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QoS Performance of Integrated Hybrid Optical Network in Mobile Fronthual networks

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Abstract

Cloud Radio Access Network (C-RAN) has emerged as a promising solution to meet the ever-growing capacity demand and reduce the cost of mobile network components. In such network, the mobile operator's Remote Radio Head (RRH) and Base Band Unit (BBU) are often separated and the connection between them has very tight timing and latency requirements. To employ packet-based network for C-RAN fronthaul, the carried fronthaul traffic are needed to achieve the requirements of fronthaul streams. For this reason, the aim of this paper is focused on investigating and evaluating the feasibility of Integrated Hybrid Optical Network (IHON) networks for mobile fronthaul. TransPacket AS (www.transpacket.com) develops a fusion switching that efficiently serves both Guaranteed Service Transport (GST) traffic with absolute priority and packet switched Statistical Multiplexing (SM) best effort traffic. We verified how the leftover capacity of fusion node can be used to carry the low priority packets and how the GST traffic can have deterministic characteristics on a single wavelength by delaying it with Fixed Delay Line (FDL). For example, for L_{1GE}^{SM} =0.3 the added SM traffic increases the 10GE wavelength utilization up to 89% without any losses and with SM PLR=$1E^{-03}$ up to 92% utilization. The simulated results and numerical analysis confirm that the PDV and PLR of GST traffic in Ethernet network meet the requirements of mobile fronthaul using CPRI. For Ethernet network, the number of nodes in the network limits the maximum separation distance between BBU and RRH (link length); for increasing the number of nodes, the link length decreases. Consequently, Radio over Ethernet (RoE) traffic should receive the priority and Quality of Service (QoS) HP can provide. On the other hand, Low Priority (LP) classes are not sensitive to QoS metrics and should be used for transporting time insensitive applications and services.

Keywords: *C-RAN, Fronthaul, IHON, BBU, GST*

1. Introduction

BSs for mobile communication have been evolved from a bulky rack-full of equipment to multiple form factors aimed at different deployment scenarios. Traditionally, the collection of these multiple stand-alone BSs/BTSs has been treated as RANs or cellular networks [1]. A single BTS had multiple transceivers to serve several different frequencies and different sectors of a cell when a sectorized BS is considered and covers a small geographical area, whereas a group of BTS may cover a large continuous geographical area. Each BTS was responsible for processing and transmitting its own signal to and from UE, and forwards the data payload to and from the UE and out to the core network through the mobile backhaul. The cellular network has evolved through a series of innovations aimed at unified targets: performance and efficiency in high mobile environment [2], beginning with the analog First Generation (1G) cellular networks to Fifth Generation (5G) (which is expected to be deployed initially in 2020 to provide about 1000 times higher wireless area capacity and save up to 90% of energy consumption per service compared with the current 4G system [3, 4]). The 1G system provided the basic mobile voice service based on analog radio transmission techniques. It employed Frequency Division Multiple Access (FDMA) to multiplex traffic flows. Nordic Mobile Telephones (NMTs) and Total Access Communication Systems (TACSs) were the two most popular analog systems, offered handover and roaming capabilities, but they were unable to interoperate between countries.

Second Generation (2G) mobile systems provided an increased voice capacity delivering mobile to the masses. They are characterized by digitization and compression which

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allowed the accommodation of many more mobile users in the radio spectrum through either time (Global System for Mobile Communication (GSM)) or code (Code Division Multiple Access (CDMA)) multiplexing [2]. Compared to 1G system, 2G system offered higher spectrum, higher efficiency, better data services, and more advanced roaming. GSM was deployed to provide a single unified standard and enable seamless services throughout Europe by means of international roaming. To support multiple users, GSM uses Time Division Multiple Access (TDMA) technology, and it has been contentiously improved to offer better services. The development of new technologies based on the original GSM technology leads to advanced systems.

In 1G and 2G cellular networks, the BTSs were equipped with its own cooling system, battery backup, monitoring system, and so on. It implies that the BTS had an all-in-one architecture, an architecture where all power, analog, and digital functions are housed in a single container as large as a refrigerator and is commonly found in large cell deployments. Since each BTS is working on its own, it doesn’t reduce the interference with other BTSs by using collaboration algorithms such as genetic algorithm [5]. In addition, it is hard to upgrade and repair because of the all-in-one BS architecture.

In addition to the shortcoming of the BS architecture, increasing network traffic demand, limited bandwidth availability and mass adoption of mobile broadband were the major challenges of traditional cellular networks. As a consequence, telecom operators were seeking new ways to increase network capacity and coverage while reducing time to market for new services and achieving lower Total Cost of Ownership (TCO) [6]. To achieve these goals, they needed a cost effective combination of several standards (GSM, LTE, and others), transport technologies, frequency band and cell layers while handling the substantial high capacity demand. To accommodate the substantial high capacity demand in cellular systems, reducing cell size to increase the network capacity by improving the spatial reuse of radio resources could be one possible solution. However, it causes an increased system cost to provide coverage areas with small cells due to construction and operation related problems. As a result, a new RAN architecture based on distributed BS, C-RAN, has been proposed [7, 8] to address the above mentioned challenges. And the 3GPP has been taken the evolution of radio access technology through High Speed-Downlink Packet Access (HSDPA) and Enhanced High-Speed Uplink Packet Access (HSUPA).

Later, in Third Generation (3G) deployment, a distributed BS was introduced where the RRHs and BBUs are separated using fiber links with digital baseband interfaces, such as CPRI and Open Base Station Architecture Initiative (OBSAI). At this stage, the concept of fronthaul was introduced. Unlike traditional cellular networks that are built with many all-in-one BS architectures, C-RAN can be viewed as an architecture evolution based on distributed BSs. To enable flexible deployment, C-RAN or C-RAN architecture divide the BS into BBU and RRHs. Figure 1 illustrates the segment where fronthaul and backhaul are located in the overall mobile network. Fronthaul is a segment that connects RRH and BBU, whereas backhaul accounts for the segment between the core network and the edge of the entire telecommunication network, and the physical medium can be fiber, copper, and microwave. As seen from Figure 1, C-RAN is a fronthaul architecture that addresses capacity and coverage issues while supporting mobile xHaul (x can be Fronthaul or Backhaul) solutions. It also provides great benefits in controlling ongoing operational costs, improving network security, network controllability, network agility and flexibility [7], [9].

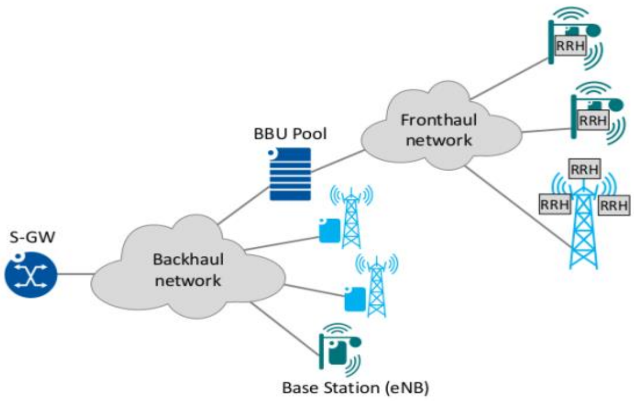


Figure 1. Mobile backhaul and fronthaul network architecture in LTE, extracted from [10]

In fronthaul network, fronthaul flows have a very high bitrate in the order of gigabits per second; For instance, for an LTE sector configured as 2x2 Multiple Input Multiple Output (MIMO) with 20 MHz carrier bandwidth requires about 2.5Gb/s, which gives a total of 7.5Gb/s for a typical 3-sector cell sites. Such fronthaul capacity doesn't not scale with time-varying traffic load condition of the cell (i.e. it leads to fully non-elastic traffic). These features constitute a relevant problem to the traditional RAN infrastructure that is designed to carry much lower bitrate. As a result, the common fronthaul solution in C-RAN is the use of an optical access networks. But this transport solution requires consumption of a number optical fiber links, which are scarce and needs huge investment by operators. For example, in areas where there is dynamic user expectation like clients are engaged in mobile-savvy activities-from texting to video phone calls such as in ultra-modern stadium and dense population area (like China), requires a new emerging technology: the C-RAN. In such scenarios, using fiber as full fronthaul network may not be economically available to the rooftop where the RRH needs to be deployed [11]. In other cases, installing fiber in existing tower may prove to be a challenging problem. And also deploying traditional small cell sites in suburban and road areas (where more capacity is needed to meet fast growing traffic demand) are not realistic solutions for these areas that form a high percentage of an operator's footprint. As a complement to the both traditional small cell and fiber, a new fronthaul network that can extend the existing traditional small sites and enable quick deployment of cell site with much lower TCO is needed. Another technology such as WDM and OTN could save fiber consumption, however, the cost of introducing these additional transport equipment makes economically not viable for operators. Hence, the current Mobile Fronthaul (MFH) solutions are rather short-term approaches and needs improvement in both the topology and technology. As an attempt to address this issue, some of the recent research is focusing on Ethernet-based fronthaul transport network pushed by their lower costs, ability to employ statistical multiplexing, and improved performance.

Using Ethernet in the fronthaul [12] has been proposed to take some advantages: lower cost equipment, shared use of lower-cost infrastructure with fixed access networks, obtaining statistical multiplexing, and optimized performance. Despite of their attractive advantages, Ethernet also comes with their own challenges: achieving low latency and jitter to meet delay requirements, and ultra high bit rate requirements for transporting radio streams for multiple antennas in increased bandwidth [12]. For the above reasons, the current fronthaul networks are increasingly integrating more cost-effective packet switched technology, especially Ethernet/Internet technologies. The former disadvantage will be explored in this study, while the latter is studied in detailed in [12].

Moving from this background, we intend to study the transport of radio signals over Ethernet signals using IHON nodes, H1. In particular, we focus on three performance metrics to evaluate IHON mobile fronthaul networks (latency, PLR, and PDV). The main motivation of this paper is dealing with the level of timing performance required and studying on how well this timing be supported in an IHON Ethernet mobile fronthaul. Furthermore, it is targeted to find how the IHON hybrid principle may be applied and how it will perform in a network containing only a few, or only a single wavelength channel.

2. Fusion Solution/IHON Network

Fusion solution is one variant of IHON that uses a packet switched nodes to transport both GST and SM traffic classes. It combines the best properties of circuit and packet switching in an Ethernet compliant network, as illustrated in Figure 2, to obtain high throughput, ultra-low delay, ultra-low PDV, and zero packet loss.

In fusion networking technology, the traffic is divided into two service classes while using the capacity of the same wavelength: namely 1) a GST service class offering QoS demands such as fixed low delay and no packet loss for the circuit switched traffic, and 2) an SM service class providing high bandwidth efficiency for the Best Effort (BE) packet switched traffic [13].

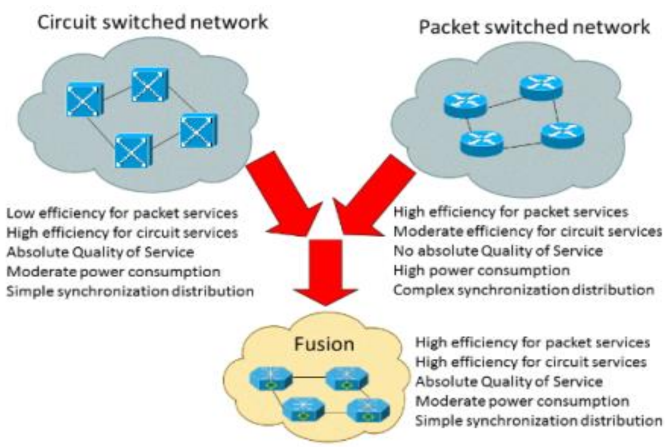


Figure 2. Fusion network: created by combining the best properties of packet and circuit switching, extracted from [14]

2.1. IHON Node Design

The basic idea in the IHON network is that the GST packets follow preassigned wavelengths through either static WRON or dynamic WRON from the sender to the receiver while SM packets are inserted in the vacant gaps to enhance link utilization. The link is divided in time without using time slots. When an Ethernet packet arrives at the input port, they are tagged with VLAN-ID in order to distinguish between GST and SM packets. If the arrived packet is GST, they are allowed to pass with absolute priority via the other 10GE interface. However, if the packet is SM, it is first processed and then either buffered until idle time gaps between GST packets is available or dropped to one of the 1GE interfaces according to their VLAN-ID.

Figure 3 and Figure 4 shows functional illustration of the IHON node design and the internal operation inside the IHON node respectively. The node consists of SM DMUX, GST gap detector, SM packet scheduler, 2x10 GE line interfaces (Xe0 and Xe1), and 10x1GE client interfaces (ge0-ge1). The line interfaces bring two benefits to the node: it can give 1+1 or 1:1 protection and enable add/drop functionality of transparent Ethernet lines [15]. Each of the GE interfaces is dynamically configurable as either Ethernet lines or SM paths.

The GST and the SM traffic classes are identified and switched at the input port according to VLAN tag used by the nodes. While the GST packet bypasses the packet switch and continues towards the output link, an SM demultiplexer (DMUX) extracts the SM packets from the channel to be processed. The processing is achieved based on the header information.

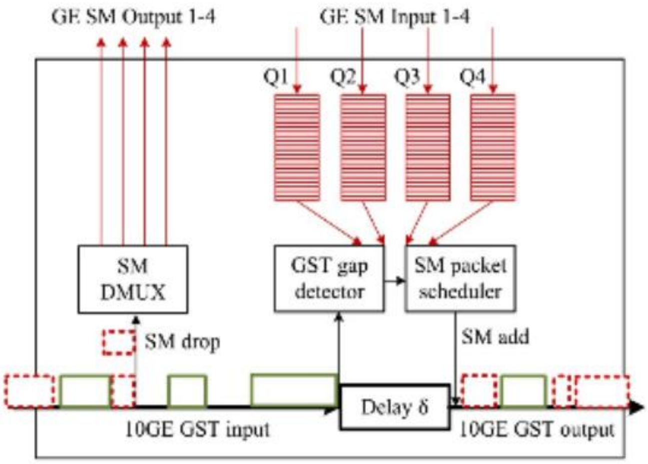


Figure 3. Schematic diagram of IHON node design, extracted from [15]

2.2. IHON Node Operation

Figure 4 illustrates the IHON node internal operation. As depicted, the classifier first classifies the arriving traffic into GST or SM traffic. After classifying, the SM demultiplexer (SM DMUX) drops the SM traffic to the packet switch while GST packets are allowed to bypass the packet switch. The dropped SM packets are placed inside a queue and are processed according to their header information. Depending on the number of input SM streams, the arriving SM packets are assigned a separate queue. This implies that the number of queue in IHON node is the same as the number of input SM streams.

At the input, the GST gap detector senses the incoming and leaving GST traffic. Using the GST gap detector, the inter packet gap between GST packets is measured, and passed the measured value to the SM packet scheduler. It continuously updates information about the vacant gaps and forwards the information to the SM packet scheduler. The queue is scanned for suitable SM packets that can fit the measured gap, and the SM packet scheduler fills the gap with this packet with the best effort QoS. As a result, using this technique, the efficiency of the link utilization increases.

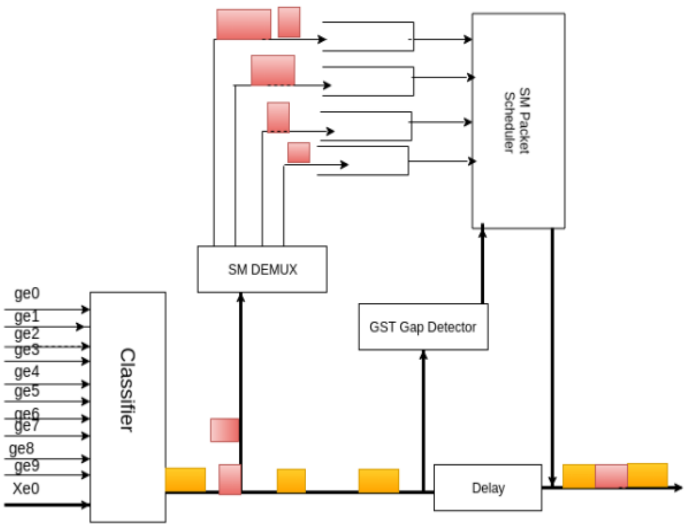


Figure 4. Internal operation of IHON node, adopted from [15]

2.3. Delay and Packet Delay Variation in IHON Node

A fixed delay, δ, equivalent to the maximum length of SM packet service time, is applied electronically to the GST packets. Within this time, the GST gap detector discovers the length of free time gaps before an SM packet is inserted; hence, prevents the preemption of SM packets by incoming GST packets. Inter-packet time gap, Δ_I , of the GST packet is detected only when the packets enter the delay line. The delay line introduces deterministic E2E GST packet delay and is proportional to the number of hopes that the light path traverses.

In order to illustrate the deterministic effect of fixed delay line on the GST traffic, let's consider Figure 5(a). The figure shows how the inter GST packet gap remains constant after the GST traffics traverse the delay component. At the input channel, the inter packet gap times of GST packets when the packet enters the delay line are expressed by (1) and (2) [15]:

$$\Delta_1 = Start(2) - End(1) \tag{1}$$

$$\Delta_2 = Start(3) - End(2) \tag{2}$$

After the delay component (t+ δ), at the output channel, the gaps of GST packets are given by (3) and (4) and are kept unchanged [15].

$$\Delta_1' = [Start(2) + \sigma] - [End(1) + \sigma] = \Delta_1 \tag{3}$$

$$\Delta_2' = [Start(3) + \sigma] - [End(2) + \sigma] = \Delta_2 \tag{4}$$

Since all packets undergo the same fixed delay δ, inter-packet time gaps Δ_1' are remained the same at the output channel, $\Delta_I'=\Delta_i$. Thus, the IHON network doesn't introduce PDV to the circuit traffic.

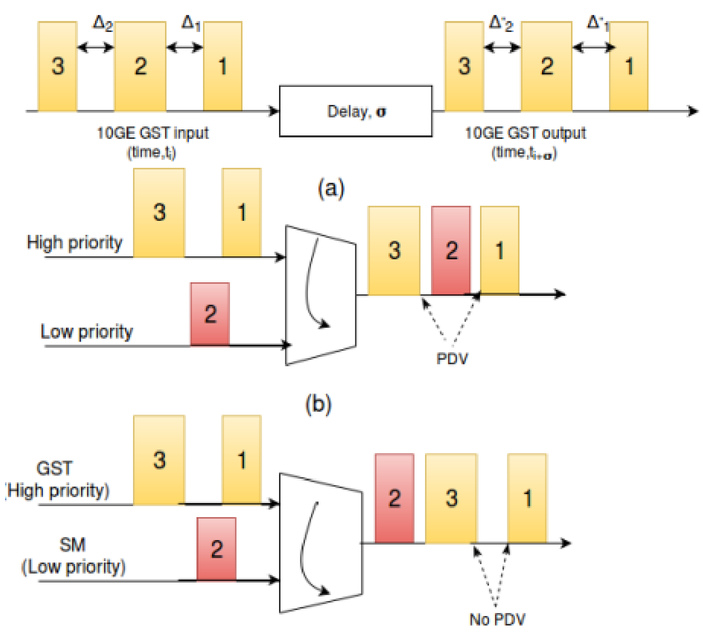


Figure 5. (a) Inter packet gap and delay experienced by GST packets, b) Scheduling in strict priority QoS in packet switches where packet delay variation (PDV) occurs on high-priority packets, c) Scheduling in fusion node where SM packets are inserted only if there is a suitable gap between the GST packets, extracted from [15]

2.4. Inter-packet Time Gap Computation in IHON Node

An algorithm called round robin gap filling scheduling algorithm [15] is used to compute the inter packet gaps between GST packets on the underutilized wavelength. A monitoring module at the delay line senses the arrival of GST packet at the delay line and the exit time value of the GST time.

Based on the incoming and leaving times of the GST packets and applied fixed time window in IHON system, the inter-packet time gap can be computed. Gaps sensed by the gap detector are saved in a time ordered list according to the corresponding time values. The first gap on each channel of the list is made available to packet scheduler. Afterwards, the SM scheduler knowing the sensed gap, search in round-robin manner to the head of SM queues, for SM packet smaller than the sensed gap. The gap computation for one channel according to round-robin gap filling scheduling algorithm is described Figure 6, and the notations used to describe the algorithm are presented in Table 1.

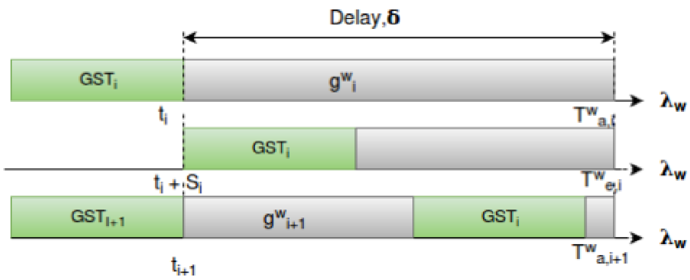


Figure 6. Detection of free time gaps within the time window created by the fixed delay, extracted from [15]

Table 1. Definition of parameters used in the gap computation

Parameters	Definition
$T_{a,I}^{W}$	The incoming time of GST packet i to the delay line of output channel λw
$T_{e,I}^{W}$	The leaving time of GST packet i to the delay line of output channel λw
δ	Fixed delay
g_i^{w}	The gap on the channel w of packet i
Si	Service time of packet i

In Figure 6, two GST packets, GST_i and GST_{i+1}, are considered in order to describe round robin algorithm, where GST_i is the first packet arrived at the delay line and GST_{i+1} is the packet arrived after GST_i.

1. When the GST packet i arrives the delay line at time ti, the arrival time of packet i is updated to the output channel λ_w(busy time starts): $T_{a,i}^{W} = t_i + \sigma$. The inter packet gap is $g_i^{w} = \delta$ if only packet i is available in the delay line and the previous GST packet (i-1) has already left the delay line (i.e. $T_{a,i}^{W} \geq T_{e,i-1}^{W} + \delta$); else the gap is given by $g_i^{w} = T_{a,i}^{W} - T_{e,i-1}^{W}$. Where $T_{e,i-1}^{W}$ is the exit time of previous packet, i-1.
2. After the last bit of GST packet i enters the delay line at ti + Si, the exit time of packet i is updated and the output channel w is released (end of busy time):

a. $T_{e,i-1}^{W} = (t_i + S_i) + \delta$.

3. The current gap value that is given to the scheduler is updated at Tw e,i-1: For instance, the current gap value is g_{i+1}^{w} computed as illustrated above if the next GST packet exist. Otherwise, it is equals to the maximum packet length, δ.

2.5. Fronthaul Network Requirements

As a consequence of decoupling the traditional BS functions into a centralized BS that will be shared among multiple RRHs, strict timing conditions between BS and RRH have been specified by RAT standards. Delay contributions due to the transportation of fronthaul signals along RAN network, "fronthaul latency", is one of the main significant challenges for the BBU RRH design and has a relevant impact on the total latency in the BS.

In general, given that the total latency is fixed by standard, as shown in the Table 2, the internal processing delays of both BBU and RRH depends on the specific software and hardware implementation, there is a standard upper limit on the latency of fronthaul network. The latency can be further categorized into two parts: namely 1) latency due to the adaptation of fronthaul signals into the RAN infrastructure services, which can be caused by the technology used such as CPRI and OBSAI transmission/reception interfaces, and other functions required by optional layer transport technologies (i.e. multiplexing/demultiplexing, buffering, reframing and error correction), and 2) latency due to the contribution of signal propagation along the RAN. The second contribution imposes a limitation on the maximum geographical distance between BBU hostel and the controlled cell sites.

Table 2. Latency, PDV, PLR, and synchronization requirements for Ethernet Fronthaul with symmetry assumption

Properties	Values	Sources
Latency budget(BBU to RRH, in cluding fiber length, PDV, bridged delays)	50 μs (for data rate 1–10 Gbit/s)	[16]
Latency budget(excl. cable, BBU to RRH)	5 μs(for data rate 1–10 Gbit/s)	[16]
Maximum Frequency Error contribution	2 ppb	[17]
Maximum Bit Error Ratio	10^{-12}	[16] [18]
Maximum End to End Latency /RTT(including fiber length, PDV, bridged delays)	100μs- 400 μs (250 μs for optical networks)	[12] [16]
Maximum PDV	5 μ or 10 % of E2E latency	[19]
Geographical distance between RRH and BBU	Less than 20 Km (current working assumption) and 25 km for optical networks	[20] [21]
PLR caused by bit error, congestion...etc	10^{-6} - 10^{-9}	[19]

PDV is defined as 2-point packet delay variation. As per ITU Y.1540 "delay variation of an individual packet is naturally defined as the difference between the actual delay experienced by that packet and a nominal or reference delay. ITU Y.1540 6.4.2.1 and RFC 5481 using the minimum delay as a reference. (Use of the average delay as the delay variation reference is depreciated.)".

To achieve the objective of this paper, the programming language chosen to construct the simulation model for the fronthaul network is **Simula** based on Discrete Event Modelling on Simula (DEMOS) software, a context class for discrete event simulation. Moreover, **Matlab** has been used for post processing of raw data's from the simulator and plotting the data's with error bars. The simulations were run 10 times by varying simulation seeds for each data points, and the results were reported with **95**% confidence interval.

3. Results and Analysis

Table 3 and Table 4 presents the set of parameters which have been used during the simulation and the list of notations used for different traffic loads on different interfaces respectively.

Table 3. Simulation parameters used in the analysis of performance metrics of SM and GST packets

Parameters	Value
Seed values	907 234 326 104 711 523 883 113 417 656
Output link capacity	10 Gb/sec
Minimum SM length	40 Bytes
Length of GST packet	1200 Bytes
Maximum SM length	1500 Bytes
Load of GST traffic	Varies
Load of SM traffic	Varies
Number of SM buffer in a node	4
Maximum number of buffer	4
Buffer size	16 MByte
Number of packets	40,000

Table 4. Notation of parameters used in the simulation result analysis

Description	Notations
The load of SM traffic on 1 Gb/s interface	L_{1GE}^{SM}
The load of GST traffic on 10Gb/s interface	L_{10GE}^{GST}
The load of GST and SM traffic on 10 Gb/s interface	L_{10GE}^{T}

4. Results and Analysis

In this work, we considered PDV, PLR, and average latency are taken as a performance metrics to evaluate performance of IHON Node. With the analysis of each metrics, an identification of parameter that restricts the overall performance is conducted. The evaluation IHON network in mobile fronthaul is also conducted. From this evaluation, we find how such networks can be dimensioned with respect to: fiber link length, number of nodes, · · · etc.

4.1. IHON Node Performance

To study the performance of IHON node while transporting GST and SM traffic, the traffic has been transported and analyzed on a 10GE output wavelength. Figure 7 illustrates how these traffic has been generated, and utilize the output link. Firstly, the GST and SM traffic were generated. Then, the GST traffic was sent to the 10 GE port of the IHON node while the SM traffic was queued in a buffer until a suitable gap was detected. Secondly, both the GST and SM traffic was processed and sent out through the same output port.

For IHON node, the average latency, PLR, and PDV of SM and GST traffic with respect to GST load are shown in Table 5. The values are obtained by holding SM load fixed, L_{1GE}^{SM} =0.3.

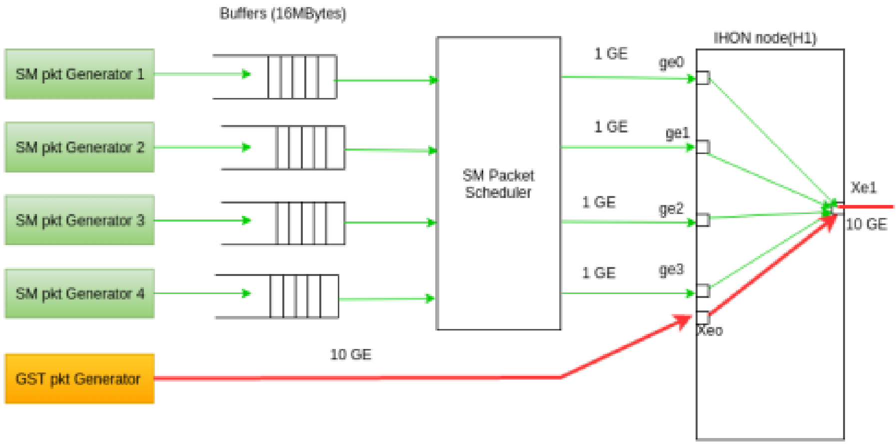


Figure 7. Diagram illustrating how the IHON node is connected to Packet generators for measuring the performance metrics.

Table 5. Average latency, PLR, and PDV of SM and GST traffic as function of GST load for SM load=0.3

SN	Total L_{1GE}^{SM}	L_{10GE}^{GST}	Average GST latency (μsec)	Average SM latency(μsec)	PDV of GST (μsec)	PDV of SM (μsec)	PLR of SM (sec)
1	0.3	0.10	1.2	$0.0140{\pm}1.37{\times}10^{-4}$	0.0	0.350	0.0000
2	0.3	0.20	1.2	$0.0210{\pm}1.69{\times}10^{-4}$	0.0	0.370	0.0000
3	0.3	0.30	1.2	$0.0270{\pm}1.70{\times}10^{-4}$	0.0	0.372	0.0000
4	0.3	0.40	1.2	$0.0340{\pm}1.77{\times}10^{-4}$	0.0	0.281	0.0000
5	0.3	0.50	1.2	$0.0390{\pm}1.70{\times}10^{-4}$	0.0	0.550	0.0000
6	0.3	0.60	1.2	$0.0417 \pm 1.41{\times}10^{-4}$	0.0	0.760	0.0005
7	0.3	0.63	1.2	$0.0422 \pm 1.14 \times10^{-4}$	0.0	1.620	0.0026
8	0.3	0.64	1.2	$0.0424 \pm 1.20 \times10^{-4}$	0.0	1.960	0.0033
9	0.3	0.65	1.2	$0.0430{\pm}1.28{\times}10^{-4}$	0.0	3.900	0.0040
10	0.3	0.67	1.2	$0.0480{\pm}1.01{\times}10^{-4}$	0.0	2.890	0.0053

4.1.1 GST Traffic Performance

The following results have been obtained by using Table 5 as a simulation parameter. The average latency, PLR, and PDV of GST traffic are discussed in the following subsections.

1. Average Latency

In IHON node, latency refers to the delay when the first bit of the packet gets into the IHON node until the first bit of the packet leaves the FDL. This parameter greatly affects how usable the nodes as well as communication are.

Every sub-simulation returns an average value for latency of GST packet, obtained by averaging all the delays experienced by every single GST packet during the subsimulation. By varying the system load (n* $L_{1GE}^{SM} + L_{10GE}^{GST}$), we observed the average latency of GST traffic. The simulated average latency of GST traffic was constant with a value of 1.2μsec, which equals to the FDL time. It shows that the 10GE GST traffic was shown to be independent of the added SM traffic and its load. This is due to the fact that the GST traffic is transmitted with absolute priority. Note that the FDL time was set to the service time of maximum packet length of SM packet, δ=1.2μsec. The average latency of GST traffic isn't affected by the system load and insertion of SM traffic. Thus, the result reveals that its average latency is constant regardless of the node congestion.

2. Packet Delay Variation

As per ITU Y.1540, "PDV is the variation in packet delay with respect to some reference metrics (minimum delay in this work)". The service quality and PDV tolerability of an application are highly influenced by PDV. By recording the time when the first bit of GST packets arrived at the delay line, and when the last bit of the packet left the start of the FDL, the maximum and minimum delays of GST packet are computed. Using this concept, the result of the simulator showed that the packet delay variation of GST packets was zero. This is because the traffic aggregation of SM traffic on the top a 10 Gb/s wavelength is done without introducing PDV to the GST traffic of following the wavelength. Furthermore, the inter-packet gap between the GST stream is preserved, and the GST streams are sent out precisely as it arrived. Consequently, it results in zero packet delay variation. Like the average latency, the PDV of the GST traffic isn't affected by the system load and insertion of SM traffic. Furthermore, GST packets in IHON node undergo a fixed delay of 1.2μsec, corresponding to the service time of a maximum length SM packet. At the output wavelength, all GST packets experience this fixed delay. Hence, it doesn't introduce PDV to GST traffic.

3. Packet Loss Ratio

When one or more transmitted packets fail to arrive at their destination, packet loss occurs. In IHON node, it is typically caused by blocking and congestion. Since different applications have different PLR tolerability, it has noticeable effects in all types of communications. Packet loss is measured as a percentage of the number of lost packets with respect to the total transmitted packets. The simulation result showed that the PLR of GST traffic was zero, i.e. all GST traffic generated by the source was received at the output port of the IHON node. This is because GST packets pass through FDL, which gives time to the monitoring module to calculate the gap length between GST packets. SM packets are scheduled only if the gap is sufficient to transmit the packet. Hence, IHON nodes avoid losing of GST packets.

4.1.2 SM Traffic Performance

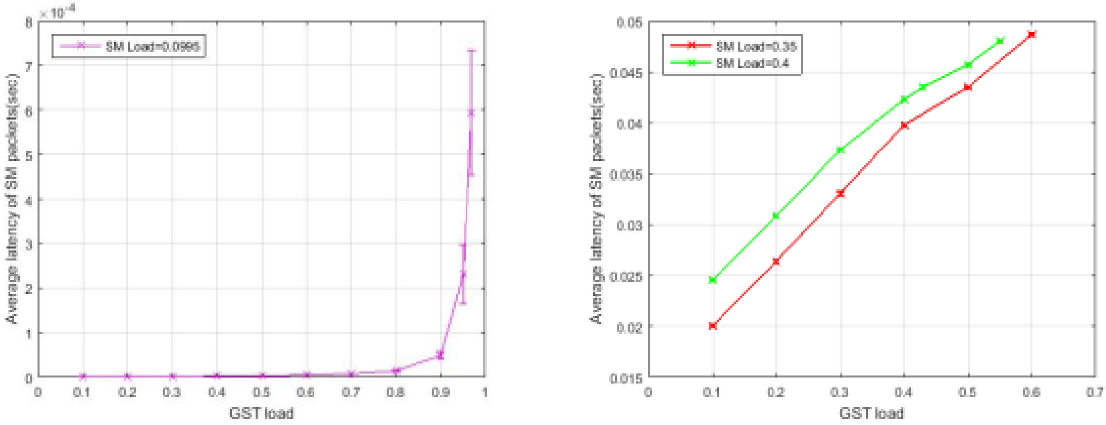
By varying the load of GST traffic, we observed the performance of SM traffic for fixed SM load is observed.

1. Average Latency

For low SM load, Figure 8a, the average latency increases from 1.2μsec to 18μsec when the GST load and L_{10GE}^{GST} was increased from 0.1 to 0.89 with an increasing interval of 0.1. However, when L_{1GE}^{SM} is increased from 0.1 to 0.3, Figure 8b, the average latency was further increased. Increasing more SM traffic, after the system load 0.8, will cause a buffer overflow. This leads the average latency to increase exponentially and causes a packet loss as shown in Figure 8.

As can be seen from Figure 8 the average latency of SM traffic is increased for increasing the GST load. The increment of GST load adds more traffic to the output wavelength which in turn increases the waiting time of SM packet at the node. This means that increasing

GST load will decrease the chance of SM traffic to be inserted. Generally, the higher the GST traffic load, the longer the average latency of SM traffic.



(a) SM load=0.1 (b) SM load=0.35 and 0.4

Figure 8. Average latency of SM traffic as function of GST load for SM load=0.1, 0.35 and 0.4

When the system load is low, then the buffers inside the node will never be full. In this simulation, since we are using variable SM packet length (40 to 1500 bytes), the average latency depends on the packet length. It means that the latency of sending a 40-byte packet and a 1500 byte is different depending on the packet length.

2. Packet Delay Variation

As it has been mentioned in Subsection 4.1.1, PDV influents service quality of an application. Thus, the average PDV of SM packets were acquired from the simulation for analysis. The PDV data on Table 5 of SM traffic and the resulting Figure 9 shows that when the GST load of the system load traffic increased, the PDV has increased from 20.1 μsec to 411.232 μsec. This indicates that the PDV of SM packet is influenced because of the service classification, i.e. traffic load and SM traffic scheduling algorithm [15].

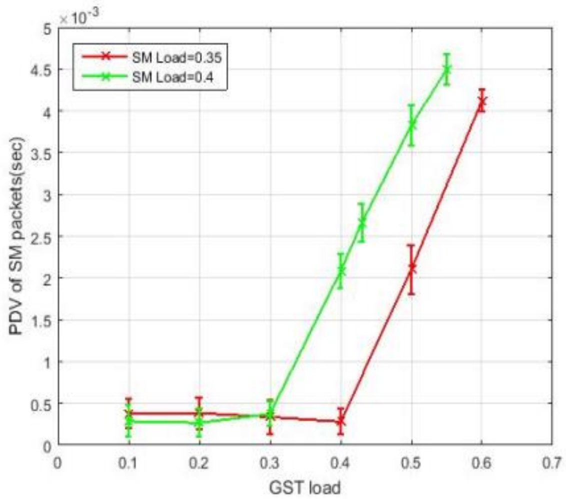
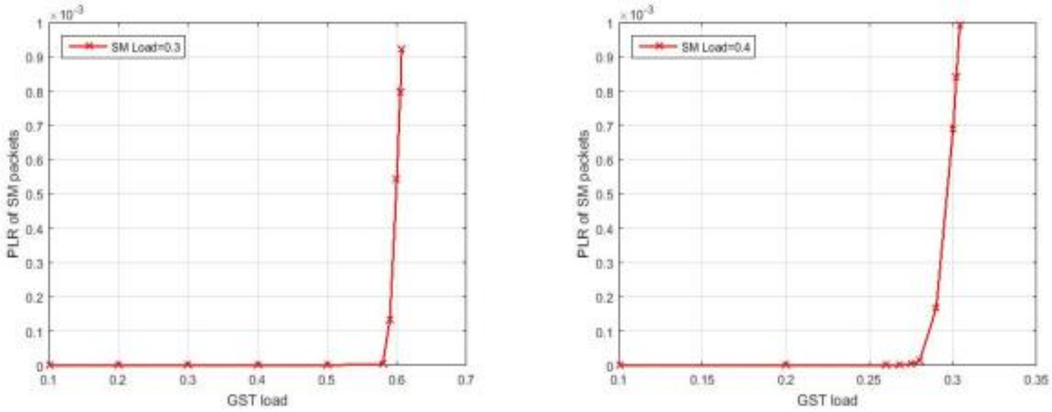


Figure 9. Packet delay variation of SM traffic as function of GST load

3. Packet Loss Ratio

One of the most important factors in the analysis of IHON node performance for SM traffic is illustrated in Figure 10. Based on the figure, no PLR was observed within system load interval [0,0.89]. When the system load reaches 0.89, SM packets start getting dropped. From that point onward buffer overflow causes the loss to increase exponentially.



(a) SM load=0.3 (b) SM load=0.4

Figure 10. PLR of SM traffic as function of GST load

For L_{1GE}^{SM}=0.3, the added SM traffic increases the 10GE wavelength utilization up to 89% without any losses asnd with SM PLR=1*E*-^{03}up to 92% utilization

4.1.2. Comparison between GST and SM Traffic Performance in IHON Node

Based on the results, Table 6, the average latency, PLR, and PDV of GST and SM traffic were analyzed and compared. The exploration of these parameters helped us to deeply understand the performance of IHON node towards traffic of different priority.

1. Average Latency

Figure 11 shows the average latency of GST and SM traffic for SM load=0.1. From the figure, it is observed that the average latency of SM traffic increases when the GST load is increased from 0.1 to 0.89. This is because IHON node has a buffer to store SM traffic when suitable gap between GST packets is not found, which results in longer delay. When the GST load is low, the buffer's queue length will be short and SM packets will pass through IHON node with a shorter delay. On the other hand, when the GST load is increased, the chance of getting suitable gap is low and the SM packet will stay a longer time in the buffer.

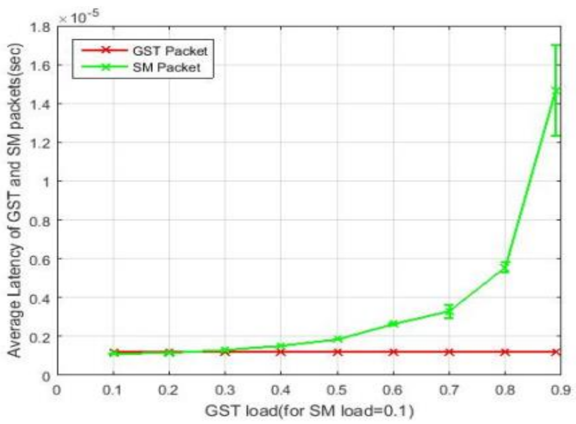


Figure 11. Average latency of SM and GST traffics as function of GST load for SM load=0.1

The average latency of GST traffic is kept constant regardless of the added traffic on the wavelength. Thus, the simulation result proved that GST traffic wasn't affected by the system load with both increased GST load and inserted SM traffic. It implies that GST traffic is transported with absolute priority.

2. Packet Delay Variation

Another important parameter for analyzing the IHONs node performance of delivering service with continuity and stability is PDV. Figure 12 illustrates the result of PDV of SM and GST traffic. For SM traffic, the PDV has increased when the load of GST traffic is increased from 0.1 to 0.9. This proved that because of the service classification in IHON node, the PDV of SM packet is influenced by the system load and SM traffic scheduling algorithm [15].

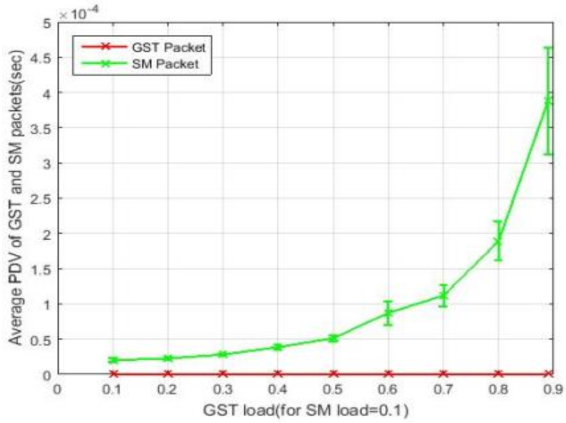


Figure 12. Packet delay variation of SM and GST traffics as function of GST load for SM load=0.1

PDV of GST traffic is kept constant at 0 level while the system load is increasing. This implies that the PDV of the GST traffic isn't affected by the system load and insertion of SM traffic.

3. Packet Loss Ratio

As described in Section 4.1.1, IHON node causes no packet loss for GST packets, and Figure 10 shows that SM packets start dropping when the system load reaches 0.89. An obvious difference occurred at the system load 0.89, where the PLR of SM packet began to increase sharply because of buffer overflow. However, the GST packets experience no packet loss and are independent of system load. This is because the traffic aggregation of SM traffic on the top a 10 Gb/s wavelength is done without packet loss to the GST traffic of following the wavelength.

4.2. Mobile Fronthaul Networks

We have gone through the fronthaul network requirement given by IEEE 802.1CM and the RoE standards for transporting radio signals over a packet switched network given by IEEE 1904.3 to evaluate Ethernet network for fronthaul C-RAN network. To evaluate the performance of these networks, let us consider a scenario when there are more than two nodes in a network as shown in Figure 13.

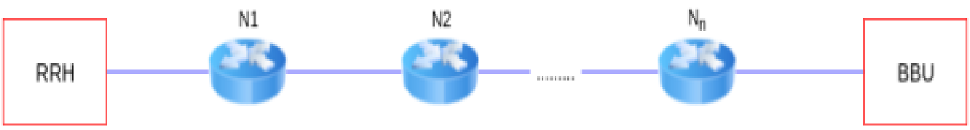


Figure 13. Mobile fronthaul network under study

In the following subsections, the different parameters of the Ethernet switches in a mobile fronthaul setting are evaluted. Our aim is to find how such a network can be dimensioned with respect to: fiber length and number of nodes. It is important to note that the latency results described below represent only the queuing and transmission delays; but the nodal delay, which depends entirely on the implementation of the node, has not been taken into account.

4.2.1. Evaluation of IHON Network for Mobile Fronthaul Network

The overall fronthaul requirements are listed in Table 2. They are mainly focused on performance metrics: PLR, average latency, and PDV. In Section 4.1, we have measured the result of these performance metrics in IHON node when transporting one 10GE GST traffic and four 1GE SM traffics aggregated on a single 10 Gb/s wavelength. The results were measured by changing the total load of aggregated SM traffic, total L_{1GE}^{SM} on 10 GE, from 0.1 – 0.4, and the number of SM streams (n) used to supply the total load were four; for each load size, each SM stream contributes an equal amount of load. The measured values are used to evaluate the performance of IHON network for mobile fronthaul network.

1. Average Latency

The first performance metric used for evaluation of IHON network for fronthual C-RAN is average latency. According to IEEE 802.1CM and 2.2, the maximum E2E latency between BBU and RRH required for mobile fronthaul is specified as 50 μsec (including fiber length and PDV), and the latency budget is 5μsec when cable propagation is excluded. Within this 50μsec latency, the maximum separation distance between BBU and RRH (link length) is limited and depends on the number of nodes in the network. To calculate the link length as function of number of nodes (N), the following equation has been used:

Maximum E2E latency (L_{total}):

$$L_{total} = N \times (D_{node} + Delay\_PDV_{node}) + D_T \times Link_{length} \quad (1)$$

where, N = Number of nodes.

D_{node}= Latency in a single node, 1.2μsec (obtained from the simulation).

$Delay\_P\,DV_{node}$=PDV in a single node, 0μsec (obtained from the simulation).

D_T =Transmission latency, 5μsec/km.

L_{total}= Maximum E2E latency, 50μsec.

$Link_{length}$= Maximum link length.

Table 6. Maximum link length and number of nodes in IHON network to meet the fronthaul requirements for GST traffic where L_{total}=50μsec, D_T =5μsec/km, and D_{node}=1.2μsec

N	Total D_{node} (μsec)	$Link_{length}$(Km)
2	2.4	9.52
3	3.6	9.28
4	4.8	9.04
5	6	8.8
6	7.2	8.56

Table 6 presents the relationship between the number of nodes in IHON fronthaul network and the maximum separation distance between BBU and RRH for GST traffic. In the table, the second column indicates the overall delay in the nodes, whereas the third column is the link length between BBU and RRH in the network. The table shows that for increasing the number of nodes in the network, the link length decreases. For instance, for IHON network with 3 nodes require 9.28 Km fiber link length. Similarly, for IHON network with 4 nodes require 9.04 Km fiber link length.

The simulation results and Table 6 proved that IHON networks are capable of carrying radio signals over packet-based fronthaul network provided that the number of nodes in the table corresponds to its respective link length. Unfortunately, obtaining the average latency of BE or SM traffic that meets fronthaul requirement is not so straightforward, since this traffic depends on a load of GST traffic.

2. Packet Delay Variation

Another performance used for evaluation of IHON network for a fronthaul network is PDV. In Table 2, the maximum PDV specified is 5μsec or 10% of E2E latency. The simulated result of PDV for GST traffic was zero. Thus, the GST traffic class meets the fronthaul requirement in PDV comparison. The fronthaul requirement is higher than peak PDV of GST traffic for any system load in the interval [0, 0.99]. Consequently, of the three performance metrics (average latency, PDV, PLR), the IHON network performs best in PDV for GST traffic. It has no restriction in wavelength utilization of IHON network.

3. Packet Loss Ratio

At last, the performance evaluated is PLR. Fronthaul networks have a very strict PLR requirement which is in the interval [10^{-6}, 10^{-9}]. As described in Section 6.2, GST packets experience no packet loss regardless of the network congestion. So, the GST traffic is transported through the IHON fronthaul network with absolute priority. In our simulation, GST packet loss wasn't observed at any system load, while SM packets getting dropped for system load beyond $L_{10GE}{}^{T}$=0.89 for SM load=0.3. With system load in the interval [0, 0.99], GST traffic class meets the fronthaul requirement, and can be served properly in IHON network.

5. Conclusion

In this paper, the overall performance of IHON node and IHON network for mobile network were analyzed. We measured average latency, PDV, and PLR for both GST and SM traffic in IHON node. With regard to IHON node, the performance of delivering high quality of service was approved and reflected on GST and fits the technical specification of fusion node. The recommendation from the IEEE 802.1CM standard and other articles were considered for examining and investigating how IHON and Ethernet fronthaul networks should provide the required quality of service. The results obtained from the simulator were compared with these recommendation standards. In a scenario where one 10GE GST stream and four 1GE sub-wavelength SM injected on the leftover capacity, was considered, the measured average latency for GST packet in a single node was approximately 1.2μsec. Using this value, the maximum separation distance between BBU and RRH (link length) is limited and depends on the number of nodes given that the maximum E2E fronthaul latency is as presented in Table 2. The results in Table 6 show that for increasing the number of nodes in the network, the link length decreases. Maximum PDV of GST traffic was measured as zero, and no GST packet loss was registered, which shows us a better performance than the recommended fronthaul requirement. Hence, we conclude that fusion network performs better than what is recommended in IEEE 802.1CM standards in PDV and PLR comparison. Since the GST traffic met the fronthaul requirement, they can be used for transporting RoE traffic while SM traffic can be used for transporting time insensitive application.

Other important points that this paper work has measured and evaluated:

1. The important design concepts of fusion node have been confirmed.
2. The fusion node aggregation of multiple 1GE SM traffic and 10GE on a single wavelength has been achieved without affecting the deterministic nature of circuit switching.
3. The simulation result confirms that the average latency of GST packet is independent of the system load and experiences a zero packet delay variation in a node.
4. The efficient utilization of bandwidth has been achieved by inserting suitable SM traffic in the computed gap between GST packets.
5. HP traffic experiences a PDV equals to the duration of maximum sized LP traffic in Ethernet switch.

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