Can OTN be replaced by Ethernet?

A network level comparison of OTN and Ethernet with a 5G perspective

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***Abstract*—Ethernet has evolved from a protocol for local area network transport to advanced carrier class metro transport as new features are brought in. Recently, industrial, automotive and 5G mobile fronthaul network applications have been addressed. Several new mechanisms are proposed and standardized, e.g. enabling deterministic latency. In light of 5G requirements, this paper reviews and discusses differences between Ethernet and ITU-T G.709 - Optical Transport Network OTN, and analyses Ethernet as an alternative to OTN for optical transport and access network applications.**

Keywords—OTN; carrier Ethernet; deterministic Ethernet; RAN; fronthaul

I. Introduction

The optical network is constantly evolving into an increasingly number of application areas. While starting in the transport network, it has now evolved into the access network with Fiber To The Home (FTTH) and is also the preferred choice for transport in the mobile Radio Access Network (RAN). SDH/SONET was originally developed for the purpose of transporting voice and data traffic across the optical network. The need for supporting the growing data-traffic and Wavelength Division Multiplexing (WDM) motivated the need for the Optical Transport Network (OTN) G.709 [1] protocol. When OTN was designed, the amount of data-traffic had increased beyond the amount of voice-traffic and a variety of transport protocols were used simultaneously in the network, like e.g. ATM, SDH, PDH and Ethernet. Thus, OTN was designed for transporting all these protocols and is currently the preferred physical layer protocol for optical transport networks.

Ethernet started out as a Local Area Network (LAN) protocol over a shared coaxial cable medium. Since then it has constantly evolved and now stands out as an alternative for telecom networks, especially for metro and mobile RAN transport applications. While the old operators still offer circuit switched services like e.g. PDH and SDH, a heritage from the past, building pure Ethernet packet based transport networks is especially attractive for operators established in a time when data-traffic transport is the dominant service. If some of their customers require transport of circuit services over the packet network, circuit emulation over packet may be applied.

The quality of packet services varies and depends on the load of the network and if Quality of Service (QoS) mechanisms are applied. Packet delay varies with load, and packet loss may occur if the network is congested. Circuit services on the other hand are known for always offering high performance, i.e. low and fixed latency and no packet loss. While packet services today are the dominant service offering compared to circuit services, the performance and reliability requirements are becoming stricter than ever. For the 5G networks, the demand for meeting low latency applications is put forward as one of the main differentiators from previous generations of networks. Furthermore, the vision of the 5G networks includes building the network with a high density of short-range radio access points for achieving high capacity and low latency. For cost efficient operation and network design, this motivates the use of disaggregated RAN, centralizing functionality in a Base Band Unit (BBU), feeding several Remote Radio Heads (RRH) through a so called “fronthaul network” [2, 3]. Recently, a new specification, eCPRI [4] targeting fronthaul networks, was released. While it does not specify a protocol for its transport, two candidate protocols for this are OTN and Ethernet.

In this paper we compare OTN and Ethernet for use in optical transport and access networks in general. Additionally, we discuss the strict delay requirements of the 5G network and how these can be met in optical mobile front and backhaul networks.

II. Optical Transport and access network requirements

A. *Mobile fronthaul and backhaul delay requirements*

There are two main drivers putting strict delay requirements on mobile fronthaul for 5G networks: the delay sensitive services targeted by the 5G network, and the fronthaul design itself. Figure 1 illustrates the maximum tolerable delay of some delay-sensitive applications that will need to be supported by both future backhaul and fronthaul networks.

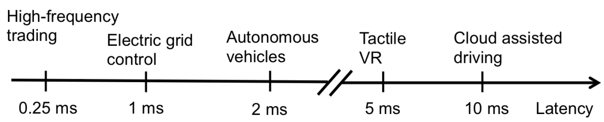

Figure 1. Delay sensitive applications, adapted from [5]

As seen in the figure, there are applications tolerating delays of 1 ms or less among the 5G target applications. The delay requirements in eCPRI-based fronthaul are even stricter. For fronthaul transport with split in the physical layer, as found in CPRI over Ethernet [6] and in eCPRI option “D” and “E” [4], the Hybrid Automatic Retransmit reQuest (HARQ) protocol sets restrictions on maximum delay between the RRH and BBU. In [7], a one-way delay of 123 μs is found as the maximum. In [4] and [8] an even stricter delay requirement of 100 μs one-way delay is set as a requirement.

B. Optical transport network requirements

While mobile backhaul and fronthaul requires transport over moderate distances, typically below 100 km, the optical backbone network offers transport over several hundred or thousands of kilometers. Hence, a dominant delay-component in the backbone network is the delay in the fibre itself, given as 5 μs/km. A key feature for long distance transport is the Forward Error Correction (FEC), enabling correction of bit-errors due to physical impairments along the optical transport path. Furthermore, Operations Administration and Management (OAM) functionality is of high importance for detecting and communicating errors, as well as characterizing performance of the network. While FEC is of highest importance for long distance transport, where physical impairments have the greatest impact, OAM capabilities are important also for metro and access networks. Furthermore, when carriers are offering services, bandwidth isolation between these services for avoiding interference between traffic of different customers is desirable. In addition, carriers with a history in offering SDH/SONET services are still offering transport of legacy protocols like e.g. SDH, PDH, InfiniBand, ATM and Ethernet. While the SDH/SONET network was natively synchronous, today mobile networks also demand frequency and time synchronization [8]. This may be supported locally by synchronizing using GPS. However, a GPS signal may be difficult to distribute, especially to base-stations located e.g. within large buildings. Furthermore GPS may be disturbed by jamming or e.g. solar storms. Hence, because of security and reliability reasons distributing time and frequency in the network is desirable.

III. OTN FUNCTIONALITY

OTN has inherited many functions from SDH/SONET. The data streams to be transported are framed into containers of fixed length, encapsulating the payload together with fields containing additional information. This information enables e.g. OAM for wavelengths, universal container supporting any type of service, communication channels for control traffic, end-to-end optical transport transparency of customer traffic and multi-level path OAM [9]. The OAM functionality has a number of features. This includes e.g. end-to-end path monitoring using parity check: Bit Interleave Parity (BIP) for finding bit errors in the Optical Payload Unit (OPU). Furthermore, the Tandem Connection Monitoring (TCM) is a powerful tool enabling monitoring across different networks and operator domains by using up to six dedicated fields for error checking. Six independent tandem connections may then be monitored, allowing both overlap and nesting of the connections [10]. The TCM allows carriers to define their own path layers for monitoring, enabling paths to go across different networks and operator domains. As an example, a connection belonging to operator A, but crossing three operator networks on its way: A, B and C is illustrated in Figure 2. Carrier A uses the end-to-end path monitoring for monitoring the customers signal from the entry to the exit of the network. Carrier A additionally uses TCM2 for monitoring the signal when crossing carrier B and C. Carrier B uses TCM1 to perform path monitoring at the entry and exit points of its networks. Likewise, Carrier C may re-use TCM1 to perform path monitoring on the signal as it enters and exits the Carrier C network [9].

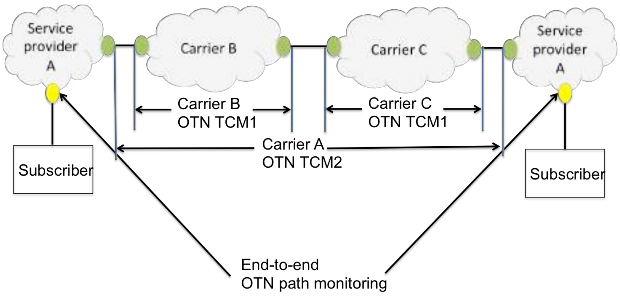

Figure 2. Example of TCM and end-to-end path monitoring in OTN.

The smallest container defined in OTN is the Optical Data Unit 0 (ODU0), operating at 1.25 Gb/s [1]. Hence, this defines the smallest channel rate in OTN, resulting in waste of bandwidth if trying to map a channel of lower bitrate into an OTN channel. OTN is suited for multiplexing client signals of 1 Gb/s bitrate and beyond into higher bitrate line-signals. On the line-side, OTN supports 2.5 Gb/s, 10 Gb/s, 40 Gb/s and 100 Gb/s. A standard multiplexing hierarchy exists enabling a mapping structure defining how to map client signals of different bitrates into higher bitrate line signals. For all channels transported in OTN yields the same benefit of full transparency and bandwidth isolation.

Furthermore, while OTN was originally a point-to-point transport and grooming technique, OTN switching is now available. Transparent switching of the client channels independent of type of service and the transported protocol is achieved. Hence, switching of fully monitored virtual links is enabled since performance and alarm monitoring capabilities are preserved end-to-end.

The General Communication channels (GCC1 and GCC2) allow communication between two network elements having access to the ODU frame structure. Since the communication channel is based on using reserved fields within the frames, both bandwidth and communication is guaranteed independent of payload content and network load.

Forward Error Correction (FEC) enables detection and correction of errors in an optical link caused by physical impairments in the transmission medium. When using FEC, a lower signal quality in the link can be accepted, e.g. by adding a 7 % FEC overhead, a gain in power level of approximately 5 dB is achieved [9]. FEC is a powerful tool in OTN. A higher gain in power level than the FEC first defined for OTN is now available. This is especially attractive for sub-sea systems where power margins are a scarce resource.

IV. Ethernet Functionality

In Carrier Ethernet, new functions has been brought in for making Ethernet more suitable for network operators building Metropolitan Area Networks (MAN) and Wide Area Networks (WAN) [11]. Ethernet is not only applicable for point-to-point transport, like OTN. Carrier Ethernet also defines point to multipoint and multipoint to multipoint transport. Furthermore, while OTN is based on framing data into fixed length frames in fixed data-rate channels, Ethernet allows framing of data of variable bitrate into variable length frames.

A main difference between OTN and Ethernet is how multiplexing is performed. OTN always applies static multiplexing of lower bitrate channels into higher bitrate channels. Ethernet typically applies statistical multiplexing, allowing efficient multiplexing of variable bitrate channels with statistically distributed packet arrival patterns. While this allows for efficient multiplexing using buffers for smoothing out packet bursts, buffering adds a delay depending on the traffic patterns. This is a challenge for some applications, like e.g. mobile fronthaul, having very strict requirements to packet delay and packet delay variations. However, Ethernet allows a number of different ways of doing multiplexing since a single method is not explicitly defined in the IEEE 802.1Q [12] standard defining Ethernet. As an example, for each output interface, one output queue may be assigned per input interface. A multiplexing method is then to go round-robin on queues, scheduling packets from the queues one-by-one to the output interface. Hence, if packets arrive simultaneously at the input interfaces but destined for the same output, one or more packets must stay in their queues before being scheduled to the output. Because the buffering delay then varies according to how many packets are arriving simultaneously at the inputs, this causes packet delay variation (PDV). Furthermore, if the volume of traffic being multiplexed to an output interface is larger than the bandwidth of the interface, queues will fill up resulting in packet loss and high delays. While this may be sufficient for e.g. Internet applications like web-browsing applying TCP for retransmission, it is not sufficient for time and loss -sensitive applications.

A. Making Ethernet deterministic

Recently, a number of mechanisms have been proposed enabling zero packet loss and a low and even fixed delay in Ethernet. This has especially been attractive for industrial applications of Ethernet, named “deterministic Ethernet”. In Integrated Hybrid (hybrid as in packet and circuit) Optical Networks (IHON) [13], mechanisms addressing optical transport with zero packet loss and fixed delay are proposed and explored for Ethernet. In the IEEE 802.1 Ethernet standardization group, mechanisms ensuring zero congestion packet loss, as well as bounded delay and PDV are proposed. Recently, main drivers for the evolvement in standardization include industrial control and automotive applications, with mobile fronthaul as the most recent.

1) Deterministic delay

In the IEEE 802.1 work, Time Sensitive Network (TSN) mechanisms include both mechanisms for minimizing delay and for controlling the delay variation, ensuring that all priority packets receive low and bounded delay. The IEEE 802.1Qbu [14] defines a preemption mechanism enabling minimized delay on deterministic traffic when mixed with best-effort traffic within the same network. By disrupting the transmission of best-effort packets when a time-sensitive high priority packet arrives, packet delay caused by packet contention is lower than e.g. the strict priority mechanism where maximum delay corresponds to the duration of a best-effort Maximum Transfer Unit (MTU) packet. Preemption is only performed if at least 60 bytes of the pre-emptable frame are already transmitted and at least 64 of the frame remain to be transmitted, resulting in a worst case delay of 155 bytes and best-case zero delay [8]. Hence, PDV correspond to the duration of transmitting 155 bytes. Preemption works hop-by-hop, reassembling incoming and fragmenting outgoing packets at every hop. Since fragments do not contain e.g. MAC address-headers, forwarding of fragments through bridges is not supported, i.e. preemption may only be activated with bridges supporting the IEEE 802.1Qbu standard.

The IEEE 802.1Qbv [15] (enhancement for scheduled traffic) defines how a set of queues, destined for an output port, may be served by a round-robin mechanism; As opposed to a round-robin scheduling, where delay depends on the number of queues populated with packets, it allows each queue to be served within a dedicated timeslot. One-by-one in a cycle of timeslots, one or more packets are scheduled in bursts from each of the queues into their designated time-slot. The duration, and hence, start of the time-slots, is deterministic. Moreover, time-synchronization is required, e.g. using the IEEE 1588 protocol [16]. The maximum delay on a packet is given by the duration of the scheduling cycle.

A mechanism not relying on packet preemption, while enabling a mix of deterministic traffic and best-effort traffic in a network, is a time-window based priority mechanism described for IHON. The mechanism eliminates PDV on the time-sensitive traffic by adding a fixed delay corresponding to the MTU of the best effort traffic. Best effort packets are scheduled in between time-sensitive packets whenever a gap is available that is equal to- or larger than- the packet waiting in a best effort queue. Thus, any interference and PDV on the time-sensitive traffic caused by best effort traffic is eliminated. As opposed to preemption, the mechanism allows packets to be transmitted also through bridges not supporting the time-window mechanism, achieving lowered PDV in the network for each node that it is applied to.

Furthermore, IHON describes an aggregation and scheduling mechanism where PDV from contention is avoided. The mechanism relies on preserving the packet gaps between packets in the individual deterministic packet streams.

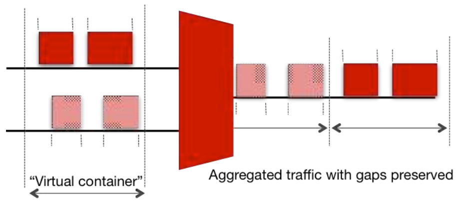

Figure 3. Aggregation of multiple deterministic packets streams into virtual containers while preserving packet gaps.

Packet streams being aggregated are scheduled into time-slots in a cycle synchronized across the network using a control packet at the start of each time-slot. However, the packet streams aggregated are allowed to be asynchronous with variable length packets and still transferred with no added PDV. As illustrated in Figure 3, the streams being aggregated are divided up into virtual containers, fitted into time-slots, before being scheduled to the output. A minimum fixed delay corresponding to one cycle time is added to each of the packet streams.

2) Ethernet performance examples

An IHON field-trial demonstrates deterministic aggregation of 1 Gb/s into 10 Gb/s Ethernet, transmission through 3.25 km of fibre and de-aggregation back to 1 Gb/s with load independent end-to-end delay of 67.22 µs and PDV of 160 ns [13]. Furthermore, experiments have been performed demonstrating combined fronthaul and backhaul traffic in a 100 Gb/s Ethernet wavelength [21]. The fronthaul traffic receives a low latency and ultra low PDV independent of load, while the less time-critical backhaul traffic experiences a higher latency and PDV. For the emulated fronthaul traffic, delay through one node was measured to 1.3 µs and PDV to 0.2 µs, independent of fronthaul and backhaul traffic loads. Hence, at 100 Gb/s speeds even tens of hops can be allowed, still meeting the 100 µs fronthaul delay limit.

3) Avoiding packet loss by controlling bandwidth

For carrier Ethernet applications, policing mechanisms for controlling the bandwidth into the network are defined [12]. A policer is a mechanism limiting the bandwidth into and/or out of a queue, enabling a service provider to offer sub-rate bandwidth services with a lower bitrate than the physical bitrate of the interface being offered. I.e. policing allows the bandwidth offered being any bandwidth equal to- or lower than- the bandwidth of the interface. A guaranteed offered bandwidth is defined as a Committed Information Rate (CIR), where packet loss in the network due to contention and full buffers should not occur. An Excess Information Rate (EIR) defines additional traffic being allowed, but that may be dropped in a congested network. Traffic exceeding the EIR is always dropped.

B. Framing legacy formats in Ethernet

The Ethernet standard [12] does not define framing of legacy formats like TDM and ATM into Ethernet frames. Circuit emulation techniques do exist for Ethernet, but applying an MPLS layer on top of Ethernet for multiservice transport is a more common approach [9]. For MPLS, circuit emulation techniques are defined enabling transport of legacy signals, sharing the links with the IP/Ethernet based data. Ethernet networks may therefore not be an efficient choice if e.g. mainly legacy services are to be transported. However, when the amount of legacy services are minor, Ethernet with circuit emulation support is likely to be the best choice for the future.

C. OAM in Ethernet

Both link OAM [17] and end-to-end service monitoring, service OAM [18], are defined for Ethernet. Different administrative levels are defined allowing different user types accessing different Service OAM capabilities. These levels are called Maintenance Entity Groups (MEGs) in the ITU-T Y.1731 [17] standard. Eight levels of MEGs are defined, allowing different levels to be applied across different service providers and between subscribers. This is applied for monitoring Ethernet Virtual Connections (EVC) or Operator Virtual Connections (OVC) defined by their Maintenance Endpoint (MEP). Maintenance Intermediate Points (MIPs) are placed between MEPs and used at internal interfaces in the carriers for additional troubleshooting purposes. This is illustrated in Figure 4; all parties are capable of individual monitoring of their service: the subscriber, the carrier delivering the service across the network (service provider A), and the individual carriers involved, carriers B and C. Performance parameters being monitored are packet loss, packet delay and packet delay variation.

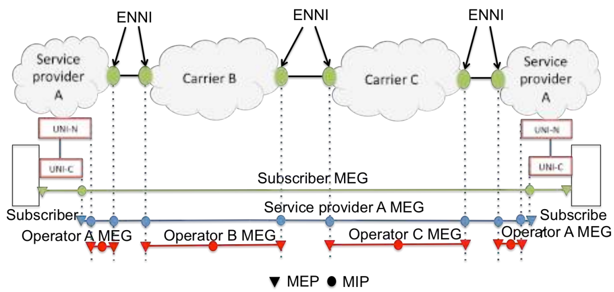

Figure 4. Different MEG levels applied between different service providers and the subscriber. ENNI: Ethernet Network-Network interface. UNI-N: User Network Interface Network side. UNI-C: User Network Interface Customer side.

D. Ethernet fault management

End-to-end connectivity Fault management for Ethernet is defined in [18]. Two important tools are continuity check and link trace. For continuity check, Continuity Check Messages (CCMs) are exchanged between MEPs. The rate of the CCM messages may be set high, enabling availability being measured every 10 ms, or even more frequent. Link trace sends Link Trace Messages (LTM) over EVCs or OVCs. The MEP and MIPs along the EVC/OVC return a Link Trace Respond message, confirming the MEP/MIP points availability. Hence, this enables a precise fault location within the network.

E. Ethernet and FEC

FEC has not been a part of Ethernet until recently. As bitrates are increasing to 100 Gb/s and beyond, FEC becomes a requirement for achieving sufficiently long reach. For 100 Gb/s, IEEE 802.3bm [19], and for 200 Gb/s and 400 Gb/s, IEEE 802.3bs-2017 [20], FEC is defined as a feature.

V. Comparison OTN and Ethernet

In this section we compare the properties and functionality described for OTN and Ethernet. An overview of the properties is given in table 1. As can be observed both OTN and Ethernet support most of the listed features. There are however some major differences, mostly related to OTN being a circuit type of transport only. I.e. OTN only supports static multiplexing with 1.25 Gb/s as a minimum bandwidth on point-to-point services. Ethernet on the other hand, supports both static and statistical multiplexing of any bandwidth and both point-to-point and point-to-multipoint transport services. While the OTN static multiplexing is known to enable absolute guarantees on the services: zero packet loss, fixed and low delay, Ethernet may achieve the same properties using IHON mechanisms, which enables static multiplexing. In addition, IHON may be used for inserting packets in gaps between packets in a static multiplexed packet stream. Statistical multiplexing may then be combined with static multiplexing, increasing throughput without imposing delay variations or packet loss on the static multiplexed packet stream. For a mobile fronthaul application, the bandwidth granularity of OTN is sufficient for transport of eCPRI rates and statistical multiplexing may not be required for this purpose. However, if fronthaul and backhaul is combined within the same link, the throughput of the backhaul transport may benefit from the statistical multiplexing capability since strict delay guarantees may not be required for the majority of the backhaul traffic volume. While for metro and backbone network transport purposes the bandwidth granularity of OTN may be sufficient, offering enterprise and residential services typically requires higher bandwidth granularities in the order of tens of Mb/s that can be satisfied by Ethernet. Furthermore, especially in the metro and access network, carriers may benefit from the statistical multiplexing of Ethernet efficiently aggregating traffic at the edge of the network.

Looking into OAM and fault handling capabilities, both OTN and Ethernet are equipped with a powerful set of tools for ensuring and documenting delivery of customer services crossing multiple carrier network domains. A major difference is however that OTN monitors errors at a bit-level while Ethernet monitors at a packet level. This makes OTN OAM more suitable for characterizing physical link quality while Ethernet OAM is more suitable for revealing congestion in Ethernet nodes. While OTN monitors bit-errors only, Ethernet OAM may be used for documenting packet loss, delay and delay variation of services.

Table 1. Comparison of features for OTN and Ethernet

Feature	**OTN**	**Ethernet**
Legacy service transport	Framing any service	Additional circuit emulation protocol required
Packet service transport	Fixed rate circuit	Native packet - variable rate statistical multiplexing
Connectivity type	Point-to-point	Point-to-point Point-to-multipoint Multipoint-to-multipoint
Granularity of bandwidth	Min. 1.25 Gb/s (ODU0)	Any bandwidth
Time-sensitive application support	No buffering for contention: Low and fixed latency	Low and fixed latency using IHON. Bounded delay using IEEE TSN mechanisms.
Multiplexing type	Static	Static and/or statistical
Switching capability	Circuit switching, 1.25 Gb/s granularity.	Packet switching with packet granularity.
Operation and Maintenance	End-to-end Path and 6 levels of TCM	End-to-end Service monitoring and 8 MEG levels for EVC monitoring
Parameters monitored	Bit errors	Packet loss, delay, delay variation
Fault management	Monitor mode TCM	Continuity check and link trace
Error correction	Correction of bit errors using FEC	FEC available for 100 Gb/s and beyond.

Furthermore, OTN is always equipped with a FEC code, enabling a high tolerance to signal quality degradation in the link. This especially comes in handy on long distance optical links where signal quality is degraded by noise from optical amplifiers and non-linear physical transmission impairments in the fibre. For mobile fronthaul and backhaul, as well as metro and access network distances, amplifier noise and transmission impairments are less of a problem, and FEC and physical link monitoring therefore typically become less important. For very high bitrates of 100 Gb/s and beyond, Ethernet also defines FEC as a feature. However, long distance transport beyond 10 km is currently not defined for these bitrates. Hence, OTNs FEC enables benefits for long distance transport networks while Ethernet will be sufficient for metro, access and mobile transport network purposes.

VI. Summary and Conclusion

In this paper OTN and Ethernet network functionality has been compared with respect to applications including longhaul, metro, access and mobile fronthaul and backhaul. Because OTN natively defines how to frame a number of different protocols into OTN frames, it is more suitable than Ethernet for transport of legacy services. We expect however this to become less relevant for future networks. We find that using the functionality added to Ethernet through Carrier Ethernet, it now offers the same level of OAM functionality as OTN. Furthermore, OTN with static multiplexing supports a zero packet loss, low and fixed latency transport with full isolation between services. This is however also achieved in Ethernet using the IHON mechanisms. Furthermore, while providing the same level of deterministic service as OTN, Ethernet may additionally allow higher throughput utilization through statistical multiplexing using IHON mechanisms. OTNs Forward Error Correction capability is known to extend the reach of long-haul transport and is available for all OTN rates. For high Ethernet rates, 100 Gb/s and beyond, FEC is added, opening up for the same benefits as earlier only found for OTN. For these bitrates current maximum distance defined for Ethernet is 10 km.

OTN therefore shows benefits for legacy service and long-haul transport. For network segments less sensitive to physical transmission impairments, including metro, access and mobile backhaul and fronthaul, we find Ethernet to deliver the same level of service quality and availability while supporting a higher throughput efficiency than OTN. Hence, our conclusion is that today Ethernet is a beneficial choice for mobile transport, access and metro networks while only OTN is defined for high bitrate long-haul transport. Furthermore, as Ethernet today also contains FEC, up to now the prime OTN benefit for longhaul, it may replace OTN in the future for long-haul if IEEE chooses to define long-haul Ethernet interfaces.

Acknowledgment

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