Evolution of Carrier Ethernet – Technology Choices and Drivers

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Abstract: The shift from native Ethernet in LANs to switched Ethernet in WANs has propelled efforts of making Ethernet as an ideal candidate technology for transport. Carrier Ethernet has the advantage of being able to be offered as a service to customers. Two questions that we desire to answer in this paper are (1) how Carrier Ethernet can scale as a service in the metropolitan and access premises and (2) what are the key applications that will most benefit from such technology development. We attempt to answer the first question by first reviewing the multiple strategies adapted by vendors in deploying Carrier Ethernet. We then show how scalable Carrier Ethernet can be used for multiple service offerings, especially focusing on video distribution/SAN/mobile-backhaul. We then discuss the service requirements which need to be satisfied to make the native Ethernet carrier class. The paper also discusses impacting underlying technologies which are crucial in making Carrier Ethernet a success. A simulations study throws light on the different strategies of implementing Carrier Ethernet.

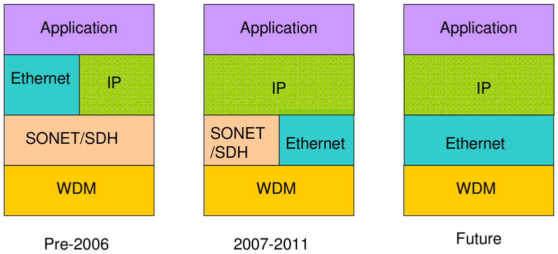

Fig. 1a.

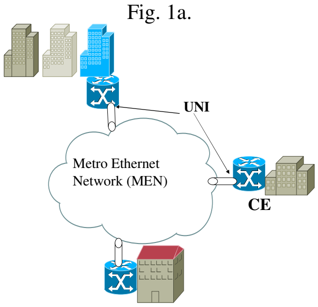

Fig. 1b.

Fig. 1a. Ethernet Transition Fig. 1bEthernet Service model.

I. THE CASE FOR CARRIER ETHERNET

Ethernet is the most successful and dominant LAN technology world-wide for well over three decades. Most of the network capable devices today have Ethernet as a standard interface [9-10]. Wide deployment of Ethernet is due to its simplicity, cost-efficiency and ease of deployment. Ethernet originally designed for simple data sharing over campus LAN has seen a significant development in the last 3 decades from 10-Mbps shared operation to switched operation at 10-Gbps today with 40 and 100-Gbps on the rising. In recent years, service providers are deploying Ethernet as a technology in the MAN or WAN space for transport purposes. Disadvantages of traditional WAN technologies like Frame Relay, ATM and SONET/SDH include high cost, lack of flexibility and scalability. Flexibility, scalability and economics of Ethernet give providers the ability to enhance profits while meeting emerging needs of customers. Ethernet is particularly becoming more appealing as it can support a multitude of services using service differentiation paradigms at low price points.

Providers are moving towards next generation packet based metro networks. This transition can be seen in Fig 1a, where packet based Ethernet moves down the layers as it gradually replaces TDM (SONET/SDH) [1]. There is a constant increase in demand for high bandwidth, new applications and connectivity from enterprises and residential customers. Networks are beginning to provision converged services like voice, video and data, each of which has diverse service needs. Enterprises, with geographically distributed offices, prefer low-cost, service friendly connectivity, prompting providers to offer Layer-2 VPN services [8]. In addition, broadband-access, residential triple-play and wireless backhaul serve as key drivers for *Carrier Ethernet*.

This paper is organized as follows: we begin by defining what Ethernet services are as a result of standardization in Section II. We then focus on the technology – how to deploy Carrier Ethernet (CE) and the associated approaches in Section III. Section IV discusses future and present applications in terms of deployment, specifically focussing on how Carrier Ethernet (CE) impacts these applications. Future technologies that would impact Carrier Ethernet are presented in Section V. A simulation study is presented in Section VI, while Section VII summarizes this paper.

II. CARRIER ETHERNET SERVICES AND TECHNOLOGIES

Metro Ethernet Forum (MEF) a global industry alliance was formed to accelerate the world-wide adoption of Carrier Ethernet. The basic Ethernet service model as defined by the MEF is shown in Fig. 1b. Connections from an enterprise or residential customer terminate at a customer edge. The customer edge is then connected to the User Network Interface

(UNI) with a standard 10/100/1000 Mbps or 10Gbps interface. Hence, from a customer perspective, the network connection from customer side of the UNI is Ethernet. UNI is the demarcation between the customer edge and the service provider's *Metro Ethernet Network* (MEN). Services inside the MEN cloud can be supported by a wide range of technologies including SONET/SDH, WDM, and MPLS etc. It is important to note that CE services are defined from the customer's perspective and are oblivious to the underlying technologies. However, Ethernet itself could be used as the transport technology in the MEN cloud, which is the main discussion in this paper.

The Ethernet Virtual Connection (EVC) is an important Ethernet service attribute. The MEF defines EVC as "*an association of two or more UNIs*". EVC performs two main functions. (1) The EVC connects two or more UNIs enabling the transfer of Ethernet frames between them. (2) The EVC prevents transfer of data from sites not part of the EVC, i.e. the EVC isolates traffic between two UNIs. EVC forms the basis for any Ethernet service type to be defined, depending on the number and the way the customer sites (UNIs) are connected. The MEF defines 3 types of EVCs – the ELINE, the ELAN and the ETREE.

II. A. E-LINE: provides point-to-point EVC *pipe* between two customer sites. This is used for Ethernet point-to-point connectivity. This can be used to construct services *analogous* to Frame Relay (FR) Permanent Virtual Circuits (PVCs). Service attributes like line-rate (granularity), delay can be set up on this pipe. E-line services are of two types:

II. A. 1. Ethernet Private Line (EPL): is a point-to-point service which assures good performance parameters like low delay, jitter and loss. EPL provides transparency between source and destination UNIs such that service frame's header and payload are identical at both ends. EPL does not support service differentiation, thereby making it a port based service with dedicated bandwidth, analogous to TDM private line. Due to its simplicity it is widely deployed and can offer strong SLAs thus making it suitable for critical enterprise applications. Voice over IP (VOIP) is a potential EPL application in which delay sensitive voice is sent across the network using fixed bandwidth pipes. Home monitoring, transport of video etc. are other important applications using this service. This service can be provided across nations or between metros.

II. A. 2. Ethernet Virtual Private Line (EVPL): is a point-to-point service with *service multiplexing* at a UNI. In EVPL, more than one EVC shares the UNI bandwidth, therefore allowing service multiplexing. EVPL does not provide full transparency of frames unlike EPL, and is hence similar to FR PVC. EVPL due to service multiplexing is like a shared connection. SLAs comparable to ATM or FR are possible, but are not *strong* SLAs due to shared medium characteristics. EVPL provides rich bandwidth profiles for EVCs as compared to the single bandwidth profile of EPL. Internet access, disaster recovery are two promising applications with this service type. Online video gaming and data-center are also being implemented using EVPL.

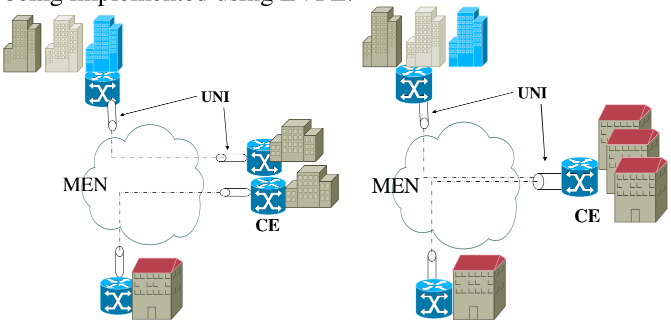

Fig. 2a. EPL and EVPL (see service multiplexing)

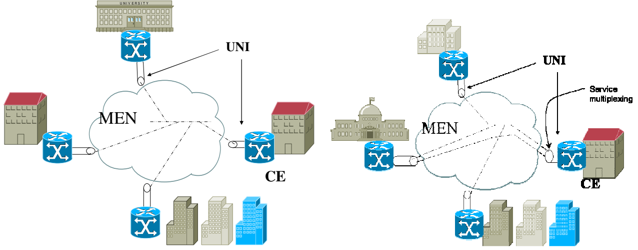

Fig. 2b. Examples of EPL and EVPL.

II. B. E-LAN: provides multipoint connectivity with more than two UNIs connected as an EVC. Ethernet's property of being able to support multipoint communication is used to create ELANs. Data sent from one UNI can be received at one or more UNIs. The multi-point aspect of CE helps to create a layer-2 private network, with offices placed at various geographic locations. When a new customer site or office is to be added, it is connected to the same multipoint EVC thus simplifying provisioning and service activation. E-LAN services are of two types:

II. B. 1. Ethernet Private LAN (EPLAN): provides multipoint connectivity over dedicated bandwidth. In EPLAN service multiplexing is not available at a UNI. Due to dedicated pipes needed to create a LAN, EPLAN requires more resources to provision and is hence not particularly popular. Key applications that use EPLAN include video conferencing and distance learning both of which require dedicated bandwidth.

II. B. 2. Ethernet Virtual Private LAN (EVPLAN): provides multipoint connectivity using principles of bandwidth sharing. From customer's standpoint, this service makes a MEN resemble a campus / enterprise LAN. Most studies [1] forecast EVPLAN to generate significant revenue due to the ability to provision a large number of services while maintaining service differentiation and implementing strong SLAs. As compared to FR, EVPLAN is more efficient and easy to provision in being able to connect a large number of sites. Video streaming, IPTV, Video-on-Demand are few of the many dominant applications using this service type.

*II. C. E-Tree***:** is a rooted multipoint EVC. Nodes are distributed between a *root* and *leaves* of a tree. The root is able to multicast to all destinations but the leaves are only allowed to respond to the root. Typical application includes broadcast of video to residential customers and this is expected to be popular with *Multi-Service Operators* (MSOs).

II. D. Ethernet Service Requirements:

In this sub-section we discuss different Ethernet service attributes. According to the MEF, certain attributes such as Scalability, Standardized services, Reliability and Quality of Service are critical CE parameters [2,8].

II. D.1. Scalability: Carrier Ethernet deployments in the metro area must support thousands of users and deliver wide range of services with the flexibility to support more customers at distributed locations. Solutions to support large number of EVCs are desired. Network should scale to support large number of edge devices. Standard interfaces for inter-connection between networks like NNI (Network Network Interface) are proposed. Scalability is also desired to support bandwidth requirements from 1Mbps to 10 Gbps (and 100 Gbps in the future), in increments of 1Mbps. Automated or dynamic provisioning is essential as Ethernet services become complex and networks continue to grow. Centralized management and improved control plane solutions often using GMPLS technology are currently being investigated to provide end-to-end *operations, administration, maintenance and provisioning* (OAMP) features evolving in a scalable metro Ethernet network. Ability to efficiently provision TDM traffic over CE solutions in a scalable manner is another area of investigation.

II. D. 2. Reliability: is an important requirement for both customers and carriers. Using CE solutions to meet 99.999% reliability of both the equipment and the network, requires smart use of redundancy (in elements, capacity) as well as deployment of well structured restoration algorithms. To match TDM services, restoration algorithms have to converge within 50 ms. Restoration algorithms include techniques for path protection, node or link protection and fast rerouting mechanisms. Similarly fast-detection of network failure is key to good restoration in CE. High availability and in-service upgrade of software on network elements are suggested by the MEF as methods to improve reliability.

*II. D. 3. Quality of Service***:** Carrier Ethernet services include transfer of voice, video and data from enterprises and residential homes over the network. Voice and video are delay sensitive applications with stringent constraints on performance parameters. Video can be real time or non real time requiring low loss and jitter. Converged Ethernet networks have to satisfy different types of services having diverse performance parameters. There is a need to ensure that customer traffic entering a UNI is compliant to traffic policy. To ensure conformance to performance parameters like delay, jitter and loss, vendors propose efficient scheduling policies and active queue management techniques as part of their CE solution. In addition, given the sensitivity of performance parameters to traffic, providers use traffic-engineering tools to plan and manage their networks. Typical traffic differentiation is based on setting the Class of Service (CoS) bits in VLAN Tags. A second and more recently emerging aspect about service quality is the *Quality of Experience* (QoE), that the customer experiences from the offered service. Rapid investigation is underway in bridging the QoS and QoE for a particular customer and service.

*II. D. 4. Service Manageability***:** Manual maintenance of CE networks is difficult. Centralized automated management solutions with a universally acceptable control plane allow efficient management of CE networks. The control plane plays a role of being able to provide interoperability between vendors as well as facilitate SLAs between carriers. Manageability includes conformance to the Connectivity Fault Management (CFM, IEEE 802.1ag) suite that dictates how to provide carrier-class services amidst network failures and faults. The CFM standard also throws light on security and intrusion detection issues, highlighting the case for customer, service and equipment isolation. This helps to prevent entry of broadcast storms from a customer.

III. CARRIER ETHERNET TECHNOLOGIES

In this Section we delve into the underlying technologies in the MEN cloud essential in provisioning CE services.

Ethernet has gone through an evolution from a simple data sharing LAN technology to present day carrier-grade technology. We now show this evolution into Provider Backbone Bridging (PBB-TE) and Transport-MPLS (T-MPLS) – the two dominant technologies for CE.

III. A. We first discuss enabling building blocks for CE, and then focusing on CE technologies themselves, i.e. PBB-TE and T-MPLS.

*III. A. 1. MAC bridging 802.1D***:** Bridges were introduced as part of the IEEE802.1D standard to segregate LAN traffic thereby limiting the delay due to increase in the number of users using CSMA/CD technology. Ethernet bridging can be *transparent* or *source route* bridging, of which transparent bridging is of interest to CE technology. In transparent bridging the bridge deploys '*relay and replicate*' [2] philosophy while connecting two Ethernet domains. Through a learning process involving examining of the source MAC address, bridges update their forwarding table. A frame whose address is not part of the forwarding table is broadcast to all bridge ports except the one from where the frame arrived. Learning results in a single active path present between a source-destination pair thereby avoiding any *broadcast storms*. To remove any bridge loops in the network, *Spanning*

Tree Protocol (STP) is used. STP provides loop-free forwarding with ability to support multicast, broadcast as well as flooding. While STP can provide for restoration, the time required for convergence of the algorithm is high making it difficult to deploy in carrier networks.

III. A. 2. VLAN 802.1Q: Virtual LANs (VLAN) were proposed as a method to bifurcate a single LAN domain into multiple domains logically. By attaching a VLAN tag to an Ethernet frame, it is possible to differentiate traffic within a network by examining the 12-bit VLAN address within the VLAN tag. With VLANs multiple networks can now share the same physical network while maintaining isolation between *logical* networks. Ports on a switch can be grouped into VLANs thereby limiting traffic flooding to only a particular VLAN. A VLAN tag also has 3 *priority* bits marked to notate a service type. With this service field it is possible now to differentiate packet streams based on different service profiles. VLANs are a powerful tool in being able to differentiate traffic. However they have a limitation – the address space is restricted by the number of bits in the address-field header – 12, which leads to an overall address space of 4096 of which 2 are reserved. The 4094 addresses are not sufficient for a carrier to denote all its customers and provider layer-2 customer and service profiling. However, using VLANs as a starting technology, it is possible to make significant advancements thereby absolving the OAMP issue in Ethernet while also adhering to scalability and reliability.

III.B. Carrier Ethernet technologies: We now showcase technologies that are instructive in migrating Ethernet into use as a carrier class service:

III. B. 1. Q-in-Q Provider Bridge 802.1ad: The 12-bit address space in VLANs implies a limitation on the number of customers that a provider can support while administering QoS to the traffic. The problem is further pronounced if the customers (enterprises) have their own VLAN tags (from their internal networks), then the provider cannot use the same tag ID which would otherwise lead to potential conflicts. To solve this problem, the *Q-in-Q* technique was proposed whereby, a customer's VLAN tag was preserved by adding a service provider's VLAN tag (S-tag), appended to the customer's VLAN tag (C-tag). This double stacking of VLANs ensures that the C-tag is untouched and the provider could differentiate customers as well as provide services. This method of stacking VLANs (with the name Q-in-Q) has gained wide acceptance. IEEE802.1ad also standardizes the architecture and protocols to allow Ethernet frames carrying *multiple* tags however the standard suffers scalability issues due to availability of only 4094 addresses.

III. B. 2. Provider Backbone Bridge 802.1ah: Apart from the issue of scalability in the 802.1ad standard, another drawback is that the customer's MAC address is visible to nodes within the MEN, implying that provider nodes would now potentially learn un-trusted (customer) MAC addresses and build forwarding tables using these. To eliminate this problem and enhance scalability the *provider backbone bridging* (PBB) standard (IEEE802.1ah) was proposed. In PBB, a customer's frame is completely encapsulated in a provider's frame, providing a clear demarcation between customer contents and provider transport. The customer frame is cleanly mapped inside a provider frame and this process is called *MAC-in-MAC*. PBB header is composed of a source and destination *backbone MAC,* (B-MAC) address, a backbone VLAN ID (B-Tag) to divide the backbone into broadcast domains and a 24-bit service identifier (I-SID). The 24-bit I-SID defines a maximum of 16million service instances thereby solving the scalability issue. The demarcation between the customer and the carrier enables enhanced security because switches are not exposed to un-trusted MAC addresses that may potentially be sent into the network. This also means that the MAC space is limited to carrier domain thereby reducing the potential complexity of switch fabric and memory size.

III. B. 3. PBB-TE 802.1ay: Provider Backbone Bridges-Traffic Engineering (PBB-TE) also popularly known as PBT (Provider Backbone Transport) is a recent technology that supports connection oriented forwarding using native Ethernet. PBT has emerged from PBB, in the sense that it makes use of both stacked VLANs and MAC-in-MAC, but with some distinction. Spanning tree protocols which result in large convergence time are switched OFF when we traffic engineer the network using PBT. This allows us to create *manual* end-to-end connection oriented Ethernet paths with predictable bandwidth and delay. A second innovation in PBT is in addressing. While use of global VLAN tags implies that the address space is limited, using MAC addresses to identify source-destination pairs simply is not safe from a provider's perspective. What PBT does is that it takes the combination of a VLAN tag along with the globally unique MAC address, leading to a 60-bit (12+48) unique address. This address need not be learned but can be *applied* to switches in order to create an end-to-end Ethernet circuit, with all the OAMP features that one might expect in a carrier-class service. The 60-bit address is now used to identify the Ethernet path (towards the destination). PBT also makes use of IEEE802.1ad (stacked tags) to provide customer and service instantiation, as well as IEEE802.1ah bridging, to provide the necessary isolation between customer LANs and provider WANs. To set up these tunnels (i.e. to inform the switches of the 60 bit unique addresses in the absence of STP), we use a control plane, whose functioning is dictated by the connectivity and fault management (CFM) standard (IEEE802.1ag). The main technical leap witnessed with PBT is the ability to continue to use the Ethernet forwarding plane, while enabling carrier-centric tunnels that can be set up resulting in deterministic service parameters.

III. B. 4. T-MPLS: In parallel to the IEEE standardization process in using VLAN tags in the emerging PBB-TE standard, the ITU too was developing a carrier centric mechanism for transporting of Ethernet or equivalent layer 2 transport. The underlying assumption guiding ITU's development centered on the abundance of IP/MPLS routers spanning the core of most metropolitan domains and these boxes using Ethernet supportive interfaces. To transport Ethernet services, the ITU initiative is called *transport-MPLS* – derived from MPLS, making it connection oriented and carrier centric. T-MPLS is somewhat similar to PBT, in the sense that both are connection oriented and the control planes are assumed to be independent of the data plane, much like the optical supervisory channel in metro WDM networks. T-MPLS has certain similarities with MPLS, such as use of labels and method of forwarding, but there are also differences. Amongst these, the primary difference is in the manner in which labels are used: while MPLS does label switching along multiple paths for a single flow and assumes bidirectional paths, T-MPLS neither supports bidirectional paths or spreading the flow into several disjoint paths. T-MPLS simply sets up one tunnel from source to destination (no stopping at the penultimate node as in case of MPLS). This tunnel due to its deterministic nature of bandwidth and delay provides a carrier class solution for transport of any payload (not just Ethernet).

T-MPLS and PBT have significant similarities in the way they function, and have been proposed almost in overlapping times to solve the same problem. While a lot of qualitative comparison exists between the two technologies [3], with work even suggesting that these technologies are complementary [4], there is not much quantitative comparison available. A quantitative analysis by simulations is presented by us in this paper in Section VI.

IV. APPLICATION OF CARRIER ETHERNET

In this section we now discuss the major applications that will make good use of Carrier Ethernet.

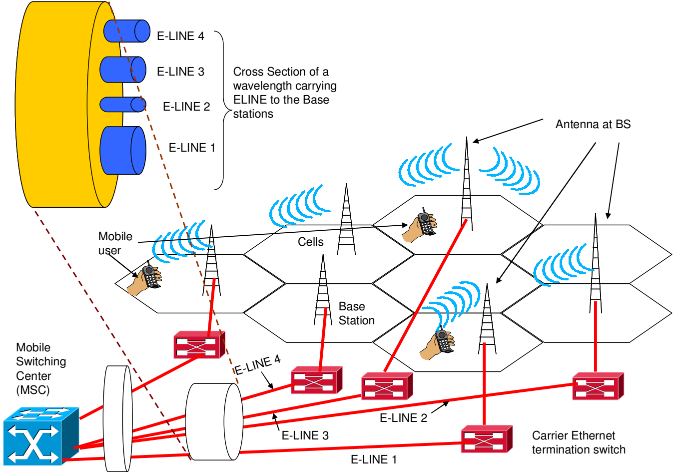

Fig. 3. Provisioning mobile backhaul traffic using ELINE

IV. A. Mobile Backhaul: Cellular traffic with value added multimedia content has been growing significantly over the last few years and is expected to grow rapidly in the foreseeable future. Much of this traffic is currently carried to the *mobile switching center* (MSC) from the *base-station* (BS) – the cell-tower, through SONET/SDH rings. With the gradual shift from TDM to Ethernet transport due to cost and granularity, mobile backhaul traffic now finds itself being increasingly transported over EVCs. The trend is certain to continue with carrier class Ethernet pipes dominating the transport for mobile backhaul. As shown in Fig. 3, the following attributes exhibited by CE are used in provisioning mobile backhaul service: dynamic bandwidth provisioning (EVC setup/tear down), low-delay service and reliable transport (with 50ms restoration). In addition, on account of the uncertainty in the number of users within a cell-site, the feature of scaling EVCs (in terms of granularity) is critical in supporting mobile backhaul traffic. SONET/SDH – the incumbent transport technology for mobile backhaul traffic, fails in scalability due to the fixed TDM hierarchy. Ethernet pipes on the other hand, are scalable (exhibiting statistical multiplexing) and with the introduction of CE, are also reliable with the associated OAMP, thereby making them the ideal choice for mobile backhaul transport as shown in Fig. 4. From a futuristic perspective, it is possible to take advantage of the ELAN concept in connecting BSs thereby avoiding the need to go to the MSC for hand-offs [5].

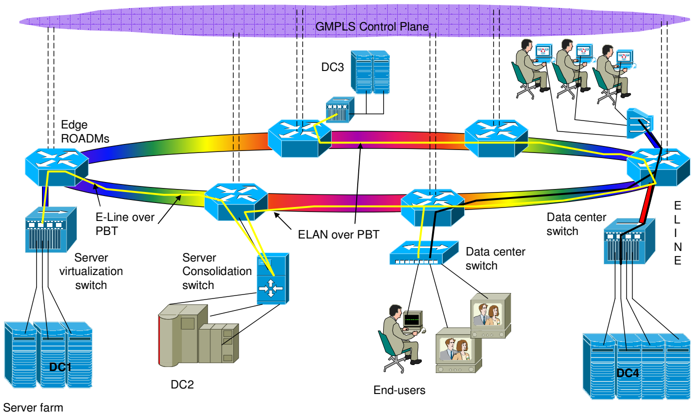

Fig. 4. Data-center virtualization using PBT technology.

IV. B. Data-center-SAN Convergence: Data center networks (DCNs) have emerged as a result of amalgamation of IT-services over telecommunication networks. Data centers (DCs) involve virtualization of services and consolidation of resources while automating transport and processing of applications over distributed entities. A typical network-attached data-center desires variable bandwidth, latency sensitive service, protocol-agnostic transport – all of which can be effectively met through PBT and T-MPLS implementations of CE. An implementation of a data-center attached network is shown in Fig. 4, where three DCs (DC1-3) are connected to the MEN. Client offices are connected to the DCs through PBT tunnels provisioned either as ELINE or ELAN. If the tunnel is provisioned as an ELAN, it implies that a particular application requires for its processing more than one DC. The ELAN hence becomes a distributed (virtual) switch. The key to provisioning DCN traffic is to be able to meet sudden application demands, in a rapidly changing traffic scenario.

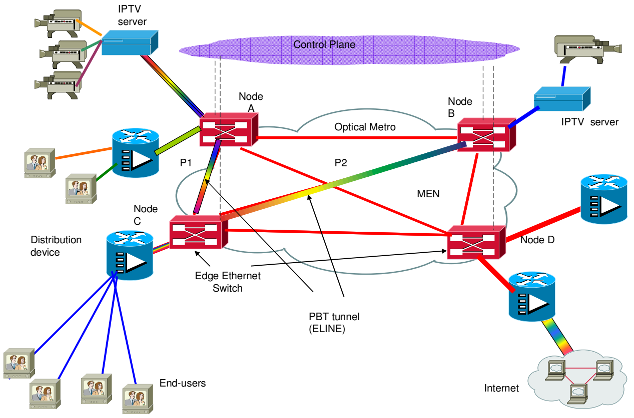

Fig. 5. Video distribution using IPTV and PBT as the underlying technology.

IV. C. IPTV and Video-on-Demand: Video applications through content providers as well as through *p2p* conferencing have become a major driver in the metro area. In fact, the growth of video traffic has been largely due to the deployment of CE technology especially in metro and enterprise networks. CE efficiently meets the delay sensitivity and bandwidth intensity requirements of video traffic. For video broadcasting, the ELAN or ETREE concept is deployed, while for p2p video streaming, the service multiplexing concept within the ELINE is deployed. Shown in Fig. 5 is a sample MEN network with an IPTV overlay. IPTV servers generate video content, which is efficiently transported to end-users through CE tunnels using PBT/T-MPLS technologies. The granularity of these tunnels is dependent on the demand of the videos, and hence making provisioning important. An out-of-band control plane is illustrated that controls edge Ethernet switches instrumental in setting up CE tunnels.

V. FUTURE TECHNOLOGIES AND CARRIER ETHERNET

In this Section we introduce technologies that would be instructive in defining the future of CE.

V. A. 100Gigabit Ethernet: The line-speed of Ethernet has increased from 10/100 LANs to 1Gbps and 10Gbps in the LAN/WAN with switched Ethernet technology. At 10Gbps, Ethernet and SONET/SDH are at cross-roads – SONET multiplying itself 4x in each version (OC3, OC12, OC48, OC192 and so on), while Ethernet multiplying itself 10x in each new variant finally meet at 10Gbps. However at the commonality point where data networks meet telecom networks (10G/OC192), there is a debate as to what the next Ethernet standard should exhibit in terms of line-rate. While, 40G Ethernet sounds unconventional (for Ethernet), it is more feasible given the nature of optical technology and impairments at 100G (with pulse width of 10ps, and severe phase penalties, as well as chromatic dispersion). However, with advances in optics (new modulation format) and smarter electronics (parallel MAC), it is indeed possible to propose a 100G standard for Ethernet, at least for short ranges to begin with. The IEEE802.3ab taskforce is currently investigating such a possibility with broad consensus being seen in terms of the complicated MAC layer (with 10 parallel lines of 10G speed being one possibility). This effort is particularly important in the growing data-center application space, connecting server farms across rooms or even between racks.

V. B. Sub-Wavelength Optical Networks: While WDM optical networks and circuits continue to dominate much of the physical transport layer, their ability to support services is somewhat rigid.

The physical transport networks using WDM technology and provisioning optical circuits have traditionally being used as a high-bandwidth static wavelength pipes. However, the requirement of emerging services is dynamism in provisioning and sub-wavelength in granularity. A lot of work is currently under way in the optical networking community trying to make networks agile, sub-wavelength and more dynamic. These sub-wavelength networks have the potential to react well to the dynamism in service needs while making efficient use of transponders and savings in CAPEX/OPEX [6] thereby maximizing CE returns on investments.

V. C. Inverse Multiplexing over Heterogeneous Networks: The bandwidth provided by optics in metro is unmatched by any other medium. However, for end-to-end provisioning, it is necessary that we travel across multiple domains, leading to a bandwidth mismatch. For example to map a GigE pipe onto a SONET/SDH signal implies using several PDUs of STS/STMs in conjunction leading to the rise of what is known as *inverse multiplexing*. The *Ethernet-over-SONET* (EoS) technology was the key to transporting *transparent LAN services* (TLS) before the rise of CE technologies. There are significant problems associated with inverse multiplexing of Ethernet signals over SONET hierarchy: a unified control plane that binds the ingress and egress nodes is mandatory; jitter control between multiple paths while provisioning end-to-end flows; and efficient fault-tolerant design. Multi-domain and hierarchical inverse multiplexing solutions are soon appearing in research articles. These have the potential to redefine CE in terms of flexibility and practicality while using existing SONET/SDH gear.

VI. SIMULATION BASED INSIGHTS

This Section discusses a simulations experiment that attempts to compare PBB-TE and T-MPLS technologies. While both PBB-TE and T-MPLS have been devised to essentially solve the same set of problems (towards Ethernet OAMP), there are some subtle working issues that we highlight through simulations. We built a discrete event simulator over an interconnected ring topology. Each node in the topology assumed to be a Re-configurable-Optical-Add-Drop Multiplexer – *ROADM*, connected to a Carrier Ethernet switch, which could support either T-MPLS or PBB-TE. Each ring assumed WDM technology with 40 wavelengths and an extra wavelength in each direction for control (GMPLS). Each of the peripheral nodes was connected to multiple enterprise offices through UNIs. The enterprises generated data traffic in form of Ethernet frames (a *class* used in the simulation), with random destinations (within the network). Frame generation was bursty – modeled as a Pareto distribution with Hurst parameter fixed at 0.8. Frame size was assumed to be exponentially distributed with a max of 1500 bytes. Traffic was assumed to have 4 priority values (000 to 010) corresponding to 3 applications (VoD, DCN and mobile) and data traffic. There are 3 aspects of T-MPLS and PBB-TE that are used for comparison: scalability, dynamism and utilization.

For scalability we compute the average delay that a packet undergoes while traversing through the network (neglecting propagation delay). Shown in Fig. 6 is a plot of the average delay for PBB-TE and T-MPLS as a function of nodes in the network. We begin with a single ring of 4 nodes, incrementing to 6 interconnected rings each of 8 nodes (total 48 nodes). Delay is measured by the amount of time a frame spends in switches, while being processed. To compute delay, the simulator models a PBB-TE/T-MPLS switch as a non-blocking switch, with a quad-core processor, with the model as described in [7]. Connection provisioning time is neglected. The x-axis can also be viewed as load, whereby the load increase as the number of nodes increases. Our primary observation is that PBB-TE has a better delay profile than T-MPLS for lower node-counts. But as the node counts increases (and so does load), T-MPLS has better performance (possibly because of easier processing due to absence of multi-stacked labels). This implies that T-MPLS is possibly a better core technology and suited to handle voluminous traffic. To validate this behavior we computed delay though the 7 ring network, with each of the peripheral rings deploying PBB-TE, and the sole central ring deploying T-MPLS. This result gives a new minima end-to-end delay thereby validating our claim.

These measurements are taken with a confidence interval (CI) of 90%, allowing a 10% statistical error.

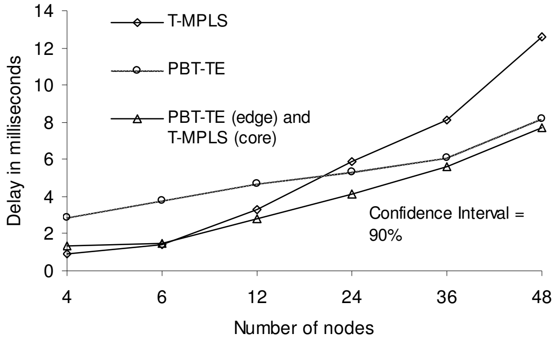

Fig. 6. Delay for T-MPLS and PBT

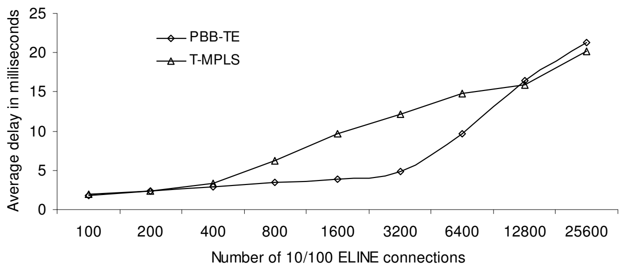

Fig. 7. Scalability for T-MPLS and PBT

Shown in Fig. 7 is a plot of average delay as a function of number of connections in the network. For this plot we consider 7 rings, with a central ring and 6 peripheral rings. The main result is that PBB-TE allows better scalability than T-MPLS at low to medium loads. Our interpretation of this is that this is because of the hierarchical structure of labels (B-tags, C-Tags and S-tags) in PBB-TE.

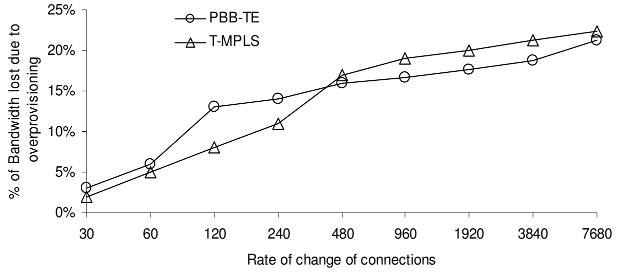

Fig. 8. Service provisioning using T-MPLS and PBT

Shown in Fig. 8 is a comparison between the two technologies for delay profile as a rate of change of connections. To generate this graph, we assumed the arrival process to change, with a *rate-of-change* parameter. Each connection was assumed to sustain for a maximum value of 20 minutes, making the system dynamic. As the rate of change increased, the average connection duration decreased. Our interest is to measure how much capacity in a GigE pipe is being wasted in terms of provisioning connections. To measure this we assume that each ELINE has to be set up within 20 ms (a hard-deadline, neglecting propagation delay), and if this was not possible, then some over-provisioning was assumed (provisioning begins ahead in time, and hence loss of bandwidth). It is this amount of over-provisioned bandwidth that we desire to investigate. As seen in Fig. 8, as the rate of change of connections increases, the amount of over-provisioned bandwidth increases monotonically, and in some sections even exponentially. The interesting observation is that PBB-TE is outperformed by T-MPLS for lower rates of change (note that the load is constant at 60%). However, at the same network load, when the rate of change is high, PBB-TE outperforms T-MPLS by about 8-10% with a CI of 97%. The two technologies somewhat converge in performance when the rate of change reaches the total number of ELINEs in the network. In summary from the three graphs it implies that

PBB-TE is more scalable than T-MPLS for most loads, while T-MPLS is more suited to voluminous traffic (core). Also, for dynamic traffic, as in the metro/access, PBB-TE performs better than T-MPLS. However, we must add, that the difference between the two in terms of performance is always less than 20 %, and in most cases less than 10 %, with a simulations confidence of about 92~97%.

VII. CONCLUSION

We have recapped the underlying technologies that make Ethernet carrier class, delving on the architectural and protocol issues as well as providing an evolutionary path. We have defined both the IEEE and ITU approaches leading to PBB-TE and T-MPLS respectively in terms of the concepts as well as the technology. We then highlight three driver applications: *data-centers*, *mobile backhaul* and *IPTV-video-on-demand* and show how each can be provisioned using CE technologies. A simulations study, comparing PBB-TE to T-MPLS in terms of delay, over-provisioning and scalability gives us insights into these technologies.

REFERENCES

[1]. www.lightreading.com 2006 Survey of Ethernet Service Providers.

[2]. D Fedyk, Dave Allan, “Ethernet Data Plane Evolution for Provider Networks,” IEEE Communications Magazine, March 2008 Vol. 26 No. 3. pp 84-88.

[3]. Website: www.tpack.com / whitepapers

[4]. S. Salam and A. Sajjassi, “Provider Backbone Bridging and MPLS: Complementary Technologies for Next Generation Carrier Ethernet Transport” IEEE Communications Magazine pp 77-82 March 2008.

[5] A. Gumaste, et. al. “Generalized ROADM/Light-trail Assisted Hand-Off for Wireless Metro Networks" to appear in the 7th The 10th International Symposium on Wireless Personal Multimedia Communications (WPMC), Jaipur, India, Dec. 2007

[6]. A. Gumaste and S. Q. Zheng, “Optical Storage Area Networks: The Light-trails Approach,” *in IEEE Communications Magazine* March 2005 pp 72-78 Vol. 21. No. 3.

[7] M. Klymash, V. Romanchyk, B. Struchaluk, “Simulation of a gigabit Ethernet switch for transporting optical networks,” Modern Problems of Radio Engineering, Telecommunications and Computer Science, 2004. Volume , Issue , 24-28 Feb. 2004 Page(s): 444 - 445

[8]. L. Fang, N. Bitar, R. Zhang, S. Amante and M. Taylor, “The Evolution of Carrier Ethernet Services-Requirements and Deployment Case Studies” IEEE Communications Magazine, , March 2008 Vol. 26 No. 3. pp 84-88. 9.

[9]. White paper: “Understanding Intelligent Carrier Ethernet,” Cisco Systems.

[10]. White paper “Provider Backbone Transport,” Nortel Networks.