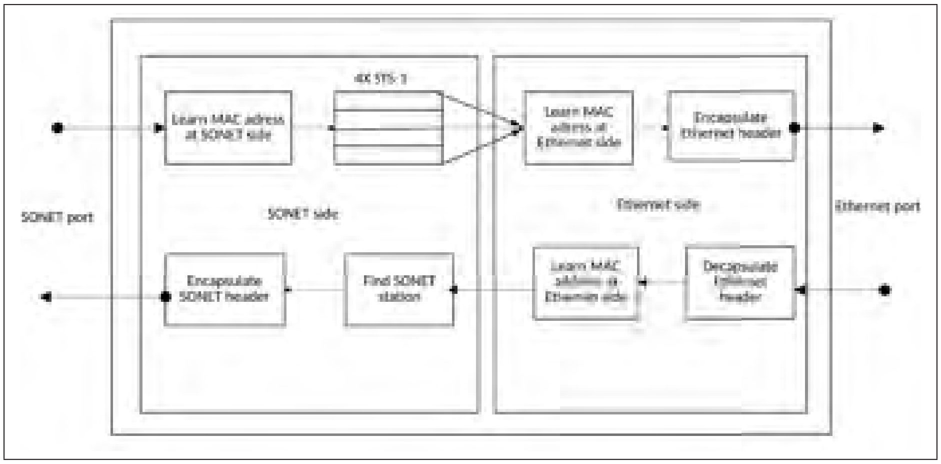


Figure 5.6   SONEToE frame format

The first category of node has two switches: a TDM switch manages the entire SONET traffic and the Ethernet switch manages Ethernet Data traffic. The second category node is used to receive or drop only TDM traffic.

In this simulation the network transport will be under Ethernet which makes the transport more efficient than TDM transport such as SONET. With this unique advantage delivery efficient data transport and resiliency, SONEToE becomes a suitable solution to build a New Large Layer 2 Network (NLL2N).

This kind of topology (SONEToE) gives the customer the possibility of creating a NLL2N. We got a better use of the bandwidth and a better performance (See Figure 5.9). Figure 5.8 shows that SONET without Ethernet perform less because the bandwidth efficiency is rigid and useless.

This behavior is due to the fact that the layer one backend is SONET, so only 50% of the bandwidth is used. Each application uses a dedicated bandwidth on SONET compared to Ethernet the bandwidth was shared.

SONEToE has the ability to protect the network from single span failures. As soon as the failure happens a protection message is sent and SONET starts use the second ring. Regardless of the protection used, the ring will be protected within 50 ms.

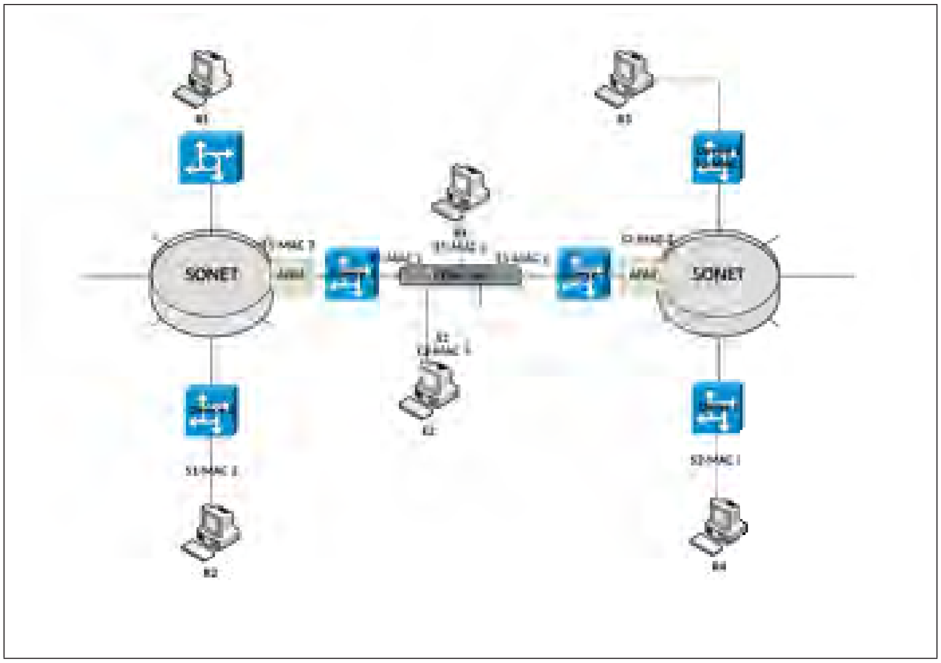


Figure 5.7   SONEToE

5.4.3 Advantages of SONEToE

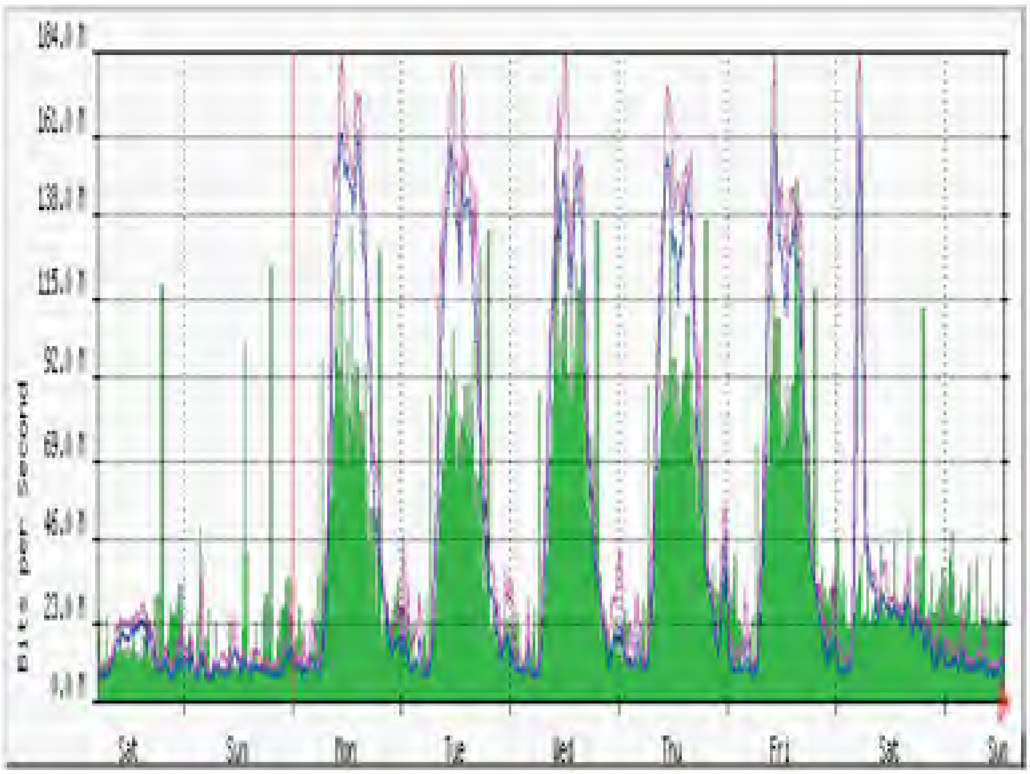
According to the simulation and analysis, we understand that the SONEToE technique in a NLL2N has many advantages:

a. In case of failure, SONEToE is still able to complete the protection, switching less than 50 ms;

b. Plug-and-play: In SONEToE solution, transit traffic is used as usual; SONET frame is transmitted transparently as an Ethernet frame. When we insert any new device to the SONET segment, there is no need to do anything. The same is true when we insert in Ethernet segment;

c. SONEToE uses the available ring bandwidth more efficiently than SONET alone;

d. Ethernet was designed for data transport and SONET for voice, so having them together will double the benefit;



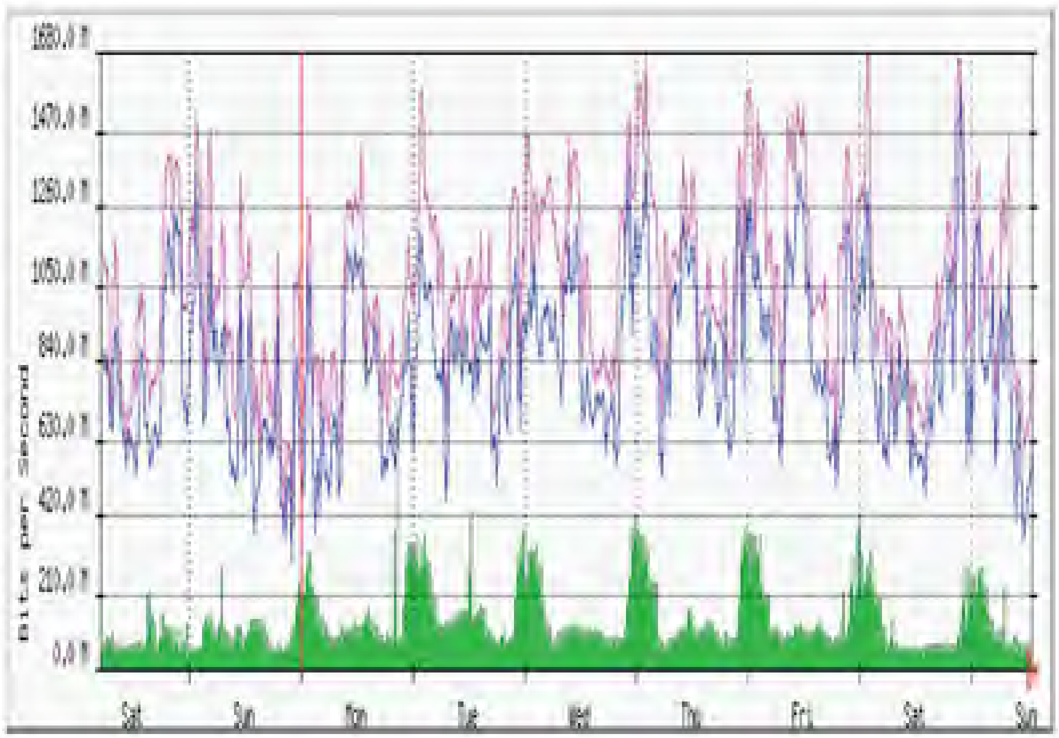
	Max	Average	Current
In	157.5 Mb/s (78.7%)	33.2 Mb/s (16.6%)	25.7 Mb/s (12.8%)
Out	183.6 Mb/s (91.8%)	42.8 Mb/s (21.4%)	9040.2 kb/s (4.5%)

Figure 5.8 In/Out without NLL2N

e. SONEToE had a good performance and the bandwidth efficiently used because Ethernet will be used in the transport layer;

f. Using Ethernet as transporter will increase overall bandwidth efficiency. The Quality of Service (QoS) will be used on the SONET side;

g. Having put in place this kind of topology, we extended our Local Area Network (LAN) to a large layer 2 network that we named: New Large Layer 2 Network (NLL2N).



	Max	Average	Current
In	734.2 Mb/s (7.3%)	103.8 Mb/s (1.0%)	31.5 Mb/s (0.3%)
Out	1678.5 Mb/s (16.8%)	824.4 Mb/s (8.2%)	601.5 Mb/s (6.0%)

Figure 5.9 In/Out with NLL2N

5.5 Conclusion

This chapter shows that it is possible to create a New Large Layer 2 Network (NLL2N) through the combination of different Layer 2 protocols, as SONET, RPR, and Ethernet. In this chapter it was focused on SONEToE; by using Ethernet segment as a transporter, the Ethernet layer 2 switches can be deployed in several applications to increase overall bandwidth efficiency. The latency was reduced and the bandwidth usage was increased. Behind this chapter, it shows that it is able to combine SONET and Ethernet to create a New Large Layer 2 Network.

CHAPTER 6

USING RPR, ETHERNET, AND SONET TO CREATE A NEW LARGE LAYER 2 NETWORKS (NLL2N)

Ammar Hamad[1], Michel Kadoch[1]

[1] Department of Electrical Engineering, École de Technologie Supérieure
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

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This chapter demonstrates the possibility of integrating the Resilient Packet Ring (RPR), Ethernet and Synchronous Optical NETwork (SONET) and creating a New Large Layer 2 Networks (NLL2N). These protocols are implemented in the layer 2 in the Open System Interconnection model (OSI) and are often are used separately. This chapter will demonstrate that RPR, Ethernet and SONET could be integrated together in the same Layer 2 Network. The chapter will explain and detail the use of RPR over Ethernet (RPRoE), the use of SONET over RPR (SONEToRPR) and integration all of them to create a New Large Layer 2 Network and to point out the benefits of it.

6.1 Introduction

RPR (Section 6.2), Ethernet (Section 6.3) and SONET (Section 6.4) have been implemented in the LAN and MAN network and work adequately by themselves.

In this chapter, the challenge is to merge the three protocols (RPR, Ethernet and SONET) and make them work as a NLL2N protocol. The methodology will be to encapsulate RPR frame in Ethernet data frame and also to encapsulate SONET frame on RPR. The method will be simulated and tested in a laboratory. The load of the link and the Input/Output of the data transmitted will be analyzed, while RPR, Ethernet and SONET are attached to the same layer 2 networks. However, the New Large Layer 2 Networks will be considered a useful solution to help businesses to set their layer 2 environments adequately and to reduce their daily load and cost. The structure of this chapter is: Section 6.2 Fundamentals of RPR, Section 6.3 Fundamentals of Giga Ethernet, Section 6.4 Fundamentals of SONET, Section 6.5 Basic principles of RPR over Ethernet, Section 6.6 Basic principles of SONET over RPR, and Section 6.7 Basic principles of NLL2N.

6.2 Fundamentals OF RPR

Resilient Packet Ring (RPR), which was standardized in 2004 as IEEE 802.17 RPR, is based on two counter-rotating fiber rings that carry data and control information [IEE (2004), Davik *et al.* (2004)]. Packet ring-based data networks were pioneered by the Cambridge Ring [Needham and Herbert (1982)] and followed by other important network architectures. Rings are built using several point-to-point connections. When the connections between the stations are bidirectional, rings allow for resilience (a frame can reach its destination even in the presence of a link failure). Since RPR is being standardized in the IEEE 802 LAN/MAN families of network protocols, it can inherently bridge to other IEEE 802 networks and mimic a broadcast medium. RPR implements a MAC protocol for access to the shared ring communication medium that has a client interface similar to that of the Ethernet's.

Furthermore, RPR uses the available ring bandwidth more efficiently than SONET/SDH by making use of destination stripping and shortest path routing both enabling spatial bandwidth reuse. With destination stripping, a packet sent along the ring from source node A to destination node B is removed from the ring by node B. The transmission of the packet only consumes bandwidth on the ring segment between node A and B as opposed to legacy ring systems that use source stripping where after passing its destination B, the packet continues its travel around the ring until it reaches the source node A. Destination stripping has the advantage over source stripping in that bandwidth is only consumed on the ring links between A and B so that other simultaneous transmissions can take place on the remaining links. In other words, destination stripping enables spatial reuse of the ring bandwidth by transmitting multiple packets simultaneously on different ring segments. Every station on the ring has a buffer, called transit queue (see Figure 6.1) [Davik *et al.* (2004)], in which frames transiting the station may be temporarily queued. Each station acts according to two basic rules. The first rule is that the station may only start to add a packet if the transit queue is empty and there are no frames in transit. Second, if a transiting frame arrives after the station has started to add a frame, this transiting frame is temporarily stored for as long as it takes to send the added frame in the transit queue. Obviously, these two simple principles need some improvement to make up a full working protocol that distributes bandwidth fairly.

6.2.1 Station design and packet priority

The stations on the RPR ring implement a MAC protocol that controls the stations' access to the ring communication medium. The MAC entity also implements access points which clients can call in order to send and receive frames and status information. RPR provides a three-level, class-based traffic priority scheme. The objectives of the class based scheme are to allow class A be a low-latency, low-jitter class, class B be a class with predictable latency and jitter, and class C be a best effort transport class. It is worthwhile to note that the RPR ring does not discard frames to resolve congestion. Hence, when a frame has been added onto the ring, even if it is a class C frame, it will eventually arrive at its destination. Class A traffic is divided into classes A0 and A1, and class B traffic is divided into classes B-CIR (committed information rate) and B-EIR (excess information rate). The two traffic classes C and B-EIR are called fairness eligible (FE), because such traffic is controlled by the fairness algorithm described in the next section. In order to fulfill the service guarantees for class A0, A1, and B-CIR traffic, bandwidth needed for these traffic classes is pre-allocated. Bandwidth pre-allocated for class A0 traffic is called reserved and can only be utilized by the station holding the reservation. Bandwidth pre-allocated for class A1 and B-CIR traffic is called reclaimable. Reserved bandwidth not in use is wasted. Bandwidth not pre-allocated and reclaimable bandwidth not in use may be used to send FE traffic.

A station's reservation of class A0 bandwidth is broadcast on the ring using topology messages (topology discovery is discussed later). Having received such topology messages from all other stations on the ring, every station calculates how much bandwidth to reserve for class A0 traffic.

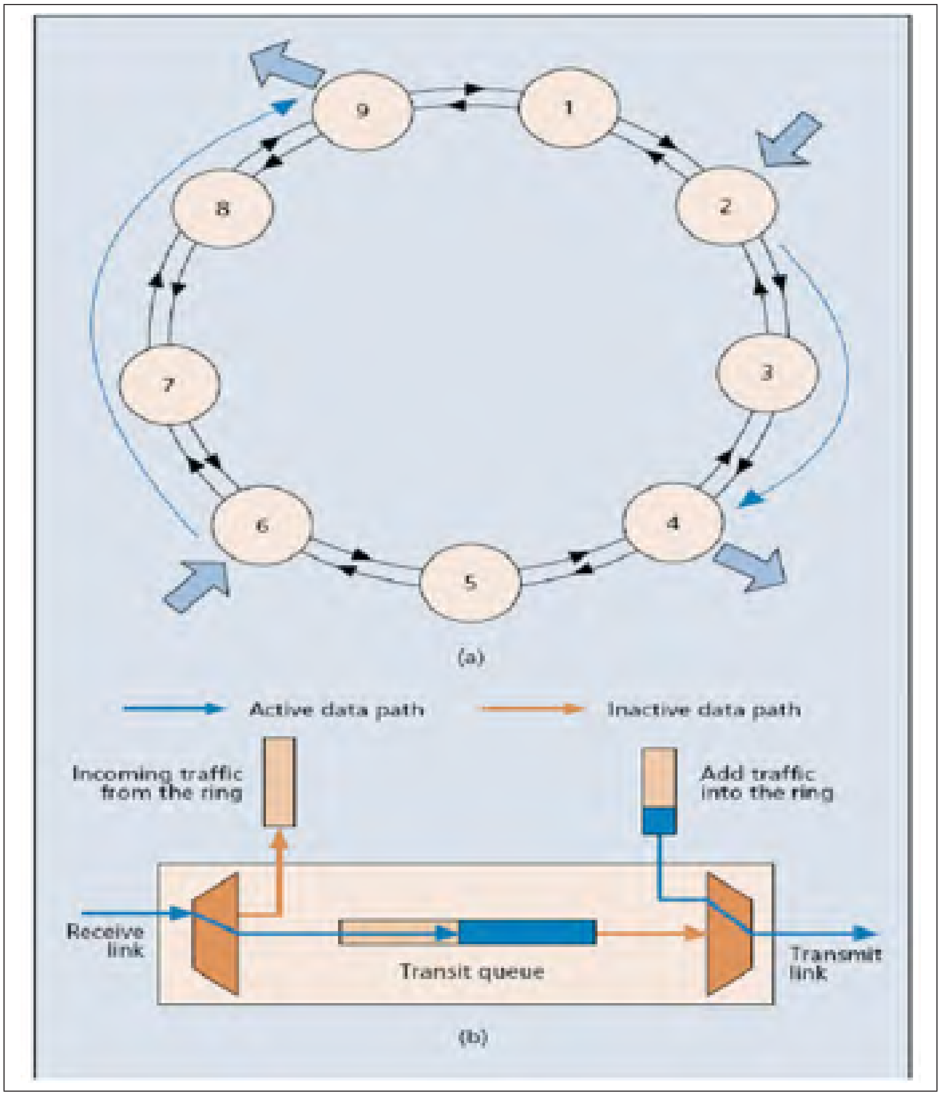


Figure 6.1 RPR network: a) destination stripping and spatial reuse; b) station's attachment to only one ringlet, showing the transit queue
Taken from Davik *et al.* (2004)

The remaining bandwidth, called unreserved rate, can be used for all other traffic classes. An RPR station implements several traffic shapers (for each ringlet) that limit and smooth add and transit traffic. There is one shaper for each of A0, A1, and B-CIR as well as one for FE traffic. There is also a shaper for all transmit traffic other than class A0 traffic, called the downstream shaper.

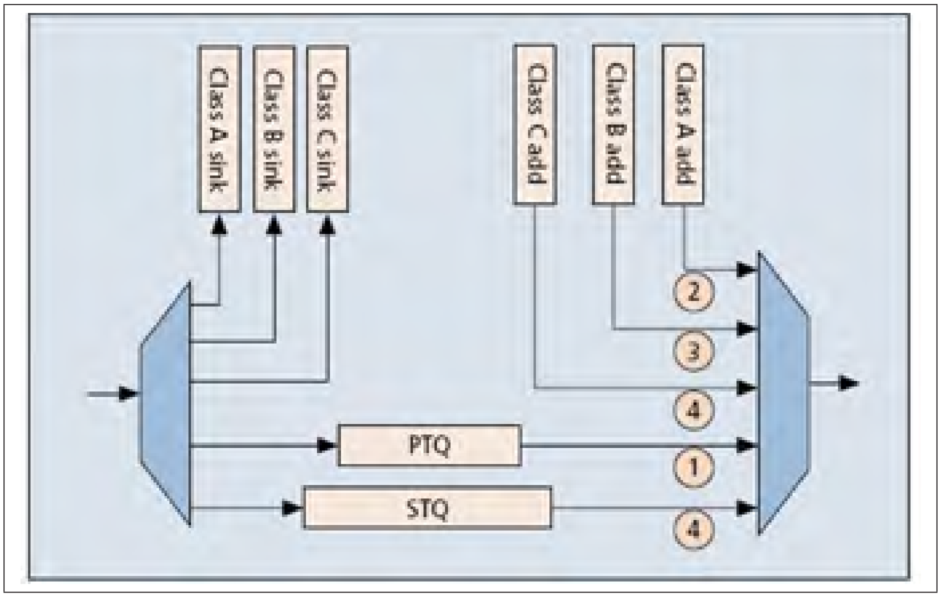


Figure 6.2 The attachment to one ring by a dual-transit-queue station. The numbers in the circles give a very crude indication of transmit link priority
Taken from Davik *et al.* (2004)

6.3 Fundamentals OF Gigabit Ethernet

Invented by Dr. Robert Metcalf and pioneered by Intel, Digital and Xerox, Ethernet has become the most commonly used LAN technology worldwide. More than 85% of all installed network connections are Ethernet, according to International Data Corporation (IDC, 2000). As a transport protocol, Ethernet operates at Layers 1 and 2 of the 7-layer OSI networking model, delivering its data packets to any device connected to the network cable. IT managers have found that Ethernet is simple, easy to use and readily upgradeable. An organization can scale from 10 to 100 or 1000Mbps Ethernet, either network-wide or a segment at a time, knowing that the new equipment will be backwards compatible with legacy equipment. This reduces the infrastructure investment that an organization must make. Ethernet is also a reliable technology.

6.3.1 Gigabit Ethernet Protocol Architecture

In order to accelerate speeds from 100 Mbps Fast Ethernet up to 1 Gbps, several changes need to be made to the physical interface. The Gigabit Ethernet will look identical to Ethernet from the data link layer upward. The challenges involved in accelerating to 1 Gbps have been resolved by merging two technologies together: IEEE 802.3 Ethernet and ANSI X3T11 Fibre Channel.

Leveraging these two technologies means that the standard can take advantage of the existing high-speed physical interface technology of Fibre Channel while maintaining the IEEE 802.3 Ethernet frame format, backward compatibility for installed media, and use of full- or half-duplex carrier sense multiple access collision detect (CSMA/CD). This scenario helps minimize the technology complexity, resulting in a stable technology that can be quickly developed.

6.4 Fundamentals of SONET

6.4.1 Introduction to SONET

Synchronous Optical NETwork (SONET) and Synchronous Digital Hierarchy (SDH) are equivalent standards with minor differences. SONET is used widely in North American, and SDH is used in Europe and the rest of the world. For the purpose of this dissertation, only SONET terminology is used and discussed. The overhead insertion mechanism, however, can be applied to both.

SONET was originally developed for the telephone network as a long-term solution for a mid-span-meet between vendors. The standard was proposed by Bell core and was established in 1984. SONET defines the rates and formats, the physical layer, network element architectural features, and network operational criteria for a fiber optic network. The standard soon became an excellent way for data communication as well, because it fits well in the physical layer of the OSI data network model.

6.5 Basic Principles of RPR Over Ethernet

RPR over Ethernet (RPRoE) is an RPR transmission technology that carries RPR frames directly on the Ethernet link layer. This solution complies with the Ethernet specification frame by IEEE 802.3. The Figure 6.3 shows the RPRoE encapsulation format.

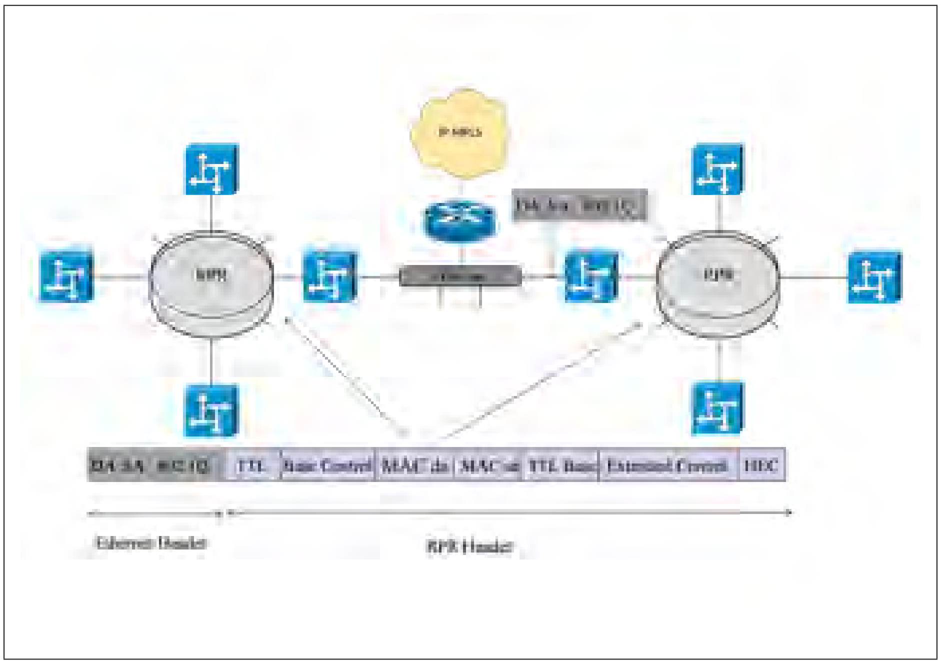


Figure 6.3 RPRoE frame format

a. All the devices on the ring or on the Ethernet segment are plug-and-play nature;

b. New stations added to the ring or to the Ethernet do not affect the existing traffic;

c. With RPR over Ethernet technology, all the transit packets are forwarded according to Ethernet header;

d. Transit stations do not learn any RPR MAC.

When a frame is inserted to Ethernet, RPR frames are encapsulated in Ethernet data frame are then forwarded on the Ethernet segment. In a copy operation, the Ethernet headers are stripped off and only RPR frames are forwarded.

6.5.1 Address learning of RPR over Ethernet

A device is logically divided into two parts. One part is at the RPR side to deal with RPR switching. The other part is at the Ethernet side to process RPRoE. When the RPR part receives a frame, it determines, according to the destination RPR MAC address, the Ethernet segment that the frame will send to. The RPRoE part finds the destination Ethernet MAC address, and the number of hops based on the user MAC address. It encapsulates the Ethernet frame header and then sends the frame to the Ethernet interface. When receiving an RPRoE data frame from Ethernet interface, the device will learn the source RPR MAC address and the Ethernet MAC address of the source Ethernet station. The Ethernet station keeps two MAC tables. One is at the RPR side recording the mapping between user MAC addresses and RPR egress ports. The other is at the Ethernet side for recording the mapping between user MAC addresses and destination Ethernet stations. See Figure 6.4 to follow the forwarding process.

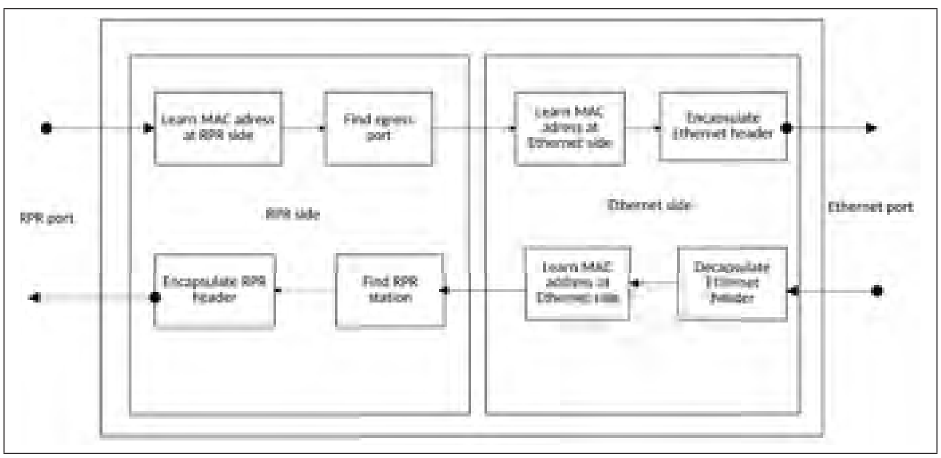


Figure 6.4 RPRoE frame format

As shown in Figure 6.6, when the first RPR frame at the user's side is sent to Ethernet E1 from device 3, the user's source MAC address R1 is learned from the RPR MAC address table of device 3. See the following table.

Table 6.1 RPR MAC address

RPR MAC	User VLAN	MAC address of destination	No. of hops to destination
R1	1	Station device 1 (R1-MAC 1)	2
R2	1	Station device 2 (R1-MAC 2)	2
R3	1	Station device 6 (R2-MAC 1)	2
R4	1	Station device 5 (R2-MAC 3)	3
E1	1	Station device 3 (E1-MAC 1)	2
E2	1	Station device 4 (E1-MAC 2)	2

After the first frame of the user is send to the segment, it passes device 4 and then arrives at device 6. The user's source MAC address R1 is learned from the Ethernet MAC table of device 4. See the following table.

Table 6.2 Ethernet MAC address

Ethernet MAC	User VLAN	Egress port
R1	1	Insert on RPR 1
R2	1	Insert on RPR 1
R3	1	Insert on RPR 2
R4	1	Insert on RPR 2
E1	1	Insert on E-MAC 3
E2	1	Insert on E-MAC 3

The Figure 6.5 shows how all the stations on the two irrelevant RPRoE segment learn MAC addresses. When a device accesses multiple Ethernet segments, the device must learn from its RPR MAC address table which Ethernet segment has the insert port that is mapped to the MAC address of user.

In the RPRoE network, the RPR MAC table of any transit station does not learn the user MAC address of traffic between other stations.

In this simulation, we attached almost the online workstations and servers to the RPR rings, and we kept the batch servers, the file servers, and the reporting servers in the Ethernet segment. In so doing, we divided the load in two categories: the heavy load and the light load. Normally the heavy loads (batch process, reporting, and the file transfer) are used during the night so there is no major impact on the users. The light loads are all the servers and workstations used during the day. So, the users need speed, bandwidth, and fast recovery.

This kind of topology (RPRoE) gives the customer the possibility to create a NLL2N, and to have a huge layer two network, with no impact on the performance. Figure 6.5 bellow clearly shows that we have a better performance with this topology configuration. Figure 6.6 shows the performance of the end-to-end link without splitting the load. The maximum output higher than the maximum input. The same goes with the average maximum output and maximum input. This behavior is due to the fact that all the servers and workstations were attached without any consideration of their load and their utilities. Figure 6.7, we have the opposite effect and this is due to the fact that having the load divided and using NLL2N, we can have that behavior with a better performance. The maximum input was higher and the maximum output was smaller. This behavior is due to the fact that splitting the load in two categories (heavy and light load) maximizes the maximum input load and minimizes the output load.

RPRoE scales as RPR and Ethernet and we can have the benefit of both. In addition, we proved that setting the layer 2 environments by load will help the business and ensure a better use of their bandwidth.

6.5.2 Advantages of RPRoE

According to our simulation and analysis, we understand that the RPRoE technique in a NLL2N has many advantages:

a. Using the steering and the wrapping, RPRoE is still able to complete the protection switching less than 50 ms and make use of the full bandwidth;

b. Plug and play: In RPRoE solution, transit traffic is used as usual; RPR frame is transmitted transparently as an Ethernet frame. When we insert any new device to the Ethernet segment, there is no need to do anything. The same goes when we insert in RPR ring;

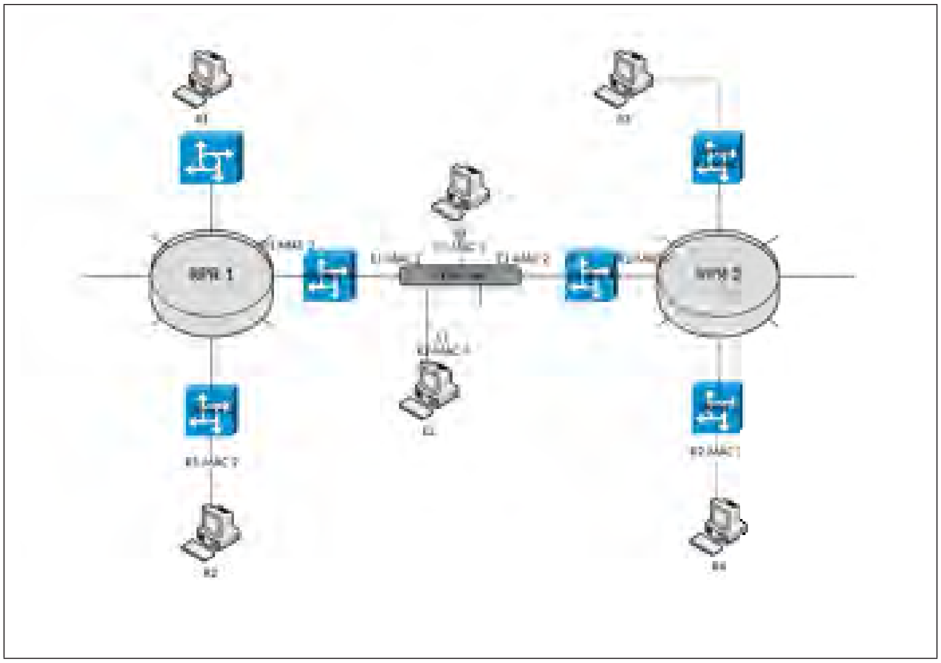


Figure 6.5   RPRoE simulation

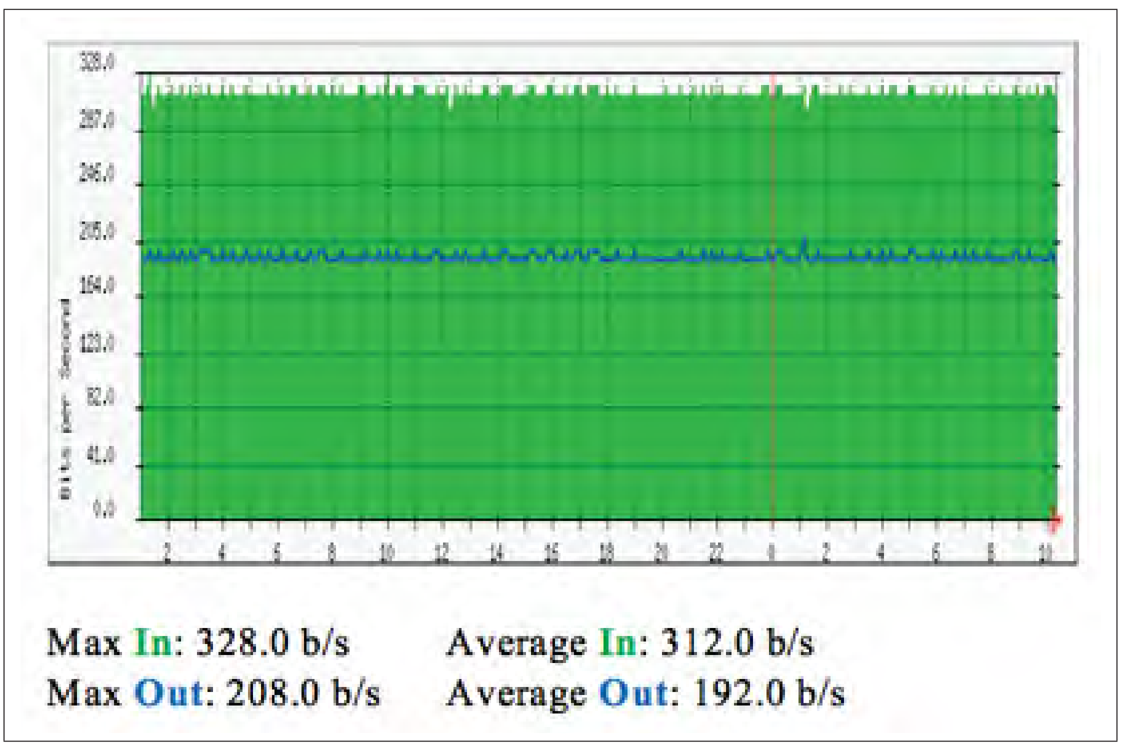


Figure 6.6   In/Out without using NLL2N

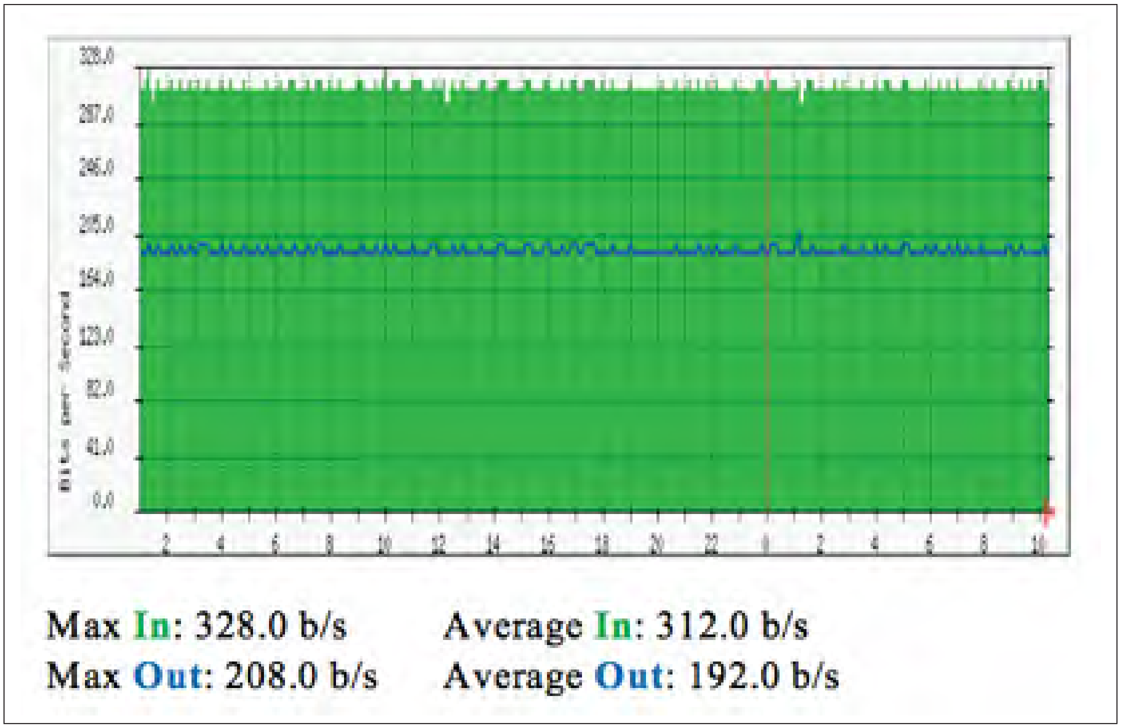


Figure 6.7 In/Out with NLL2N

c. The two technologies use almost the same MAC address to identify the destination device. The transmission can bridge to any other Ethernet;

d. We had a good performance; our monitoring static shows that there is sometimes some latency, but this problem could be resolved by adding the Quality of Service (QoS);

e. Our Local Area Network (LAN) will be extended to a New Large Layer 2 Network (NLL2N).

6.5.3 Conclusion

This chapter shows us that we are able to create a NLL2N by combining different Layer 2 protocols, like RPR, Ethernet, and SONET. In this chapter, we focussed on RPRoE. By setting the server separations by functionalities in the company, we successfully identified and divided the load in two categories: Heavy and Light load. In so doing, we increase the Input speed and we decrease the output speed. We showed that we are able to combine RPR and Ethernet and create a New Large Layer 2 Network which facilitates better infrastructure management in a better way by implementing this kind of architecture. In our next chapter, we will investigate SONEToRPR.

6.6 Basic Principles of SONET Over RPR

SONET over RPR (SONEToRPR) is an SONET transmission technology that carries SONET frames directly on the RPR link layer. The physical path SONET connections are used by RPR boxes. This solution complies with the RPR specification frame by IEEE 802.17. Figure 6.8 shows the SONEToRPR encapsulation format.

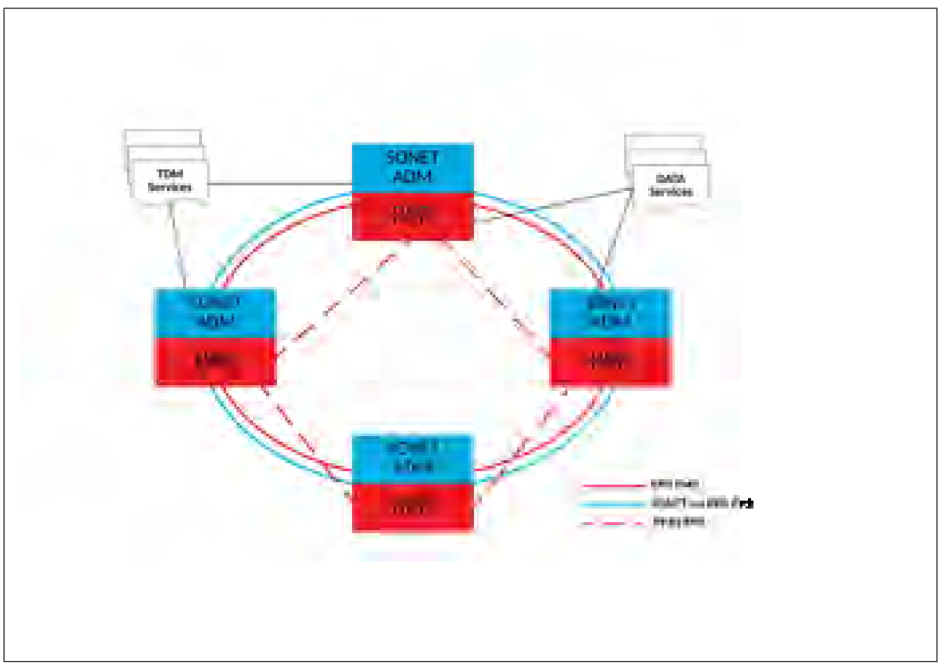


Figure 6.8 SONEToRPR frame format

a. All the devices on the SONET ring or on the RPR ring are plug-and-play nature;

b. New stations added to the SONET ring or on the RPR ring do not affect the existing traffic;

c. With RPR over SONET technology, all the transit packets are forwarded according to SONET header;

d. Transit stations do not learn any RPR MAC;

e. Co-exiting of SONET rings, UPSR and BLSR, and RPR;

f. UPSR and BLSR interwork with RPR;

g. To gain efficiency, SONET allows sharing paths for data among multiple nodes.

When a frame is inserted to SONET, RPR frames are encapsulated in SONET data frame for forwarding on the SONET segment. In a copy operation, the RPR headers are stripped off and only SONET frames are forwarded. By disabling the SONET ring protection, we can interperate SONET and RPR and resiliency becomes a suitable solution. But, the SONET and RPR protection will not work together.

6.6.1 Goals for SONET over RPR

Having SONEToRPR, we support TDM traffic and we are still supporting packet optimization. SONEToRPR supports all RPR rates: STM-1/OC-3, STM-4/OC-12, STM-16/OC-48, and STM-64/OC-192. It also supports full concatenated payloads (*e.g.,* STM-16) for channelization for mixed data and TDM traffic and data traffic.

The protection switching is at MAC layer or Layer 1. Figure 6.7 shows SONET and RPR using the same ring. We have shown that by disabling the SONET ring protection, we can interoperate SONEToRPR using the RPR resiliency. But SONET and RPR protection will not work together.

SONEToRPR helps to share and use the same paths for data traffic among multiple nodes on a ring to gain efficiency.

6.6.2 SONEToRPR Simulation

Figure 6.8 shows how all the nodes on the SONEToRPR set and work. Two categories of node are used: one was set to receive and send TDM and Data traffic; the other was set receive and send TDM traffic only.

The first category of node has two switches: a TDM switch manages the entire SONET traffic and the RPR switch manages RPR Data traffic. The second category node is used to receive or drop only TDM traffic.

In this simulation, we use the two RPR rings (Outer ring and Inner ring). The network transport will be under RPR which makes the transport more efficient than TDM transport such as SONET. With this unique advantage delivery efficient data transport and resiliency, SONEToRPR becomes a suitable solution to build a New Large Layer 2 Network (NLL2N).

This kind of topology (SONEToRPR) gives customer the possibility to create a NLL2N. We achieved a better use of the bandwidth with less latency and no impact on performance (See Figure 6.11).

This behavior is due to the fact that the layer two backend is RPR, so all the bandwidth in the two rings are used. If we analyze our load and adequately set the different nodes while taking into consideration the quality of service, the outcome is a better performance.

SONEToRPR has the ability to protect the network from single span failures. Figure 6.10 shows who the ring protection works when a failure occurs. As soon as the failure happens, protection messages are sent and RPR uses the two mechanisms:

- Wrapping – Nodes neighboring the failed span will direct packets away from the failure by wrapping traffic around the other fiber (ringlet);

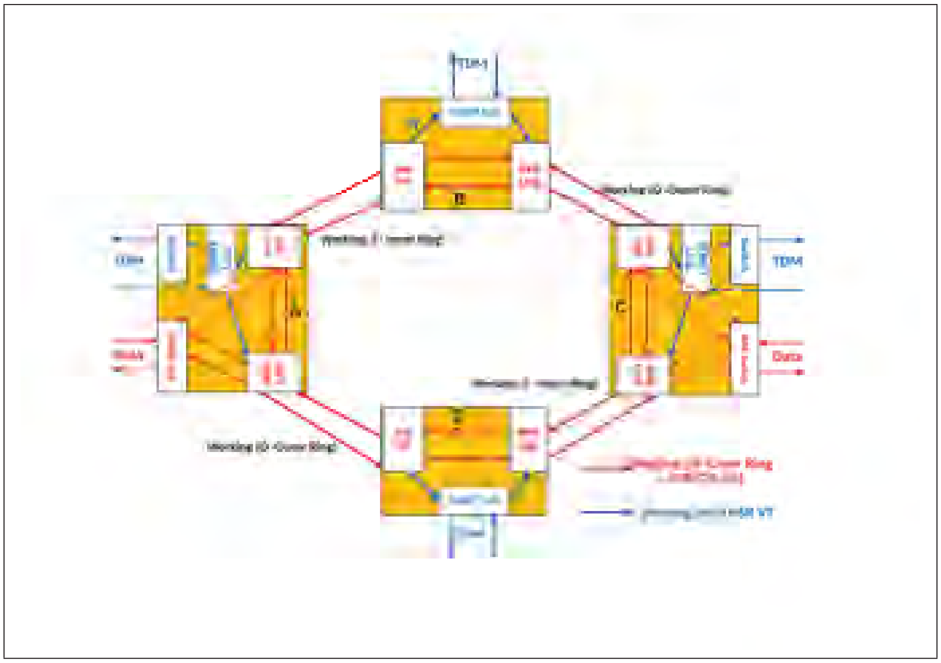


Figure 6.9 SONEToRPR simulations

- Steering – The protection mechanism notifies all nodes on the ring of the failure span. Every node on the ring will adjust their topology maps to avoid this span. Regardless of the protection used, the ring will be protected within 50 ms.

6.6.3 Advantages of SONEToRPR

According to our simulation and analysis, we understand that the SONEToRPR technique in a NLL2N has many advantages:

a. Using the steering and the wrapping, SONEToRPR is still able to complete the protection, switching less than 50 ms and making use of the full bandwidth;

b. Plug and play: In SONEToRPR solution, transit traffic is used as usual; SONET frame is transmitted transparently as an RPR frame. When we insert any new device to the SONET segment, there is no need to do anything. The same is true when we insert in RPR ring;

c. SONEToRPR uses the available ring bandwidth more efficiently than SONET alone;

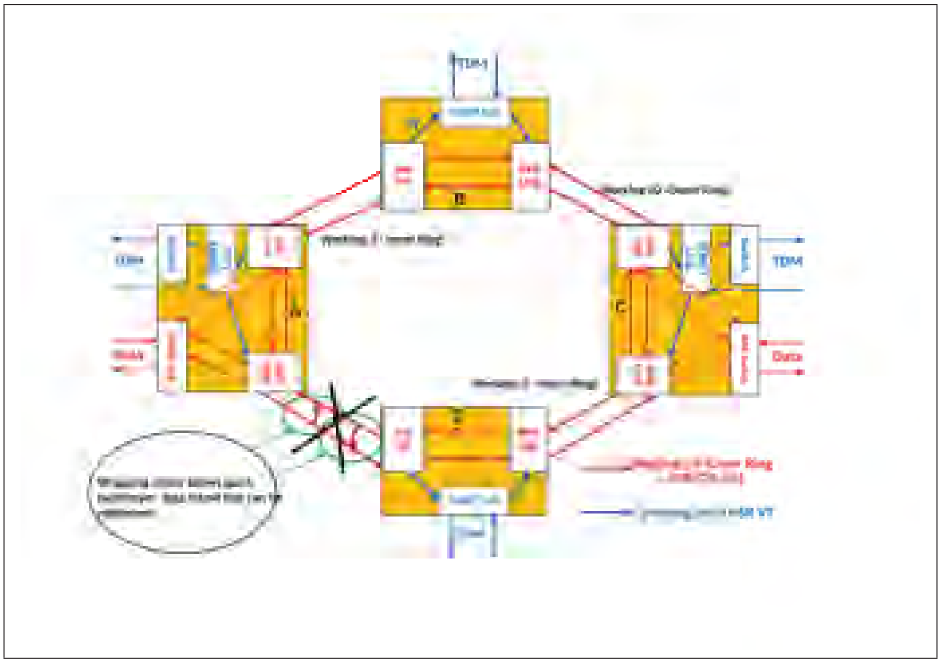


Figure 6.10 SONEToRPR simulations

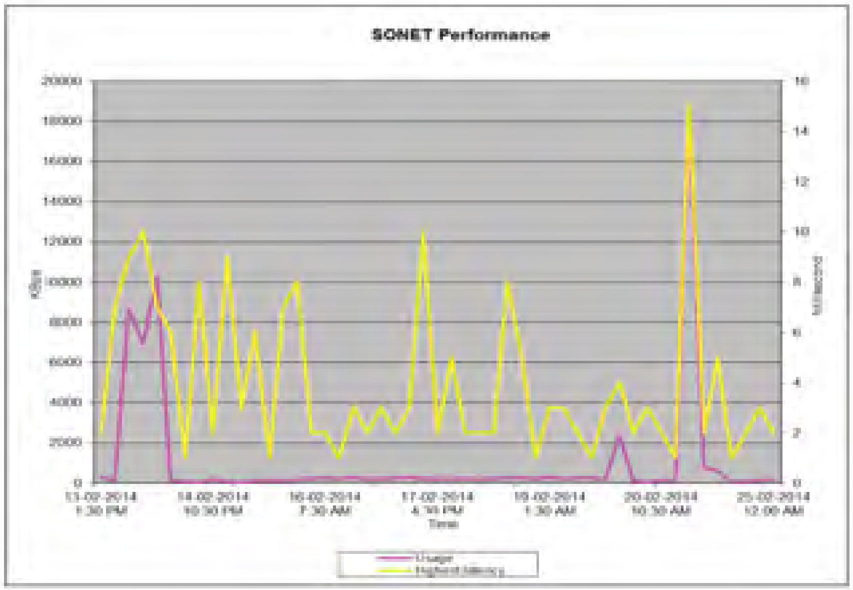
d. The two technologies are using almost the same technic to identify the destination device. The transmission can bridge to any other RPR;

e. We achieved a good performance; our monitoring static shows that sometimes there is some latency. But this problem could be resolved by adding the Quality of Service (QoS);

f. SONEToRPR uses destination stripping, which doubles the ring capacity compared to source stripping.

6.6.4 Conclusion

This chapter demonstrated that we are able to create a New Large Layer 2 Network (NLL2N) by the combination of different Layer 2 protocols, as SONET, RPR, and Ethernet. In this chapter we focused on SONEToRPR; by using RPR rings as a transporter we automatically used the destination stripping and we gained efficiency. We reduced the latency and increased the bandwidth usage. We demonstrated that we are able to combine SONET and RPR to create a New Large Layer 2 Network and Make possible better infrastructure management to



	Maximum	Minimum	Average
Usage (KBps)	18393	50	1139.551
Highest Latency (ms)	15	1	3.980

Figure 6.11 In/Out using NLL2N

companies that implement this kind of architecture. In our next chapter, we will investigate the combination of SONET, RPR, and Ethernet.

6.7 Basic Principles of NLL2N

NLL2N is a combination of RPRoE [Hamad and Kadoch (2014)] and SONEToRPR [Hamad and Kadoch (2015a)]. It is a large layer 2 protocol. This solution complies with Ethernet specification frame by IEEE 802.3, SONET and also with RPR specification frame by IEEE 802.17 [IEE (2004)]. Figure 6.12 shows the NLL2N encapsulation format.

a. All the devices on the RPRoE or SONEToRPR are plug-and- play nature;

b. New stations added to RPRoE or SONEToRPR do not affect the existing traffic;

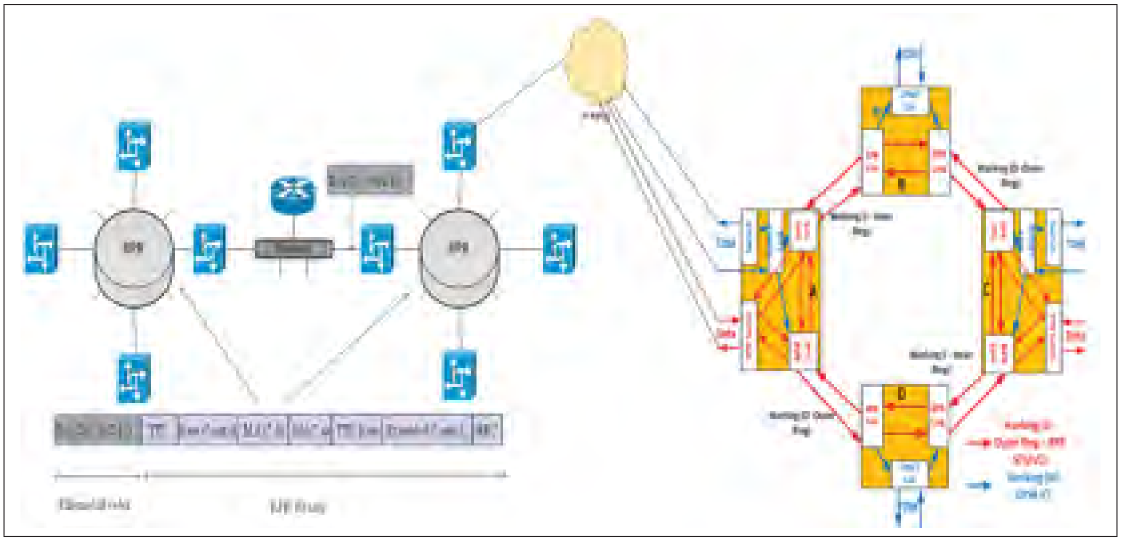


Figure 6.12 RPRoE attached to SONEToRPR
Taken from Hamad and Kadoch (2014) Hamad and Kadoch (2015a)

c. With RPRoE or SONEToRPR, all the transit packets are forwarded according to RPR header;

d. Transit stations do not learn any RPR MAC;

e. Co-exiting of SONET rings, UPSR and BLSR, RPR and Ethernet;

f. UPSR and BLSR interconnect with RPR and Ethernet;

g. To gain efficiency, SONET allows sharing paths for data among multiple nodes.

When a frame is inserted to SONET, RPR frames are encapsulated in SONET data frame for forwarding on the SONET segment. Also, when a frame is inserted to Ethernet, RPR frames are encapsulated in Ethernet data frame and then to be forwarded on the Ethernet segment.

6.7.1 NLL2N Simulation

Figure 6.12 shows how all the nodes on the RPRoE and SONEToRPR set and work. In the side of RPRoE when the device accesses multiple Ethernet segments, the device must learn from its RPR MAC address table which Ethernet segment has the insert port that is mapped to the MAC address of user. In the RPRoE network, the RPR MAC table of any transit station does not learn the user MAC address of traffic between other stations.

From the other side, SONEToRPR, two categories of node are used: one was set to receive and send TDM and Data traffic; the other was set receive and send TDM traffic only. The first category of node has two switches: a TDM switch manages the entire SONET traffic and the RPR switch manages RPR Data traffic. The second category node is used to receive or drop only TDM traffic.

The connection between the two sides (RPRoE and SONEToRPR) is an MPLS network. As such, no change is necessary as demonstrated in our previous chapters [Hamad and Kadoch (2014)] and [Hamad and Kadoch (2015a)]. We ran our simulation and we did not face any performance issues other than the latency detected in the two sides. This kind of topology (NLL2N) gives the customer the possibility of merging their entire layer 2 networks (Ethernet, RPR and SONET) and having the benefit of each one of them.

6.7.2 Advantages of NLL2N

According to our simulation and analysis, we understand that the NLL2N technique has many advantages:

a. Using the steering and the wrapping, NLL2N is still able to complete the protection switching less than 50 ms;

b. Plug and play: In NLL2N solution, the usual transit traffic is used; Ethernet, RPR or SONET frame is transmitted transparently. When we insert any new device to any of the topology, there is no need to take any further action;

c. The three technologies use almost the same MAC address to identify the destination device. The transmission can bridge to any other protocols (Ethernet, RPR and SONET);

d. We had a good performance; we demonstrated it in our previous chapters [Hamad and Kadoch (2014)] and [Hamad and Kadoch (2015a)]. No change in our new protocol (NLL2N).

6.8 Conclusion

This chapter shows us that we are able to create a New Large Layer 2 Network (NLL2N) by combining different Layer 2 protocols, like RPR, Ethernet, and SONET. In this chapter, we merged the two simulations that we created and demonstrated in our previous chapters [Hamad and Kadoch (2014)] and [Hamad and Kadoch (2015a)]. Using RPR, Ethernet, and SONET we proved that these layer two protocols are able to work together and help businesses to set their infrastructure in better way. We are still working to simulate and test SONET over Ethernet (SONEToE). In the next chapter, the investigation will be SONEToE.

CHAPTER 7

RESULTS AND ANALYSIS

This chapter analyses and comments on the final results of our investigation. We will walk through our previous proof-of-concepts (POC) from RPR over Ethernet (RPRoE), SONET over RPR (SONEToRPR), SONET over Ethernet (SONEToE) and finally the New Large Layer 2 Networks (NLL2N). During these POCs, we proved that we got a better use of the bandwidth and a better throughput.

7.1 RPR over Ethernet

Based on our simulation, described in chapter 3, we recreated the same POC with more data. We can see in the graphic bellow that RPRoE has a better throughput than Ethernet and RPR by themselves. We still have the same advantages:

- Using the steering and the wrapping, RPRoE is still able to complete the protection switching in less than 50 ms and make use of the full bandwidth;
- Plug-and-play: In RPRoE solution, transit traffic is used as usual; RPR frame is transmitted transparently as an Ethernet frame. When we insert any new device to the Ethernet segment, there is no need to do anything. The same goes when we insert in RPR ring;
- The two technologies use almost the same MAC address to identify the destination device. The transmission can bridge to any other Ethernet;
- RPRoE has a better performance debit that RPR and Ethernet by themselves. Figure 7.1 clearly shows that we have a better throughput.

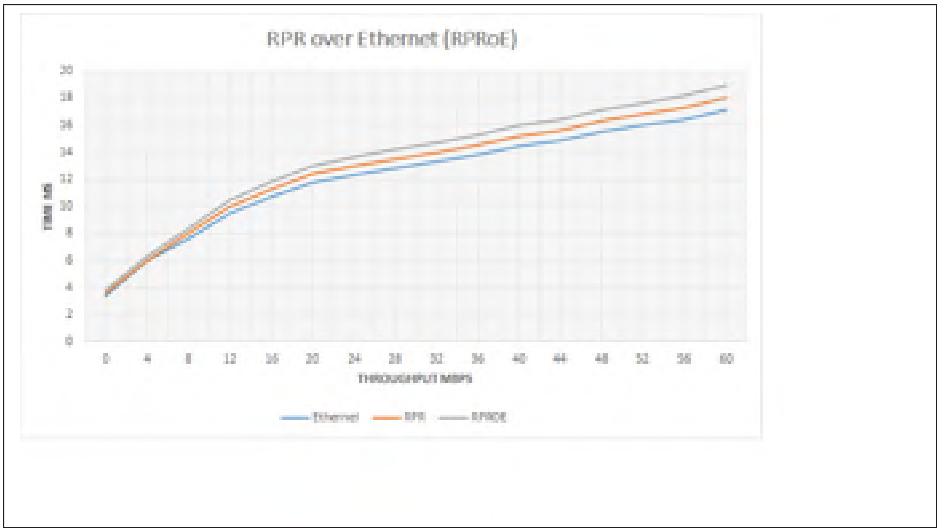


Figure 7.1 RPR over Ethernet

7.2 SONET over RPR

Based on our simulation, described in chapter 4, we recreated the same POC with more data. We can see in the graphic bellow that SONEToRPR has a better throughput than SONET and RPR by themselves. We still have the same advantages:

- Using the steering and the wrapping, SONEToRPR is still able to complete the protection, switching less than 50ms and making use of the full bandwidth;
- Plug-and-play: In SONEToRPR solution, transit traffic is used as usual; SONET frame is transmitted transparently as an RPR frame. When we insert any new device to the SONET segment, there is no need to do anything. The same is true when we insert in RPR ring;
- Due that the two technologies that used almost the same MAC address to identify the destination device. The transmission can bridge to any other RPR;
- SONEToRPR uses the available ring bandwidth more efficiently than SONET alone and better throughput that the two protocols by themselves. Figure 7.2 shows this behaviour.

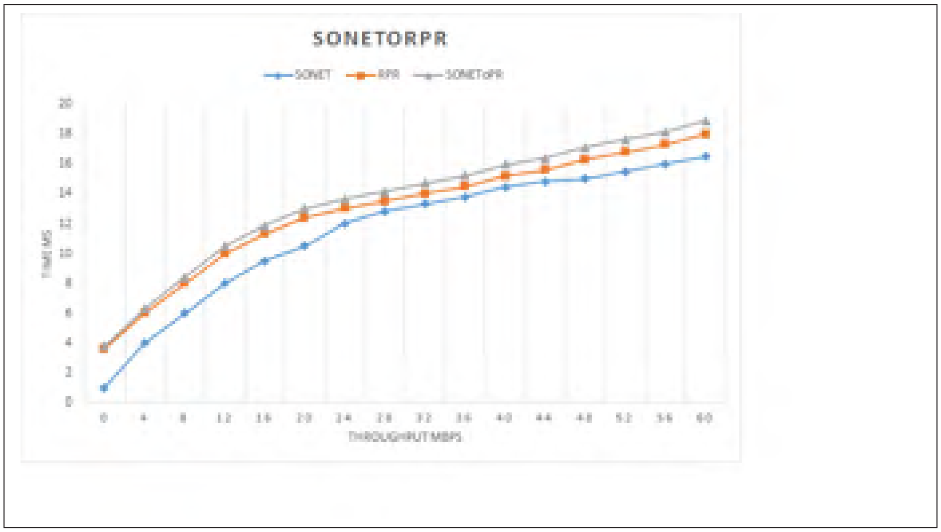


Figure 7.2   SONET over RPR

7.3 SONET over Ethernet

Based on our simulation, described in chapter 5, we recreated the same POC with more data. We can see in the graphic bellow that SONEToE has a better throughput than SONET and Ethernet by themselves. We still have the same advantages:

- In case of failure, SONEToE is still able to complete the protection, switching less than 50 ms;
- Plug-and-play: In SONEToE solution, transit traffic is used as usual; SONET frame is transmitted transparently as an Ethernet frame. When we insert any new device to the SONET segment, there is no need to do anything. The same is true when we insert in Ethernet segment;
- SONEToE uses the available ring bandwidth more efficiently than SONET alone;
- SONEToE had a good performance and the bandwidth efficiently used because Ethernet will be used in the transport layer;
- Using Ethernet as transporter will increase overall bandwidth efficiency and the throughput is better see Figure 7.3.

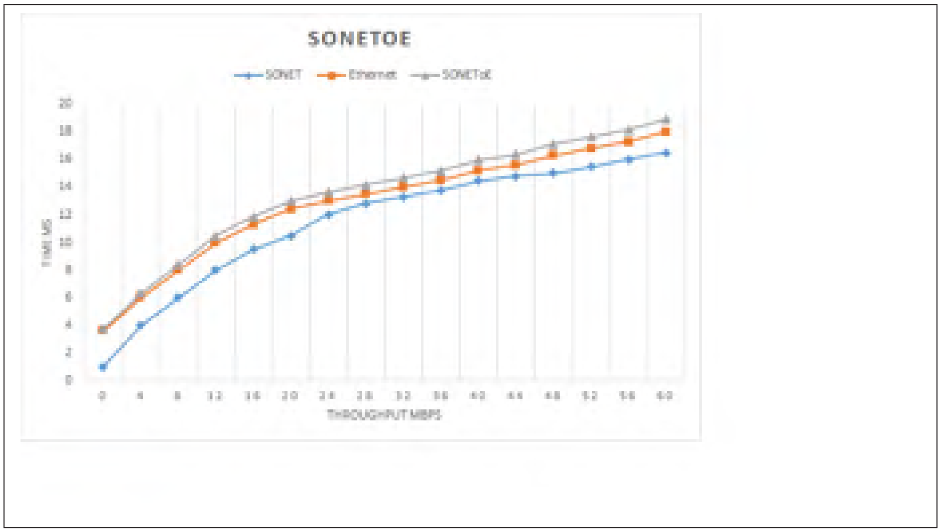


Figure 7.3 SONET over Ethernet

7.4 Using RPR, Ethernet, and SONET to create a New Large Layer 2 Network (NLL2N)

Based on our simulation, described in chapter 6, we recreated the same POC with more data. We can see in the graphic bellow that NLL2N has a better throughput than Ethernet, RPR and SONET by themselves. The three technologies use almost the same MAC address to identify the destination device. The transmission can bridge to any other protocol (Ethernet, RPR and SONET); we demonstrated above that combining these protocols and creating a New Large Layer 2 Network could help the business to have a better use of their bandwidth and especially to increase the debit. We are still working to evaluate this new topology (NLL2N) in future research. We will include the Quality of Service (QoS) to help reduce some latency; See Figure 7.4;

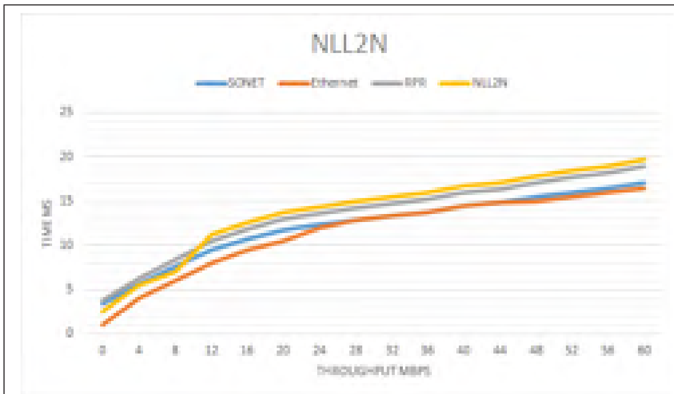


Figure 7.4 NLL2N

CONCLUSION AND RECOMMENDATIONS

Conclusion

Our main objective, to create a New Large Layer 2 Network, has been successfully achieved. During our research we did a few simulations and we investigated a series of scenarios using various layer 2 protocols. Our investigation was developed in different papers (three conference papers) and one journal with a review committee. All these papers were accepted and published.

In the first conference paper [Hamad and Kadoch (2014)], we investigated RPR over Ethernet. During our simulation, we successfully identified and divided the server loads of our company into two categories: Heavy and light load. Doing that we increase the input speed and we decrease output speed and the latency. This paper shows that we are able to combine RPR and Ethernet and make them work together.

In the second conference paper [Hamad and Kadoch (2015a)], we investigated SONET over RPR. During our simulation, we successfully used RPR rings as a transporter by using the destination stripping to gain efficiency. We reduced the latency and we increased the bandwidth usage. This paper shows that we are able to combine SONET and RPR and make them work together.

In the third conference paper [Hamad and Kadoch (2015b)], we investigated SONET over Ethernet. In this paper, the focus was on SONEToE; by using Ethernet segment as a transporter, the Ethernet layer 2 switches can be deployed in several applications to increase overall bandwidth efficiency. The latency was reduced and the bandwidth was increased. This article shows that it is possible to combine SONET and Ethernet and to make them work together.

The last paper was a journal paper [Hamad and Kadoch (2015c)], we investigated RPR, Ethernet and SONET to create a New Large Layer 2 Networks (NLL2N). This paper shows that we are able to create a New Large Layer 2 Network (NLL2N) by combining different Layer 2 protocols, as RPR, Ethernet, and SONET. In this paper, we merged the previous simulations that we created and demonstrated in our three previous papers. Using RPR, Ethernet, and SONET we proved that these protocols are able to work together and help businesses to set their infrastructure in a more efficient way.

We see throughout our research and our tests that it is very important to understand that the network is not only a set of hardware, cables, switches, routers, etc. It is more than that. The network represent the dorsal of the company; its culture, way of thinking, vision and strategy. So, it is very important to look on the Network as part of the company's growth, and support it with the network's evolution and make sure that we have in place a clear roadmap aligned with the company's vision to help them grow!

Recommendations

As the discussion of the NLL2N demonstrated, we are able to make all these layer two protocols work together and increase the overall bandwidth and reduce the latency. Of course, several aspects can still be refined. For example, we are planning to do some testbeds to evaluate the quality of server (QoS) while at the same time evaluating the benefit of using the NLL2N. Our plan, which is part of our actual discussion, is to work closely with a company to implement a testbed as a proof-of-concept of this new network topology.

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