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MASTER'S DEGREE IN
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MASTER THESIS
IN

NETWORK MODELLING AND DESIGN

SIMULATION OF CPRI TRAFFIC ON OPTICAL ETHERNET

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Session I

Abstract

Evolution of mobile networks calls for novel ways of reducing delays while improving the network capacity. All application types require a system to utilize the expanding data. In the future, the projection is that quality of service (QoS) will be a key measurement of any network. Delay and jitter present a challenge to achieving the QoS needed. This is due to the loss of packets experienced during transmission and retransmission. Hence, the thesis proposes a Hybrid switching solution to increase the efficiency of transport networks for mobile data. This is done by designing a model that reduces the number of wavelengths needed to transport Common Public Radio interface (CPRI) over Ethernet while sharing the same optical resources for conventional backhaul traffic. CPRI over Ethernet is an ideal method to aid in better exploitation of the resources. The proposed strategy minimizes the loss of packets by making use of the available gaps during the transmission. Implementing such a model requires a Guaranteed Service Traffic (GST) class, which does not allow for packet loss and is treated as high priority traffic. Additionally, GST has a fixed low delay that makes it resilient to any form of network failures. Moreover, CPRI assists in saving costs by exploiting the unused wavelength capacity left by the GST traffic. Backhaul traffic can exploit this unused capacity to make the system compact. The thesis considers two classes of service levels with possible set of services that have QoS. These are CPRI over Ethernet (CPRIoE) and traditional packet based Backhaul traffic. CPRIoE is considered as the GST traffic while Backhaul is the Best Effort (BE) traffic. Both traffics are transported over the same links, sharing wavelength resources. The results indicate the effectiveness of combining services in managing multiple flows, thus saving resources and optimizing the network.

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Table of Contents

1) Introduction

With the advent of 5G, networks are expected to offer high speed, ultra-low latency and reliable interconnections among different users. Additionally, the networks are expected to support various services and applications, not only human oriented but also on a machine to machine basis. In the future, networks should be of high flexibility and have high reconfiguration abilities [1]. Various studies have been done in the past regarding transport technologies, protocols and algorithms [2]. In achieving and meeting the requirements of future networks, it is significant to consider the various services and requirements that future networks will present in the scene. Some of them will have considerable similarities with the present services and applications. At the same time, some of the services will demand more regarding bandwidth, dependability, and strict real time operation [2, 3]. Therefore future research should consider the increase in QoS in the network and other emerging services like human and machine-oriented sensor and communication networks [3].

Services requiring real time exchange of information, such as for the so-called tactile internet, and large bandwidth demands are enablers of the future networks [4]. Other requirements like security, QoS, and dependability are vital for some services but not mandatory in some cases and dependent on the network on which they rely on [4]. Demands for future services will increase significantly compared to the existing services. For example, transportation of high quality video for interactive two ways communication or television broadcasting are some of the high demanding services expected to be considered in the future networks [2]. In some quarters, it is argued that quality video communication that include 3D TV, and Ultra HD, which produce burst information, will dominate the bandwidth needs while real time video interaction will dominate the consumer internet traffic [1].

To meet the strict demands for future networks, such as high-speed requirements and wide bandwidth, optical networks should be employed as transport technology and to perform the switching functions [5, 6]. This type of network will play a significant role in future networks, especially in mobile networks, where high capacity links are required to transport large amount of data generated by the new radio interface, along with traditional IP based backhaul traffic.

The thesis focus is on improving transport network efficiency by utilizing hybrid switching and packet scheduling at the aggregation level. To do so, two different service profiles are considered while maximizing the traffic throughput, one for guaranteed service and one for best effort traffic. Thanks to the hybrid switching technology, these traffics can be multiplexed over the same wavelengths, thus increasing the network resource utilization [7]. This is possible thanks to the combination of the properties of Optical Circuit Switches (OCS) and those of Optical Packet Switches (OPS) provided by the hybrid switching technology. In this thesis, a simulator resembling the behavior of a hybrid optical switch has been extended and adapted including the traffic characteristics of mobile networks.

The thesis outline is the following:

a. In section 2, the paper presents an overview of mobile networks, Fronthaul and CRAN. It gives also information on the requirements of 5G networks, encapsulation of CPRI in the Ethernet frames and an overview of Hybrid technology.
b. Section 3 illustrates CPRI over Ethernet traffic simulation. Here, the thesis discusses how to model CPRI traffic for Hybrid switches and the implementation of the simulator by illustrating how the chosen model works.
c. In section 4, the thesis illustrates the performance of the architecture in terms of results based on BE packet success probability, BE throughput, and the average waiting time of BE packets in different scenarios.
d. In the final section, the conclusion of the work is provided.

2) Background

2.1 - Mobile networks, Fronthaul and C-RAN

This section will give a brief introduction on mobile networks and requirements of the next generation of mobile networks (5G). It will cover the requirements and architecture of Fronthaul and Centralized or Cloud Radio Access Network (C-RAN) architecture, which are essential for 5G networks design.

2.1.1 - C-RAN Architecture

Growth in Mobile access and machine to machine applications has led to high demands, which exceed the capabilities of contemporary technologies [8]. The next generation mobile and Internet of Things (IoT) applications need high capacity, QoS, and continuous access to internet. Research [6] is on-going on the development of 5G to solve the high demands of future networks and cope with the ever-increasing traffic demand. The introduction of small cells in 5G creates a huge requirement in the transport network to carry large data with minimal delay requirements [6, 9].

The widespread usage of smart devices and smart phones has led to the increase in bandwidth consumption in cellular networks. This calls for effective ways of improving the cellular capacity. One of the main objectives for 5G is to make it have a bandwidth availability 1000x higher than 4G [8, 10]. This calls for new radio access network (RAN) architecture, which can support higher bandwidth while being more cost efficient. Already, novel ideas of splitting the functionalities of 4G are already taking place in various companies. It involves splitting the traditional eNodeB (eNB) into radio equipment (RE), performing analogue RF processing, and radio equipment controller (REC), that performs the digital signal processing from the physical layer and above [9]. The REC is also known as baseband unit (BBU). In C-RAN, BBUs are centralized into a pool called BBU Hotel or Central Office, where multiple RECs could be put together in a single centralized place, and one REC could be shared among various REs, depending on the traffic load [11]. Centralizing together RECs in the same place allows to reach high network performance, thanks to the ultra-low latency coordination between different RECs, and to reduce the network capital and operational expenditure, thanks to shared and more efficient power supply and cooling systems.

Fig.1 depicts an example of 5G aggregate network employing C-RAN to significantly increase the cellular coverage density. This is possible through the deployment of many REs that are lightweight in comparison to the full-fledged macro base stations, thereby reducing the network cost using fewer and more efficient RECs. Latest proposals have pushed the REC function into the "cloud" that is "virtualizing" REC, thus moving from centralized RAN to cloud RAN and Virtualized RAN (VRAN) [8].

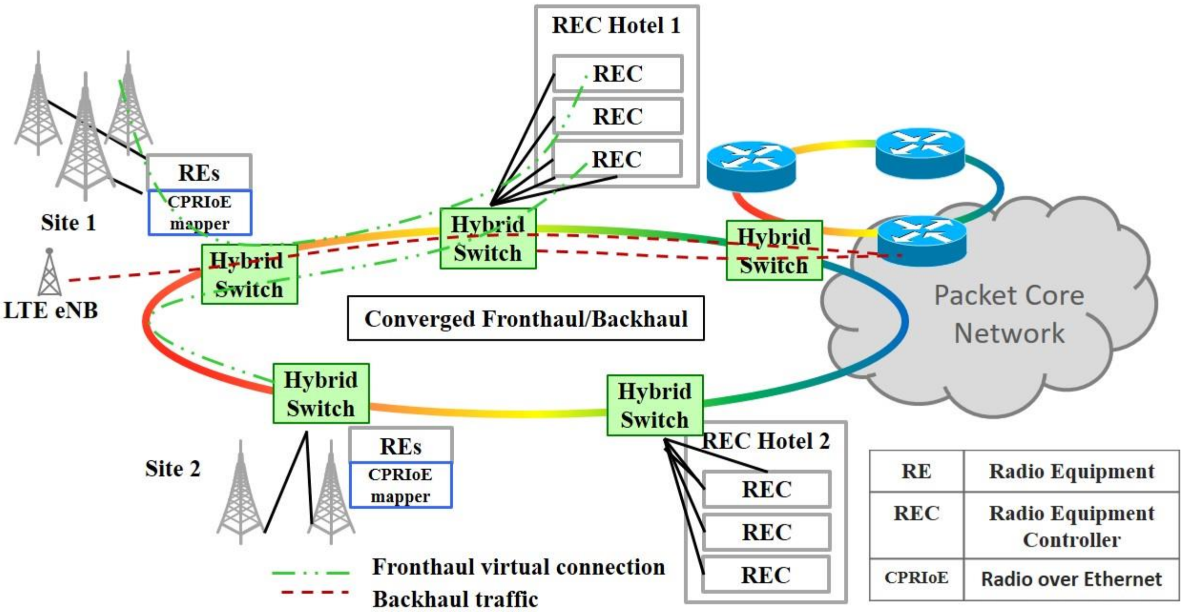


Fig. 1. Schematic diagram of 5G networks

The link between RE and the REC is called Fronthaul, and CPRI is the leading standard for this interconnection. Many distributed radio heads configured for massive multiple input multiple output (MIMO) to exchange compressed digitized radio samples of cloud-based processing can be deployed in the area to cover [9]. The challenge is to offer a standardized interface of high capacity switches which can meet the bandwidth, latency, and jitter requirements needed for all future applications. An interconnection which supports high capacity copper, fiber, wireless optics, and millimeter wave wireless links is necessary. Such a link should provide backward compatibility that is cost effective [12]. CPRI aims at providing a common protocol to enable this communication.

The novel concept of CRAN relies on this link to exchange data between the REC and the RE [13]. This is done by exchanging the digitized radio signals by means of high bandwidth constant bitrate traffic flows. As opposed to the Fronthaul, the traditional packet based backhaul is the link that exists between a base station, or a BBU, and the core of the mobile network. Traditionally, it consists of a coax or fiber cable, or in some cases employs proprietary wireless links [7]. Fronthaul, Backhaul, and varied hybrid architectures are required to satisfy cost efficient, dense deployment, backward compatibility, and low latency demands for future networks [14].

Centralized or Cloud Radio Access Network (C-RAN) architecture comes in handy in addressing 5G networks. Nonetheless, offering high quality of service in end to end connectivity is a challenge presented in 5G C-RAN. Networks need to be cost effective and reliable [15]. Therefore, new architectures and technologies that can meet the main requirements of 5G network such as delay budgets and bandwidth requirements at a low deployment costs are needed [7]. This thesis identifies a possible solution to overcome these problems in C-RAN.

2.1.2 - Fronthaul and CPRI Requirements

There are various on-going projects that are trying to define an interface (optical, electrical, or wireless), between the RE and REC. The requirements of the interface depend largely on the functional split. [11] 3GPP proposes a set of functionalities, which exist in REC and RE. Splitting can be in any of the protocol layers, thereby leading to varied delay and bandwidth requirements of the mobile Fronthaul. This study considers the situation where the split is on the physical layer of the eNB, which is Option 8 in TR 38.801 [16] that includes the whole of layer 1 and above functionalities of REC, while on the other hand, RE is a lightweight antenna with just the RF functionality. Utilizing the option, In-phase quadrature (IQ) samples of the baseband signal transportation is between REC and RE. Leading telecom vendors have developed a well-known radio interface called Common Public Radio Interface (CPRI) to transport sampled RF data between the REC and RE [10]. Fig. 2, shows the representation of the interface that exist between REC and REC. This radio interface is a constant-bit-rate (CBR) interface that has line rate options which range from 614.4 Mbps (option 1) to 24.33 Gbps (option 10) [11]. This thesis considers range of 614.4 Mbps (option 1) to 6144.0 Mbps (option 6). Even if the most common choice among vendors is to use CPRI, that is a product of industry cooperation and therefore of closed nature, alternative interfaces of open nature like Open Radio Equipment Interface (ORI) and Open Base Station Initiative (OBSAI) are available [8].

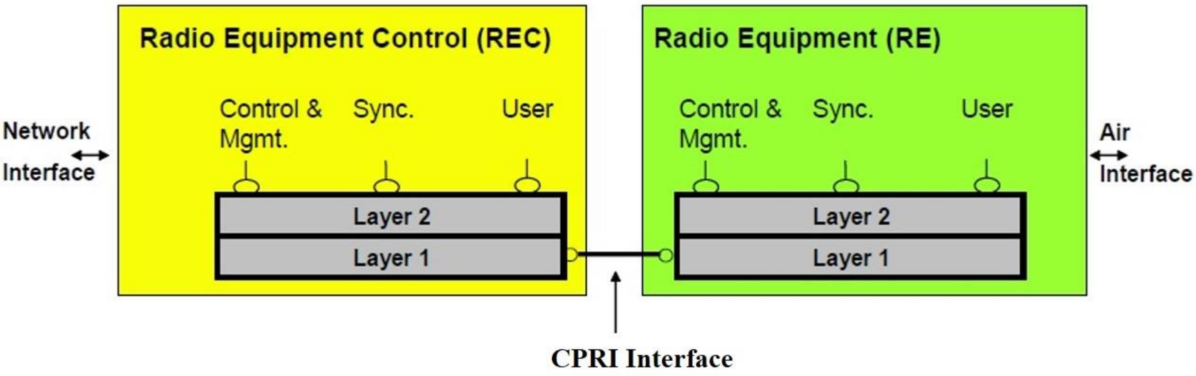


Fig. 2. Illustration for CPRI Interface definition

To satisfy the strict requirements imposed by the Fronthaul traffic, advanced optical access technologies are employed. Example of such solutions is the time and wavelength division multiplexing that combines both the time division multiplexing (TDM) and wavelength division multiplexing (WDM) abilities [13] to offer a cost effective broadband access. To efficiently utilize the fronthaul bandwidth, researchers [10] propose a data compression scheme in the CPRI signal and trying it on the TDM-PON architecture. Spatial division multiplexing is another system that can assist in increasing the fronthaul capacity. This method takes advantage of the multicore fiber to offer a MIMO optical fronthaul. Optical MIMO processing by use of multicore fiber can be optimized using radio MIMO processing [17]. Apart from the bandwidth, fronthaul latency is another significant aspect that requires consideration. The low latency in Fronthaul is due to the hybrid automatic repeat request (HARQ) procedure of the Long-Term Evolution (LTE) protocol stack, limiting the reach of Fronthaul links to 40 km [18]. It is difficult to design switching equipment for CPRI because the manufacturing is in low volumes. This makes it very expensive option to implement. There is mention that CPRI can support various topologies such as chain, ring, and tree; however, there is no mention of how to manage the topologies [19]. Moreover, CPRI has stringent jitter and delay requirements that are achievable through high-speed front haul solutions like dedicated optical links. These factors make it imperative to design and reconfigure a cost effective mobile front haul, which supports network paradigms as explained later in this thesis. The architecture should solve the stringent requirements of 5G Fronthaul network [20]. In this case CPRI fronthaul technology is considered in its ability to fulfil 5G capacity and latency requirements.

Evolution of the RAN architecture towards 5G and beyond has led to the adoption of fiber optics in the networks. However, using dedicated resources for the fronthaul segment may lead to insufficient utilization of the resources. The thesis focuses on introducing Fronthaul flexibility to improve the efficiency of the transport network resource usage.

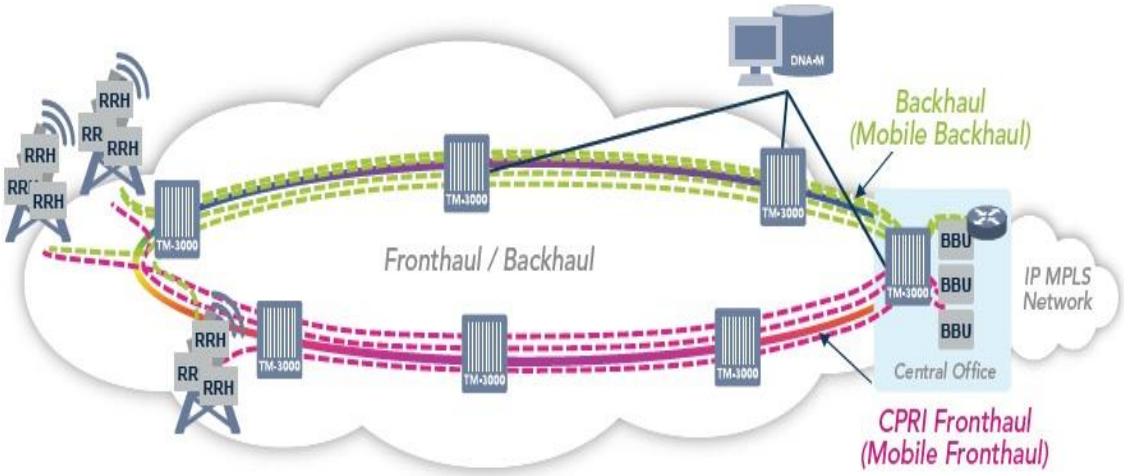


Fig. 3. Mobile Fronthaul and Backhaul overlapping [20]

C-RAN is a novel cellular network architecture that promises to lower costs and boost the efficiency of small cell RANs. CRAN architecture separates the RE and REC by use of CPRI [12]. Deployment of centralized RECs at central office locations or macro cell sites allow for more spectrum control and control of interference in the reduction of power consumption [8, 12]. This efficiency and flexibly on radio access presents Fronthaul connectivity challenges. As a standard, CPRI is digitized, serial radio interface that has capacities of the range of multiple Gigabits per second, which is past the rate of the user traffic [10]. Additionally, CPRI has strict requirements regarding jitter and latency in transmission. Requirements for high transmission capacity that has low latency performance between REC unit and RE has led to the development of CRAN deployment by dedicated and direct fiber connectivity from the mobile network operators [13]. This is through the dark fiber. However, the infrastructure is different from other technologies such as the Multi-Protocol label Switching (MPLS) and optical transport network (OTN) as Fig. 3 shows. In dark fiber it is not possible to easily identify faults and impairments. OTN and MPLS systems have issue with jitter and latency performance too and do not support CPRI specifications [20]. Cost is also a major concern in the deployment of dark fiber in CPRI based Fronthaul. Novel solutions to meet the requirements and the cost when connecting REC and RE are now feasible as envisioned in this thesis. To further reduce the network cost, existing networks based on Ethernet switching can be used. However, CPRI traffic is sensitive to jitter and CPRI frames must be suitably encapsulated into Ethernet frames. The next subsection analyses the latter aspect.

2.2 - Encapsulation of CPRI into Ethernet frames

This section discusses on the topic of CPRI and Ethernet. It looks at CPRI overview and the use of CPRI in networks. Ethernet concept is discussed in this section and how it can be combined with CPRI links to improve the network. CPRI over Ethernet (CPRIoE) encapsulation, the effectiveness in improving the network, and how the mapping can be achieved is this section.

Deploying CPRI is expensive, as it consumes large bandwidth, and presently CPRI configuration is statistically deployed [8]. Ethernet based mobile Fronthaul, on the other hand is efficiently cost effective and the configuration is easy. Therefore, encapsulation of CPRI over Ethernet (CPRIoE) is an attractive option. For example, existing 10 Gigabit (10G) Ethernet links are quick enough to carry high data rate sampled IQ signals from REC to RE (i.e. a 10G Ethernet interface can handle a 20-MHz single antenna I/O sampled radio signal) [12].

From [5] research, Ethernet use in the Fronthaul between REC pools and REs has various advantages. These can range from shared use of infrastructure that have fixed access networks, lower cost equipment, to software defined networking, optimized performance through probe-based monitoring and statistically multiplexing [12]. Nonetheless, there are various challenges that exist. These include; low latency and jitter to meet demands of joint processing and delay requirements, ultra-high bit rate requirements from the increased bandwidth ratio streams to various antennas in future mobile networks. The paper [17] proposes a novel Fronthaul functional division that can improve the most demanding bit-rate requirements through the transportation of baseband signal of sampled radio waveforms and allow for multiplexing gains. The idea helps to solve synchronization and delay issues. In trying to reduce the bitrate requirements through compression, latency may increase [12]. Additionally, this can augment jitter through the transmission of radio signals, thereby increasing the phase noise and the transmitted signals.

The results reported in [21] indicate that CPRIoE encapsulation by use of fixed Ethernet frame sizes needs tens of microseconds. Additionally, numerical experiments indicate that the proposed CPRIoE flows on Ethernet scheduling policy can reduce jitter in case redundant Ethernet capacity is offered. Reduced jitter is large as 1μs to indicate that Ethernet based mobile Fronthaul is a viable technology [22]. Mapping of CPRI to Ethernet considers the CPRI data, MAC header, and the CPRIoE header during the encapsulation [12]. At the output, the total header includes the CPRI data on the Ethernet and length of the Ethernet frame.

Research has been on going to confirm if Ethernet which is a high cost-effective technology can meet the strict latency and jitter requirements of CPRI. In understanding the concept, the simulation involved transmitting CPRI traffic on Ethernet line. This involved two Ethernet enhancers standardized by IEEE that is frame pre-emption (802.1Qbu) and scheduled traffic (802Qbv) [11]. In [23] results of the simulation showed that Ethernet networks that have frame pre-emption or those without whether shared or dedicated to CPRI are not able to meet the CPRI jitter requirements of 8.138 ns. Moreover, the results indicated that enhanced scheduling traffic of Ethernet with a scheduling algorithm can lower or remove jitter completely and therefore, meet CPRI jitter requirements.

Encapsulation of CPRI into another protocol introduces much latency and jitter. Therefore, it is best to transport it in dark fiber through Dense Wave Division Multiplexing (DWDM) and Coarse Wave Division Multiplexing (CWDM) [24]. The CWDM systems are more passive and accept various wavelength transportation on a single fiber by “colored” SFP’s in the remote radio end and baseband [24]. About 16 CPRI wavelengths combinations on a single fiber by use of passive filter are possible. Using passive DWDM, about 40 CPRI wavelengths can be implemented on the same fiber through ring or chain topologies to make drop and continue method in which parts of the wavelength can be dropped at site while the rest of the wavelengths continue to the next site [24]. The passive xWDM has low latency, low cost, has high reliability and technology needs no power. Therefore, the technology has various advantages for CPRI Transport. However, to avoid underutilization of the optical resources, multiplexing techniques can be considered to further enhance the appealing of Ethernet based solutions.

Encapsulating CPRI over Ethernet (CPRIoE) is therefore an appealing solution, but strict jitter and delay and CPRIoE need to be met. By use of simulation, this thesis investigates the efficiency of CPRIoE meeting the mentioned requirements.

2.3 - Hybrid technologies

There are various hybrid technologies in place. Due to the evolution of technology and networks, several research attempts are taking place to improve the hybrid networks. This part discusses on the model of hybrid aggregated switch. It goes further to illustrate how the model hybrid aggregated switch works. In the last part it gives an overview of the Integrated hybrid optical network (IHON) and how it can be efficient in network technology.

2.3.1 - Hybrid Aggregated Switches

Most demanding applications provide QoS by giving priority to the GST while delaying or dropping BE traffic. This maximizes the effective utilization of network resources for the varied services. Generation of optical networks call for ideal solutions. Such a solution is in the form of Integrated hybrid optical network (IHON) [22]. It permits networks with strict service guarantees of circuit switching and high throughput efficiency of packet switching. IHON offers the advantage of combining properties of both circuit and packet switching in an integrated method at the link level [22]. Each switching paradigm provides a quality service class, segmented further into various classes. GST provides circuit switching performance characteristics, which include fixed end-to-end delay without packet delay variation and no packet loss. The class offers carriers with premium quality service, the same way, legacy technologies like leased line time division multiplexing [24]. BE on the other hand, provides for high resource utilization. The class offers flexible, cost efficient and future proof network that can provide services for present and prospective classes of services and maximize resource utilization.

Proposed scheme [23] provides a multi service queuing model that can be used to improve the performance of the network. The service integrated optical interconnection network shows the behavior of the proposed aggregation switch. Fig. 4., shows the output of the abstracted model of the proposed interface hybrid switch. The scheme uses the same concept as [23], however in this scheme we only consider two traffic classes as used in the thesis.

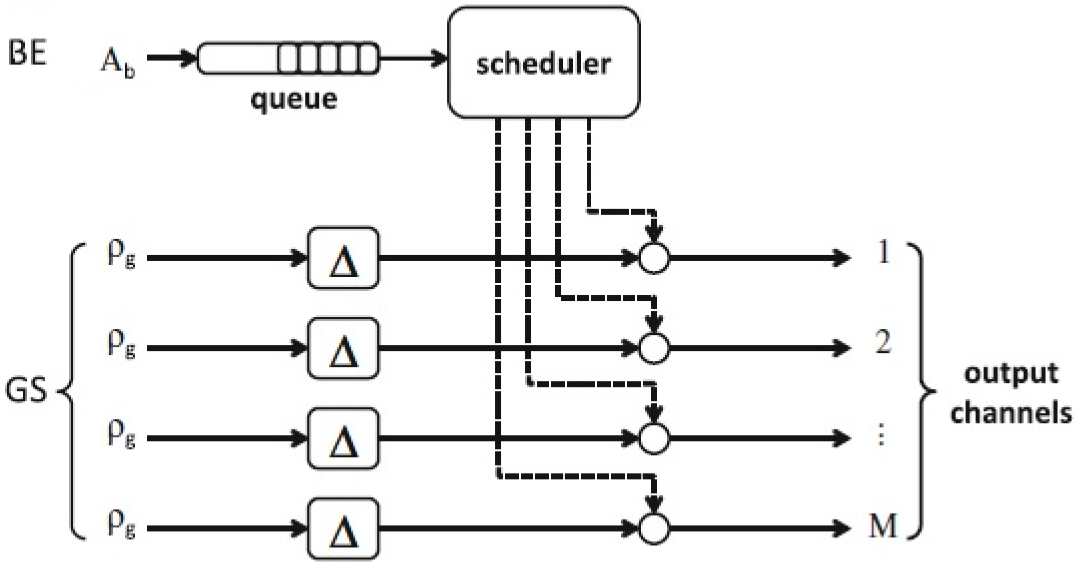


Fig. 4. Model representation of output interface hybrid aggregation switch

The switch is an example of a multiple output switch that has input traffic, which is uniformly distributed on the output switch. At the output, we have M wavelengths. These are the output channels of the proposed model. Every *M* output channel receives the GST traffic (ρ_g). This traffic is dedicated by a GST source and are delayed by a given [23] to prevent contention with the BE traffic. The other input is BE traffic, which has an intensity of A_b that feed the output interface with packets which are scheduled to transmit at the *M* channels. As such the total traffic at the output interface becomes $M\rho_g + A_b$ depending on the availability of the channels the BE traffic can be transmitted immediately or queued in case all the channels available are busy. This is done by the scheduler as explained before. The work of the scheduler is to monitor the flow of traffic in the model and give priority to the traffic.

2.3.2 - Working Principle and Practical Implementation

In aggregating the classes of traffic on generic hybrid switch optical output interface wavelengths, each GST virtual path is associated with a given channel. On this channel, different types of packets are time multiplexed, meaning BE packets can be transmitted on any of the channels during idle periods of associated GST source [23]. This allows efficient exploitation of the optical channel to optimize transmission resources. The evaluation of the amount of statistically multiplexed traffic transmitted on the interface and related performance is important, and therefore is the main goal of this thesis.

GS traffic is typically organized in bursts of multiple packets and must be forwarded to the pre-established virtual path on the corresponding output wavelength channel without loss and delay. In most studies, fixed delay is introduced on the bursts equal to maximum duration of BE traffic to avoid collision [22, 23]. The GST burst considers the GST burst transmission time and the reservation time. The evaluation of the amount of statistically multiplexed traffic transmitted on the interface and related performance.

GST has the highest priority and traffic is without loss and delay. It can interrupt (pre-empt) BE packets in transmission. Contention avoidance by selecting any of the available wavelengths is performed. To avoid collisions between BE packets and GST bursts, some fixed delay is introduced on the GS bursts. This is to ensure that GS traffic does not need to pre-empt BE traffic. The value of maximum duration of BE packets is conventionally defined as the value of the duration of BE packets which is overcome with an acceptably low probability. In practice, BE packets are much smaller than GS bursts.

When GST transmits, channel is not available for transmission of a new BE packets for a time equal to the effective duration of the GST burst plus a time equal to the fixed delay introduced, for contention avoidance, since the channel is immediately reserved when a GS burst is detected. As for the contention between GST and BE packets, BE traffic transmission is immediately stopped when a GST packet needs the same channel. This way GST traffic has pre-emptive priority over BE traffic. The interrupted BE packets are blocked and need retransmission [24]. In this thesis, packets needing retransmission are considered as new BE packets re-entering the queue. BE packet starts its transmission after the end of the transmission of a GS burst, or when a BE packet is successfully transmitted. So, the BE traffic offered to a channel can be significantly higher than the maximum channel utilization.

Total traffic offered to the output interface is a portion of the total traffic, divided equally among the output channels. Based on channel availability, GST packets are either immediately transmitted, whereas BE packets can be queued if all channels are busy. The scheduler performs these actions, by performing pre-emption [21]. Arrivals from GS traffic flows in this thesis are assumed to be continuous in the time frames provided. Arrivals from BE traffic flows follow independent Poisson processes. The service time (i.e., the transmission time over any output channel) is fixed for GST packets and exponentially distributed for BE packets.

Since GST packets are not queued, we are only interested in the performance metric BE packet success probability and throughput. GST bursts are much longer than BE packets. Given that we know the probability of a GST burst in service on a given channel, the probability of having output channels available to BE traffic is the GST traffic performance which is not influenced by BE traffic. BE packets can be pre-empted by GST bursts. So, BE traffic uses the spare capacity left by higher priority flows and only a subset of the BE packets that begin transmission can successfully complete their service. BE determines the throughput of the system.

3) CPRI over Ethernet traffic simulation

The chapter discusses on how o model CRPI traffic for hybrid switches. It will consider the model that is proposed in the thesis. It works on assumption of the model that is described in section 2) to explain how CPRI over Ethernet can be exploited to reduce the number of wavelengths needed in a network.

3.1 - Simulation of CPRI traffic with Hybrid switches

The simulation of the model follows the hybrid aggregation switch design discussed in [23] to increase efficiency. This is to minimize the use of wavelengths in the switch when CPRIoE and conventional packet based Backhaul traffic are transported over the same link. In this model the CPRIoE is considered as GST traffic, while the Backhaul used as BE traffic. The model has only two kinds of traffic as there is no RT traffic. The main idea behind the simulation is to create fixed GAPs in the output link to be filled with Backhaul packets to save resources. Fig. 5., shows the schematic representation that describes the encapsulation of CPRI into Ethernet frames as presented in the simulation.

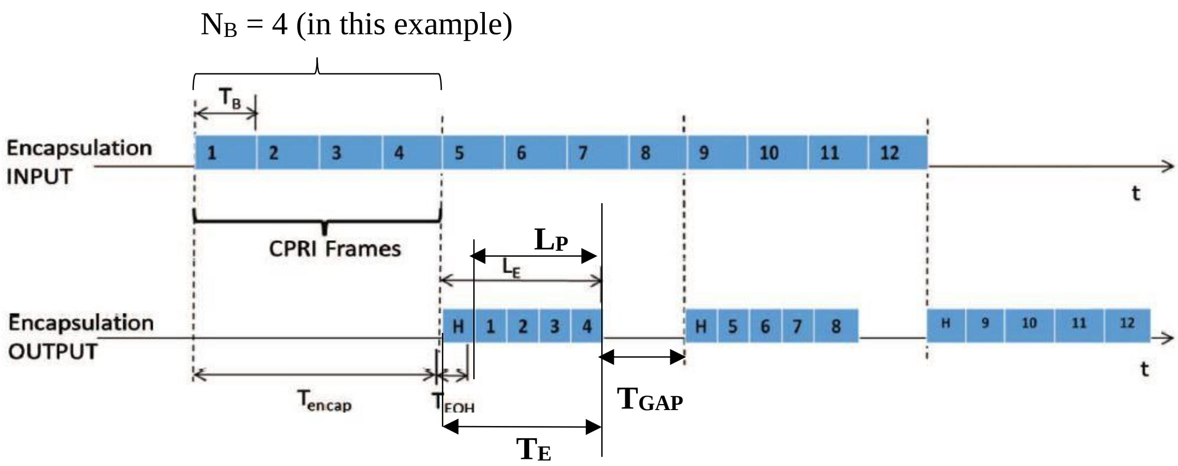


Fig. 5. CPRI encapsulation over Ethernet [23]

Using the idea of the hybrid aggregated switch in [23], the encapsulation input of GS traffic is the CPRI line. Table I, shows the notations used in modelling the design for simulation, and the schematic representation. The parameters are used in calculating the numerical values for the Ethernet frame size, and the GAP created. GST burst is generated at the input and equals to encapsulation delay (T_{encap}). The traffic is encapsulated in the Ethernet payload which is at the output.

Table I

CPRIoE Parameters

Duration of the CPRI frame	T_{encap}
Ethernet Payload size	L_P
Number of CPRI Basic Frame[s]	N_B
Duration of basic CPRI Frame	T_B
CPRI Line bit rate [bit per second]	R_{CPRI}
Duration of Ethernet Frame	T_E
Duration of the GAP	T_{GAP}
Header Overhead per Ethernet Frame[s]	T_{EOH}
Ethernet Rate [bit per second]	R_E
Ethernet Header Size [bit]	L_{EH}
Length of Ethernet Frame [bit]	L_E

This GS traffic is defined as;

$$L_P = N_B * R_{CPRI} * T_B \qquad (1)$$

where N_B is the number of CPRI basic frames at different line rates and T_B is the length of basic CPRI frame kept and it has a minimum duration of CPRI basic frame duration is 260ns (1/3.84 MHz) [16].

R_{CPRI} is at six different line rates ranging from option 1 (614.4Mb/s) to option 6 (6144.0Mb/s). Therefore, payload (L_P) is made of various number of CPRI basic frames (N_B).

The choice N_B is made in such a way that L_P is between 200-1500bytes. This is to make the Ethernet frame to remain an integer value to avoid basic frame fragmentation.

To get the number (N_B) of CPRI frames that can be placed in an Ethernet packet, the model considered the upper and a lower bound for N_B as indicated in the next equations.

Duration of CPRI frame from equation (1) becomes;

$$T_{encap} = \frac{L_P}{R_{CPRI}} \qquad (2)$$

This duration depends on R_{CPRI} because L_P from equation (1) we already know the length of the frame.

Therefore, the system works if

$$T_{encap} - T_E > 0 \qquad (3)$$

By defining T_{GAP} as;

$$T_{GAP} = \frac{L_P + L_{EH}}{R_E} = \frac{L_E}{R_E} \qquad (4)$$

Equation (4) gives the duration of the GST burst where R_E= 10Gbps, therefore, it becomes;

$$T_{GAP} = T_{encap} - T_E > 0 \qquad (5)$$

And knowing that:

$$T_{encap} = N_B * T_B \qquad (6)$$

and

$$T_E = T_{EOH} + \frac{L_P}{R_E} = T_{EOH} + \frac{N_B * T_B * R_{CPRI}}{R_E} = T_{EOH} + \frac{T_{encap} * R_{CPRI}}{R_E} \qquad (7)$$

By combining (5), (6) and (7), we can derive the lower bound for N_B;

$$T_E = T_{EOH} + N_B * T_B * \frac{R_{CPRI}}{R_E} < N_B * T_B = T_{encap} \qquad (8)$$

$$N_B * T_B * \left(1 - \frac{R_{CPRI}}{R_E}\right) > T_{EOH} \qquad (9)$$

$$N_B > \frac{T_{EOH}}{T_B * \left(1 - \frac{R_{CPRI}}{R_E}\right)} = \frac{\frac{L_{EH}}{R_E}}{T_B * \left(1 - \frac{R_{CPRI}}{R_E}\right)} = N_{Bmin} \qquad (10)$$

To find the upper bound for N_B, it is sufficient to impose the maximum payload size for an Ethernet frame (1500 Byte);

$$L_P = N_B * R_{CPRI} * T_B \text{ with } L_P = 1500\,Byte \qquad (11)$$

$$N_{Bmax} = \frac{L_P}{R_{CPRI} * T_B} = \frac{1500\,Byte}{R_{CPRI} * T_B} \qquad (12)$$

Therefore:

$$\left\lceil \frac{\frac{L_{EH}}{R_E}}{T_B * \left(1 - \frac{R_{CPRI}}{R_E}\right)} \right\rceil \leq N_B \leq \left\lfloor \frac{1500\,Byte}{R_{CPRI} * T_B} \right\rfloor \qquad (13)$$

The choice of N_B impacts T_{encap}, T_E and T_{GAP}.

The ρ_g parameter in [13] becomes:

$$\rho_g = \frac{T_{encap} - T_{GAP}}{T_{encap}} = \frac{T_E}{T_{encap}} = \frac{N_B * T_B * \frac{R_{CPRI}}{R_E} + T_{EOH}}{N_B * T_B} \qquad (14)$$

that also depends on N_B.

In general, the choice of N_B impacts the GAP duration which, in turn, increases or decreases the performance as shown in the simulation results section.

3.2 - Implementation of the simulator

The section explains how the simulator works. It provides details of the proposed hybrid switch through a simulation. It starts by giving the overview of the encapsulation of CPRI over Ethernet. Then it discusses about the traffic used in the simulation and how they are transmitted from the input to the output link. This section also gives the scheduling algorithm that is used in the simulator to achieve the results envisioned for the network.

3.2.1 - Overview of the simulator

Encapsulation of CPRIoE needs a mapping between CPRI and Ethernet frames. The simulator considers a structure of agnostic mapping of CPRIoE, in which, CPRI flows are sequentially packetized into an Ethernet frame without CPRI data knowledge [21]. Various CPRIoE can utilize a common Ethernet link. Parameters and notations in Table I and Fig. 5

describe the mapping between CPRI and Ethernet frames. CPRI flows are encapsulated in the payload of Ethernet frames. The input is at the CPRI line rate and output is at the Ethernet link rate. CPRI frames at the input are encapsulated with the Ethernet frames at the output. The CPRI input data in the Ethernet frame is a multiple of CPRI basic frame. Only two classes of traffic are considered in the simulation, that is the CPRI flow (GST) and backhaul traffic (BE).

3.2.2 - Classes of traffic used in the simulator

This simulator involves establishing and utilizing the gap created by transmission and retransmission of the GST and BE packets. The input which is at CPRI flow is produced at a constant line rate and it is deterministic. The simulator considers only two forms of traffic, that is the GST and BE traffic, which are the input and delivered to the output link;

- Guaranteed service traffic - this type of traffic resembles an optical circuit switch service in that it does not allow for any information loss in the network. The traffic is suitable for service classes which require HQ with medium bandwidth and application services that generate lager volumes of information units needed for transport. It considers packets that have the high requirements of packet loss and jitter. The traffic in this class is aggregated into bursts and transported in a connection-oriented method in the pre-established end-to-end lightpaths [24]. This is the traffic given the highest priority as in Fig. 6. The arrangement guarantees no losses resulting from contention. In addition, GST traffic minimizes delay jitter.
- Statistically Multiplexed Best Effort – the second-class category involved is the BE traffic that has loose requirements. This traffic is handled without reservations through packet switching losses resulting from contention and delays jitter because of deflection or buffering routed allowed [23]. This kind of traffic resembles a packet switched service that has a very small overall packet loss. It can be achieved by allowing the retransmission of packets. However, it does not guarantee delay inside the nodes. The

traffic is suitable for main parts of service class and applications which do not generate large information units for transport. Additionally, this traffic is recommended for service class that requires low real time services.

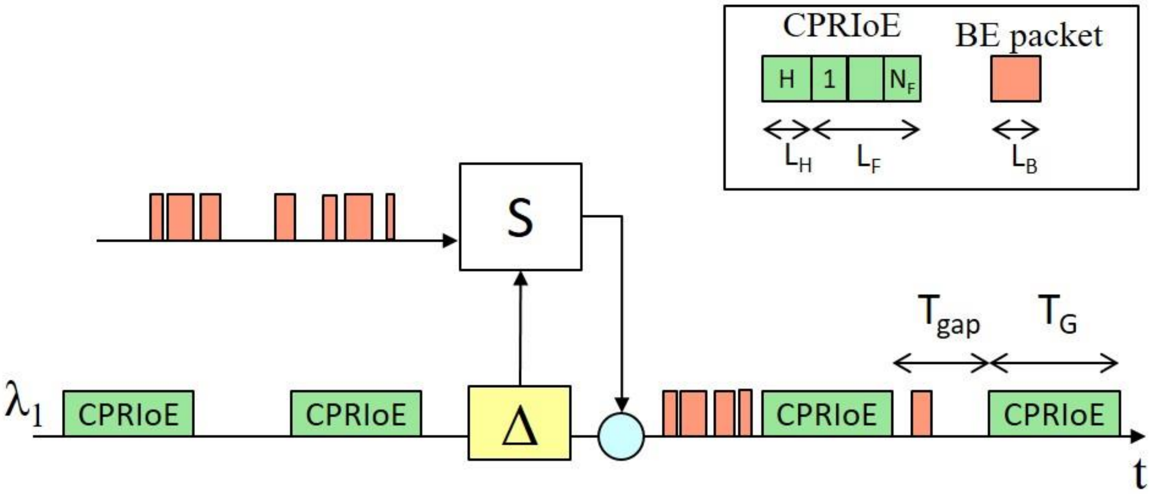


Fig. 6. Illustration of traffic flow of the simulator

The input duration of the simulator is T_{encap} as in equation (2) it is the input time and the duration that the CPRI traffic takes at given line rate to be encapsulated into an Ethernet payload. It also means the time taken by the Ethernet line to receive the CPRI payload. The simulator considers the time taken to determine the T_{encap} and T_{GAP} between the GST bursts and how it is generated at the output. In the model of the simulator, both the T_E and the time of the T_{GAP} resulting from the encapsulation are fixed. Additionally, we consider the delay generated while encapsulating. They are synchronized to start are different times. Encapsulation is performed on CPRI line which acts as GS traffic.

Despite the separation, the two traffic categories sequentially transmit their traffic capacity in the same wavelength. GS traffic with zero packet loss and fixed delay is forwarded through a wavelength-routed optical network. Remaining packets contains packets of header control information and is forwarded by use of packet switches. In GST traffic, the hybrid aggregation switch concept allows for high security, high reliability, and transparency [19].

3.2.3 - Scheduling algorithm

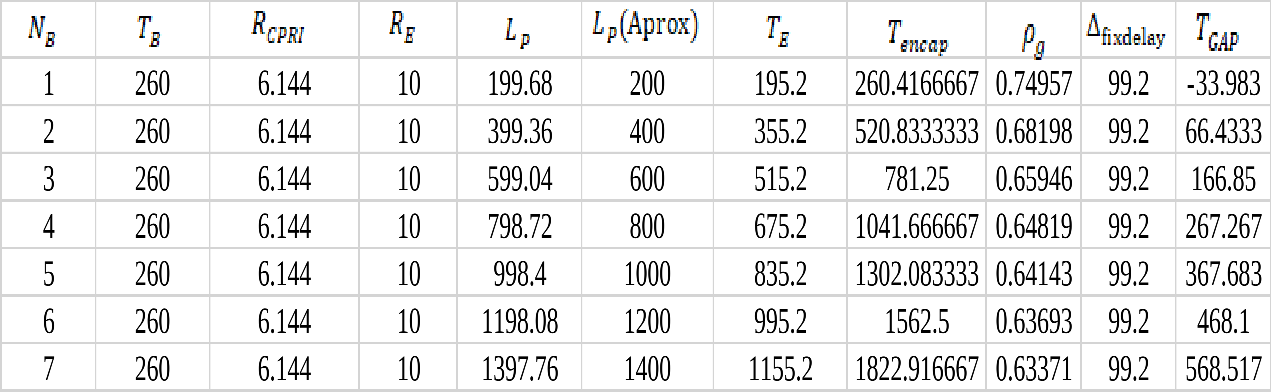
A scheduling algorithm is developed to monitor the gaps created between the GST packets. Utilization of the gaps is through fitting suitable BE packets created by the GST transmission. Results show an increase in efficiency in utilization of presented capacity. Scheduling is important to assist a high priority traffic like GST. Moreover, it helps in BE distribution that enter the system. Packetized traffic pattern is significant as it describes the traffic pattern of time sensitive service class which needs premium services like GST service.
The GS traffic bypasses the packet switches, thus a reduction of the required size of packet switch can be possible in case transit traffic is handled like GST traffic. High resource utilization and better performance is guaranteed by the optical migration network that is hybrid. The GST traffic path has priority over the BE traffic. Therefore, interleaving GST and BE assists in sharing the transmission resources.

In the simulator, various parameters for the CPRI flow are considered as already discussed in the other sections. These parameters help to determine the T_{encap} and T_{GAP} , as in equation (2) and (4) respectively. The durations largely depend on Ethernet Payload size (L_P) because L_{EH} is fixed at 44 Bytes [23].

The model proposed has antennas of the same type and are independent, starting the generation of CPRI flows at a random instant of time. The Table II indicates the numerical results as calculated on Option 6. From Table II, it can be seen that T_{GAP} does not permit transmission of any BE packet that does not meet the requirement of equation (13).

Table II

Numerical calculations



N_B	T_B	R_{CPRI}	R_E	L_P	L_P(Aprox)	T_E	T_{encap}	ρ_g	Δ_{fixdelay}	T_{GAP}
1	260	6.144	10	199.68	200	195.2	260.4166667	0.74957	99.2	-33.983
2	260	6.144	10	399.36	400	355.2	520.8333333	0.68198	99.2	66.4333
3	260	6.144	10	599.04	600	515.2	781.25	0.65946	99.2	166.85
4	260	6.144	10	798.72	800	675.2	1041.666667	0.64819	99.2	267.267
5	260	6.144	10	998.4	1000	835.2	1302.083333	0.64143	99.2	367.683
6	260	6.144	10	1198.08	1200	995.2	1562.5	0.63693	99.2	468.1
7	260	6.144	10	1397.76	1400	1155.2	1822.916667	0.63371	99.2	568.517

Input traffic is evenly distributed and called in the simulation. This gives a traffic flow of ON/OFF where we have the duration of CPRI frame and the gap. CPRI line rate is mapped to Ethernet link at the output. The simulation considers the delay produced from encapsulation of the CPRI over the Ethernet line. Additionally, the delay time of encapsulation is also considered. At the input, the CPRI line rate considers the CPRI data, MAC header, and the CPRIoE header. On the output at Ethernet line rate we have total Ethernet header caused by encapsulation of CPRI data on the Ethernet and length of the Ethernet frame. The word length depends on CPRI line rate provided at the input. The link between RE and REC has a fixed bandwidth and has a TDM connection.

The scheme accommodates GTS traffic that are transparent in Ethernet lines. Ethernet line connection has similar properties and advantages as the circuit switched network discussed in the section 3. The network permits BE traffic to be multiplexed onto the network utilizing the spare capacity in the Ethernet lines. Enhanced scheduling schemes which involve other techniques are significant in GS traffic load to augment resource utilization and at the same time fill the gaps. The scheduling scheme motivates further research on other management schemes which propose a method to adapt a segmentation of BE packets on GS rate to limit delay performance of BE. The QoS requirements of the current and future services required for the future networks. It also describes the architecture and possible mapping of the services with the available transport applications and services.

In case GST packet is detected; the network must not consider other channels for contention resolution of the incoming packets. The network can exploit other wavelengths for contention resolution tasks where GST in not in transmission. Moreover, to avoid collision in channel, when the network detects GST packet is over, it will send out a new BE packet immediately. BE must immediately stop sending out packets under transmission for collision avoidance and should not consider channels for contention resolution for the incoming packets. Therefore, GST packets preempts BE packets to prevent additional delay, thus avoiding creating jitter. A very short delay is required to allow the network to stop transmission. BE packets will be retransmitted on any free wavelength by use of cheap wavelength converters.
GS traffic experience short delays because this is one of the advantages of new architecture as short packets with high real time demands because they are not carried by the GST transport class. The priority class delay can be set at a higher value to allow for the BE traffic to transmit during this period. This allows for more backhaul traffic to be transmitted at the GAP as higher delay means larger GAP, hence more BE packets. Similarly, it means that the ratio between average GST and BE packet length is larger, thus, leading to better utilization of the bandwidth.

4) Numerical Results

This part gives the results obtained from the simulator and discusses the effect of the traffic and parameters on the simulator. It also uses the results to check on the effectiveness of the proposed hybrid switch. The performance of the model is determined by the success probability of BE and throughput of the backhaul traffic.

4.1 - Parameters for Performance Analysis

Considering the model discussed in the previous sections, the hybrid aggregated switch behavior can well be understood by the simulator results. The simulator helps in validating the accuracy of the model presented and assist in the evaluation of the performance of the BE traffic. This section thus presents some preliminary results of the architecture. It considers the relative classes which are GST and BE. A mixture of GST and BE is considered, and packet success probability is considered in a single output fiber. GST traffic travels through the network without loss, while BE traffic is sent in gaps in between the GS packets.

GST which is an input service is constant and continuous flow, therefore; BE, which is exponential must be small enough to fill the GAP created by the flow of GST packets. The smallest size of one packet is 64Bytes and service time is 51ns the smallest Ethernet frame size [16]. In the simulations we consider the size of 124Bytes with service time as 99.2ns to compare the results with previous model architecture like the one in [23]. The size of BE packet (L_B) and $\Delta < T_{GAP}$ for BE traffic to be successfully inserted into Ethernet line for transmission.

The success probability of BE packets is;

$$\Pi_S = \frac{\frac{1}{\theta_B}}{\left(\frac{1}{T_{GAP}}+\frac{1}{\theta_B}\right)} \qquad (15)$$

While BE throughput is

$$\text{BE Throughput} = \frac{BE\ successful\ packets}{Total\ BE\ packets} \qquad (16)$$

Therefore, under saturated conditions and considering equation (13), equation (17) will apply in saturating traffic conditions:

$$S_B = \Pi_S(1 - \rho_G) \qquad (17)$$

The maximum value that BE load can reach before entering saturation becomes smaller when GS load increases, because of the smaller average number of available channels. However, when GS load increases, a significant part of each interrupted BE packet is not transmitted, due to more frequent pre-emption events: Therefore, saturation is reached for larger values. The availability of channels to transmit BE packets decreases as GST increases. As expected, maximum BE throughput decreases when GST increases due to the combined effect of higher number of interruptions and reduced channel availability. Design is in terms of required number of channels and the optical output interface of the hybrid aggregation switch. As a general statement, the mapping of the mix of traffic in a data center to network service provided by the integrated approach can be optimized by the application of the described model with the aim to properly set up the aggregation switch.

4.2 - Performance of BE

The performance of BE traffic packets is measured through BE packet success probability and BE packet throughput as a function of payload L_P for different parameters of BE packets load. BE traffic is assumed to be exponentially distributed as well as inter-arrival time. We consider R_{CPRI} Option 1 (614.4 Mb/s) to Option 6 (6144.0 Mb/s) in this thesis. We also consider delay as 99.2ns and report an analysis of the impact of different delays on performance. BE load (ρ_B) is 1.0 and we compare the behavior of the system with other load capacities. The number of channels is M=1 for the first evaluations, and then the performance with cases where M>1 are reported. The rate of each the output channel is assumed to be 10Gbps. The curves in the figures indicate the behavior of the performance where for higher payload at Ethernet link, we achieve high BE probability success rate. This is what the model envisioned by use of the hybrid switch in data center.

4.2.1 - Case I

In case I, we consider delay as 99.2ns, $L_P$from 200-1400Bytes, ρ_B from 0.001 to 1.2 and *M*=1, for Option 1 and 6.

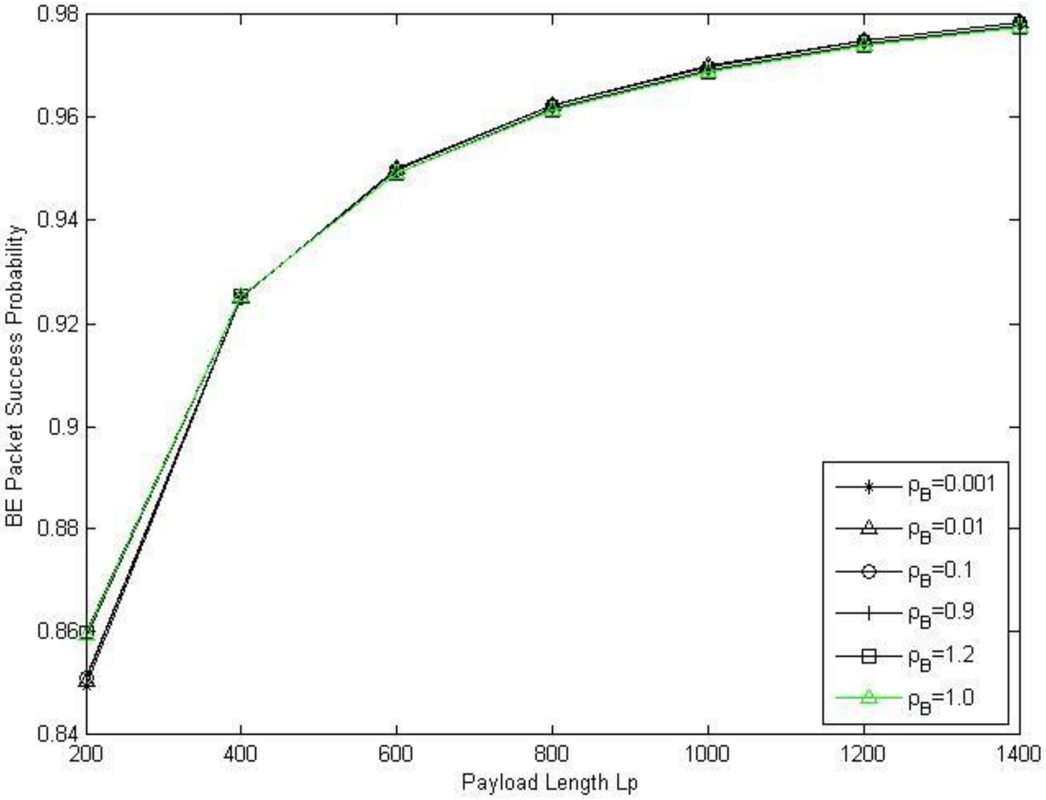


Fig. 7. Option 1. BE traffic success probability, as a function of L_P *with varied* ρ_B*. M=1*

When we consider Option 6, under the same condition, we have Fig. 8.

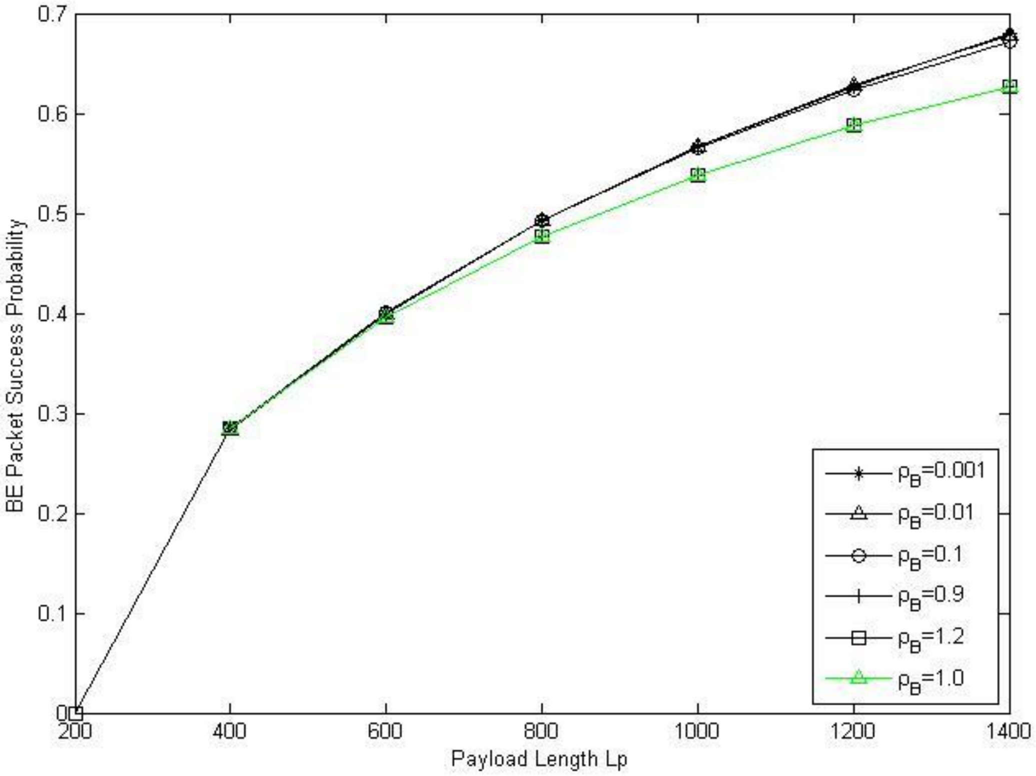


Fig. 8. Option 6. BE traffic success probability, as a function of L_P *with varied* ρ_B*. M=1*

From Fig. 7., and Fig. 8., we can see that the BE success probability increases with increase in L_P. We have a higher BE success probability when we are dealing with Option 1, compared to Option 6. This is because in Option 1, we have a bigger gap to be filled by the BE packets hence the higher success probability. The load behaves in a similar way until we reach the saturation point where $\rho_B > \rho_B^{MAX}$ like in the case of where ρ_B=1.2, the model becomes overloaded with BE packets, hence the system is saturated, i.e.

$$\rho_B^{MAX} = \frac{1-R_{CPRI}}{R_E} \qquad (18)$$

As

$$\rho_B = \frac{A_B}{M} \qquad (19)$$

Equation (18) and (20) is best illustrated by Fig. 9 and Fig. 10, when we use CPRI line rate of Option 1 and 6 to check BE Throughput. Increasing $\rho_B$more than the ρ_B^{MAX} does not increase the throughput because already the channel or the interface is saturated.

In case of BE throughput, we have Fig. 9., for Option 1, and Fig. 10 for Option 6.

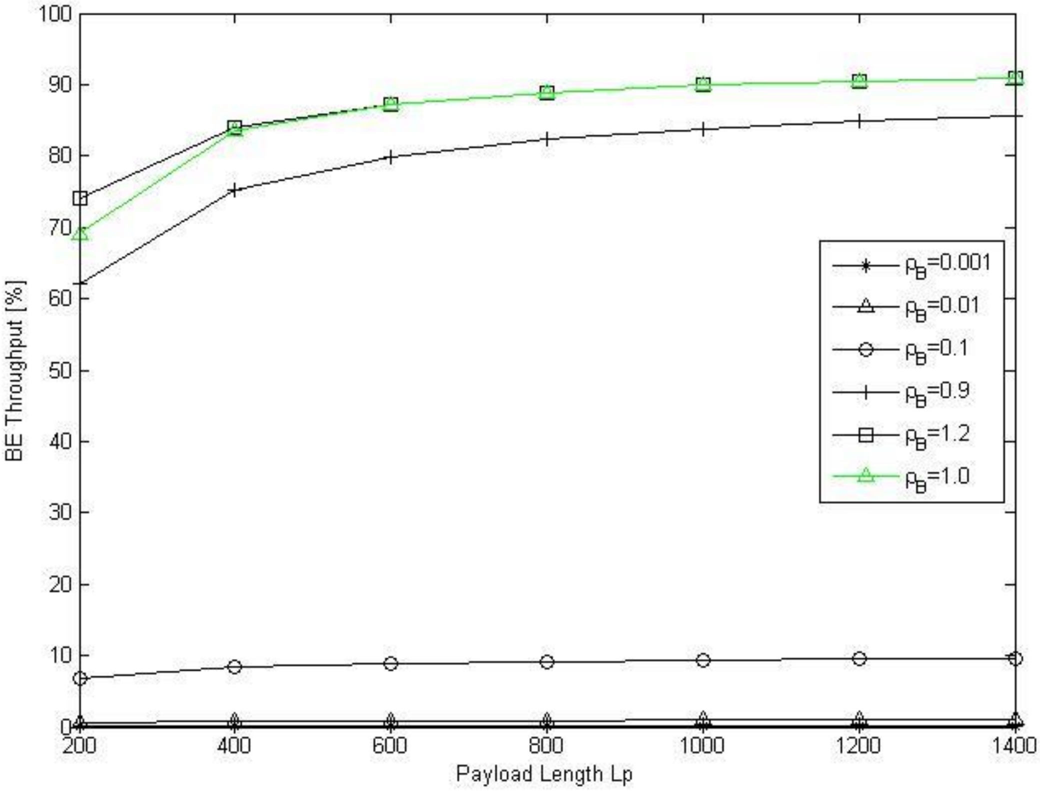


Fig. 9. Option 1, BE throughput, as a function of L_P *with varied* ρ_B*. M=1*

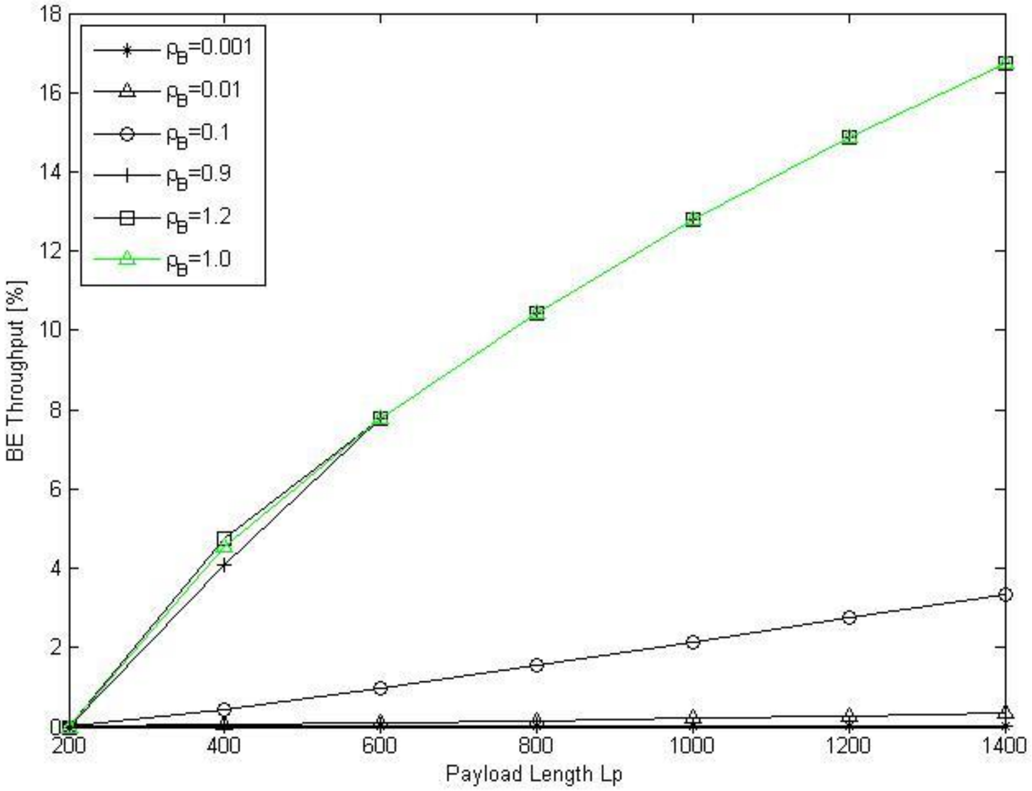


Fig. 10. Option 6, BE throughput, as a function of L_P *with varied* ρ_B. *M=1*

When comparing the CPRI line rate Option 1 and 6 we note that throughput is much higher for Option1 because you can accommodate many more packets on the output interface since the CPRI rate is low. Looking at the throughput of BE packets from the results we note that while traditional solutions requires one channel for each CPRI flow and some channels for statistically multiplexed traffic, this solution proposed as indicated by the simulation allows for the reduction on the number of channels by sharing the one with CPRI traffic. The throughput that you can carry is provided in the graphs.

4.2.2 - Case II

Here we consider different BE packets size from 200-1000Bytes, for Option 1 and 6, with delay as 99.2ns, $L_P$from 200-1400Bytes, ρ_B=1.0 and M=1, for Option 1 and 6.

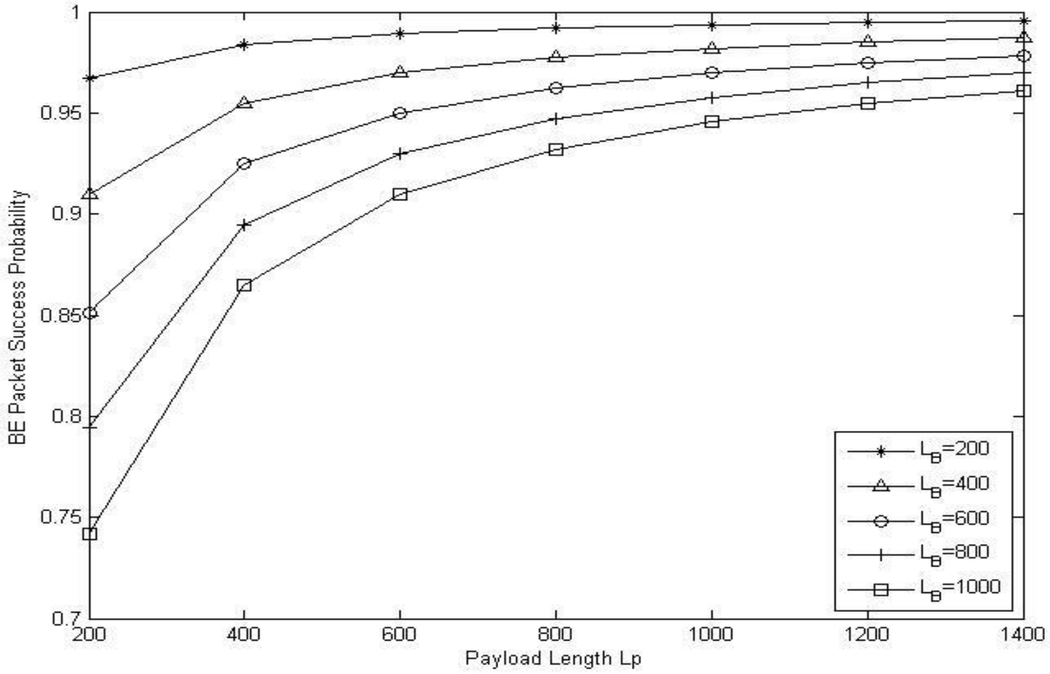


Fig. 11. Option 1. BE traffic success probability, as a function of L_P *with varied BE traffic packet size. M=1.*

With shorter BE packet size, we witness a higher BE success probability as in Fig. 11., and Fig. 12., show for Option 1 and 6, respectively. This is because with shorter BE packets more packets can be accommodated and serviced in the gaps created on the output link. However, in Option 6, we can notice a behavior where we do not have any BE packets being transmitted. At higher CPRI line rate, with low $L_P$there is no gap and no BE packet can be transmitted on the output link.

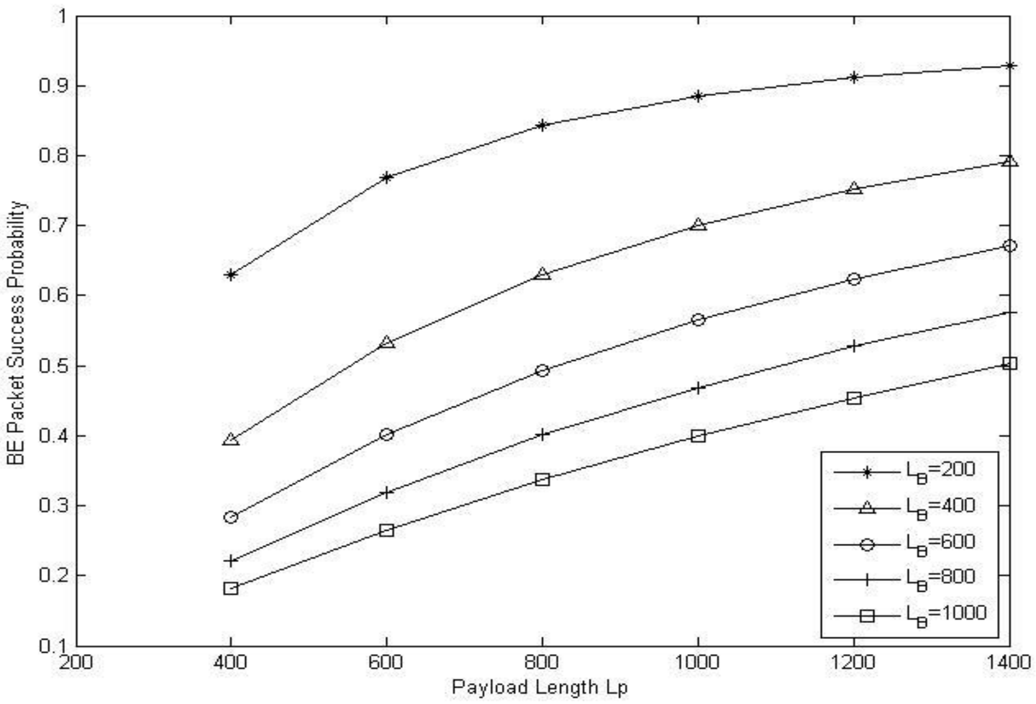


Fig. 12. Option 6. BE traffic success probability, as a function of L_P *with varied BE traffic packet size. M=1.*

We can see from Fig. 12., that GST traffic is being transmitted at a constant rate, the gap created can only be filled by BE packets of smaller size which are exponentially inserted in the gaps at the Ethernet link, therefore equation (13) holds. This is best illustrated using BE throughput measurement as in Fig 13. It shows that the BE throughput increases when L_P increases, and with lower BE packet size we witness a high BE throughput rate.

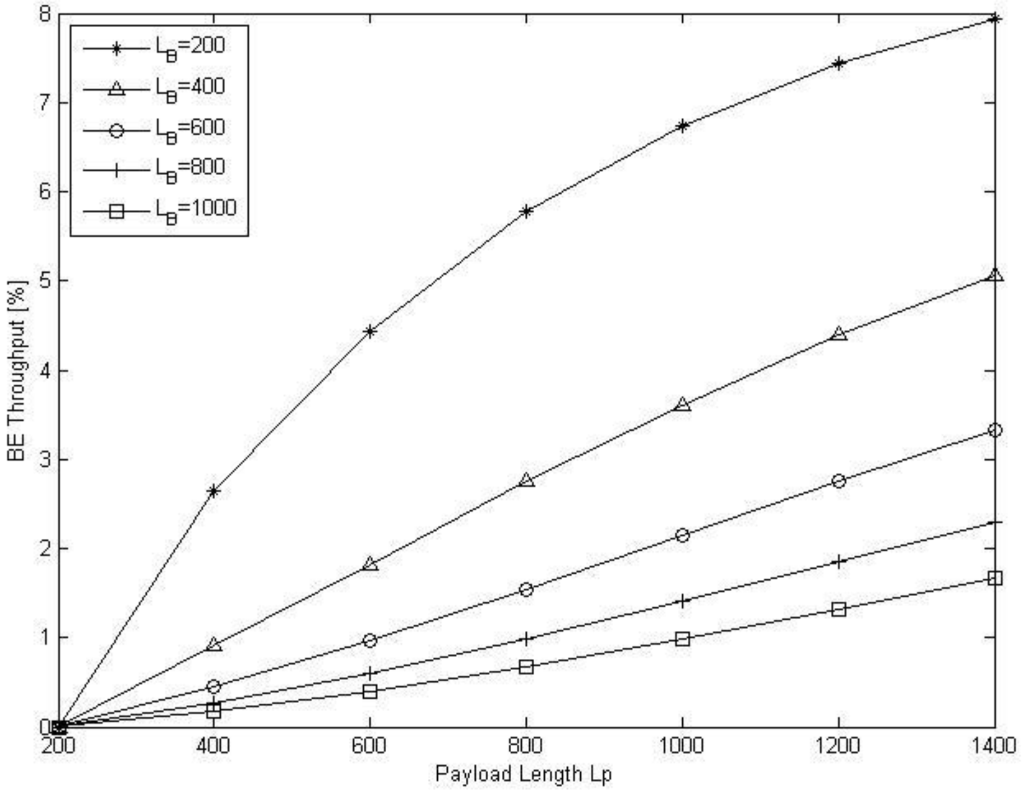


Fig. 13. Option 6. BE throughput, as a function of L_P *with varied BE traffic packet size when M=1.*

4.2.3 - Case III

With different CPRI line rates, with the same the same load ρ_B=1.0.

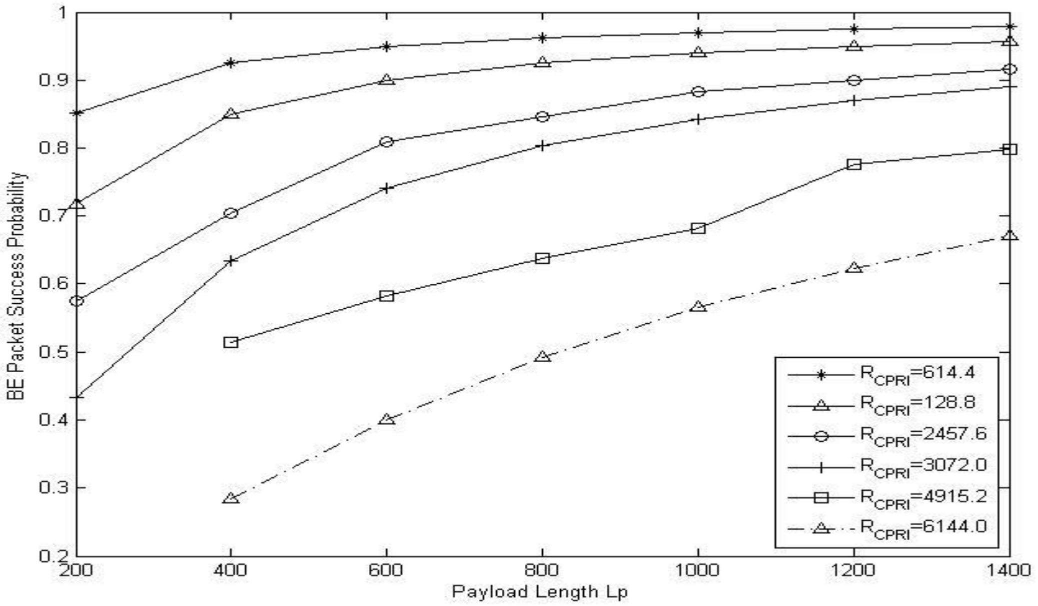


Fig. 14. BE traffic success probability, as a function of L_P *with different CPRI lines rates, and M=1.*

From Fig. 14, we see that when we transmit CPRI traffic at a higher rate of R_{CPRI} Option 6 (6144.0Mb/s) we experience lower BE success probability when compared with R_{CPRI} Option 1 under the same conditions. This is because at higher rate we have a smaller GAP for BE traffic to be inserted at the output link. Fig. 14, shows the behavior of BE packets when they are exponentially transmitted. The irregular curve indicates that the BE packets are inserted when they find free gaps during the transmission period.

4.2.4 - Case IV

When we consider different fixed delays for Option 1 and 6 we achieve Fig. 15 and Fig. 16, respectively. This is by varying L_P for the different line rates. We use one channel in this simulation.

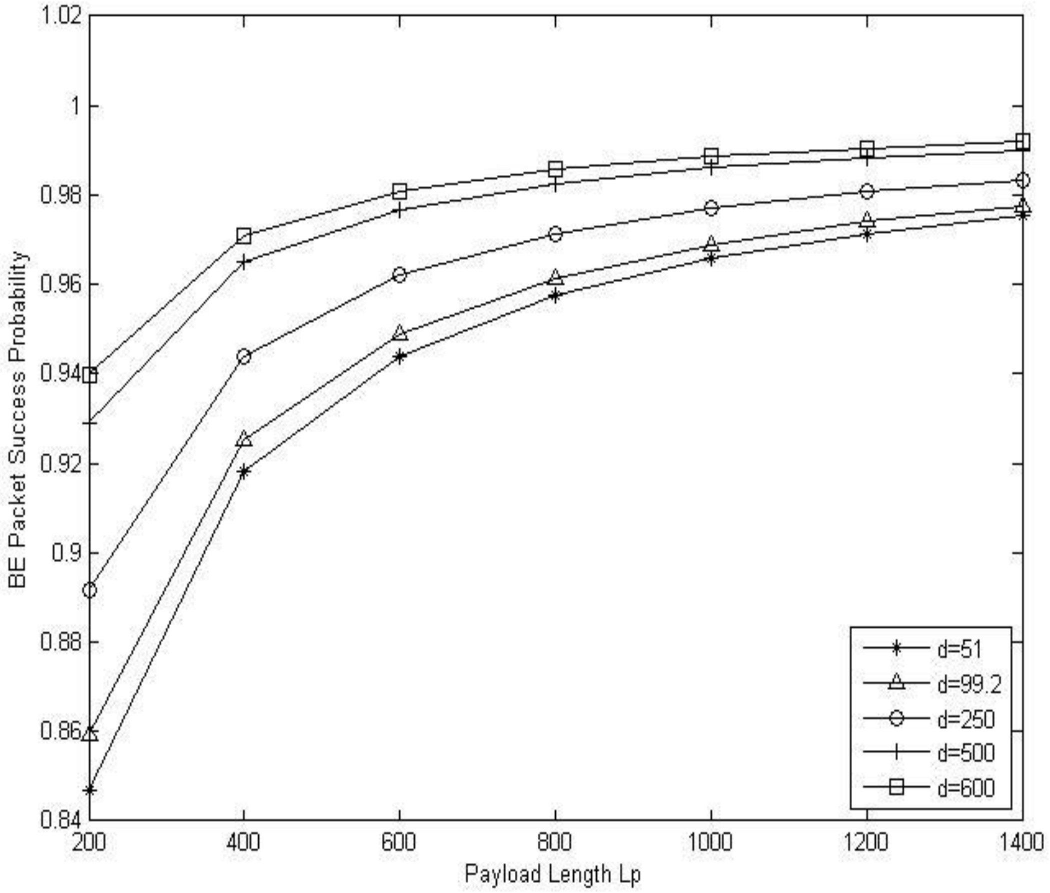


Fig. 15. Option 1. BE traffic success probability, as a function of L_P *with different delay, and M=1.*

For Option 6, we achieve;

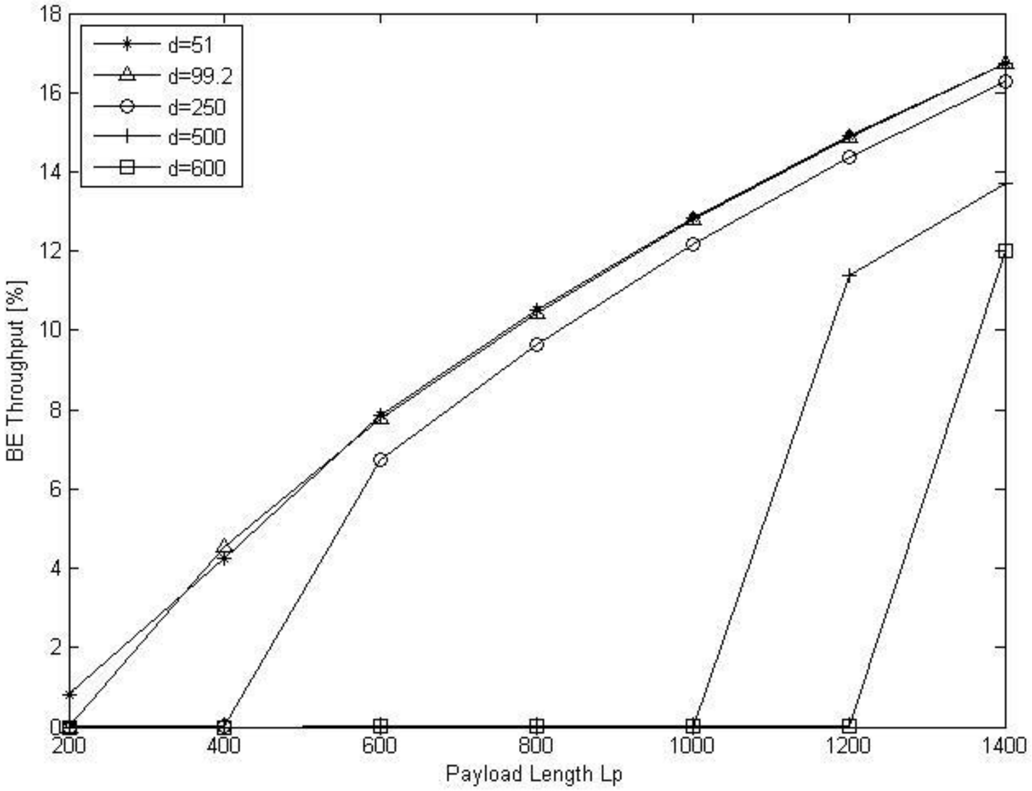


Fig. 16. Option 6. BE traffic throughput, as a function of L_P *with different delays, and M=1.*

From Fig. 15, we notice that the BE success probability is high for higher delay in the channel. This is the case for CPRI line rate of Option 1, where the high delay gives time for the BE traffic packets to fit into the empty gaps for transmission. GST traffic packets will take longer period before transmitting hence the high BE success probability. When it comes to CPRI line rate Option 6, as in Fig. 16, we witness a strange behavior on the BE throughput. Due to the smaller gaps in the line rate, we witness a low throughput rate with the different fixed delay options. With a lower delay we have high BE throughput. This is in consideration of the N_B which determines the size of the gaps to be filled by the BE traffic packets.

4.2.5 - Case V

In the case of multiple channels (M>1), with ρ_B = 1.0, and different CPRI line rates we the behavior is as shown in Fig. 17.

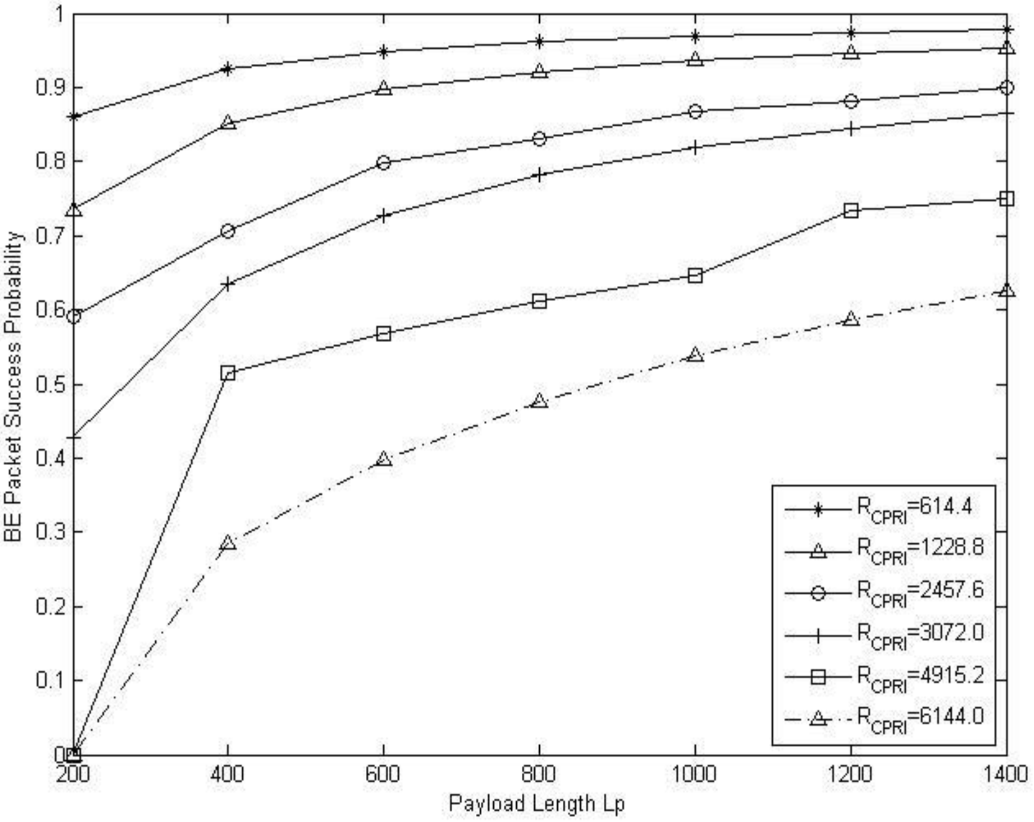


Fig. 17. Average BE success probability (per channel), as a function of L_P *with different CPRI line rates, and M=2,*

From Fig. 17, it is possible to notice that the BE success probability of the model increases with increase of L_P for different CPRI line rates. The BE success probability of low CPRI line rate Option 1, is higher than subsequent high CPRI line rates. The behavior is very similar to the case M=1. The load is divided equally in the channel hence the behavior of BE transmitted packets.

With *M*=5, under the same conditions as in Fig. 17, we have the results as in Fig. 18.;

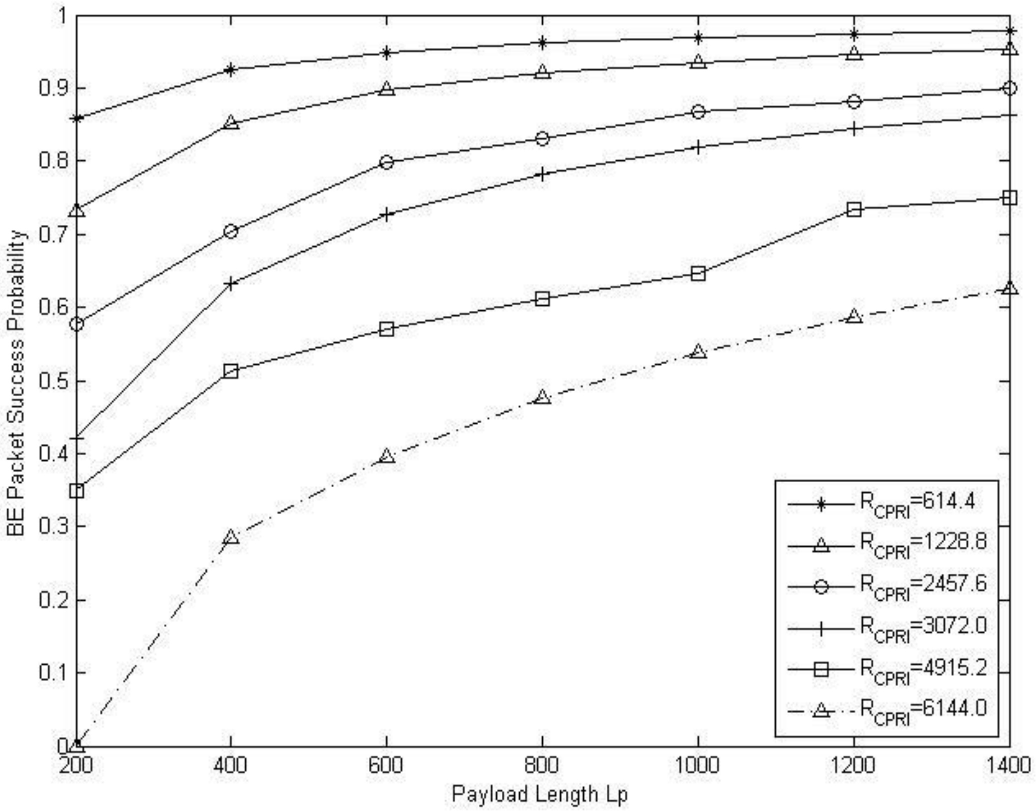


Fig. 18. Average BE success probability (per channel), as a function of L_P*, and M=5, for the different CPRI line rates*

The behavior of the channel when *M*=5 and ρ_B = 1.0 is same to the behavior of the model when the *M*=1 and ρ_B = 1.0.

4.2.6 - Case VI

When we have multiple channels (*M*=2) with ρ_B = 2.0, the behavior of the model is as in the Fig. 19.

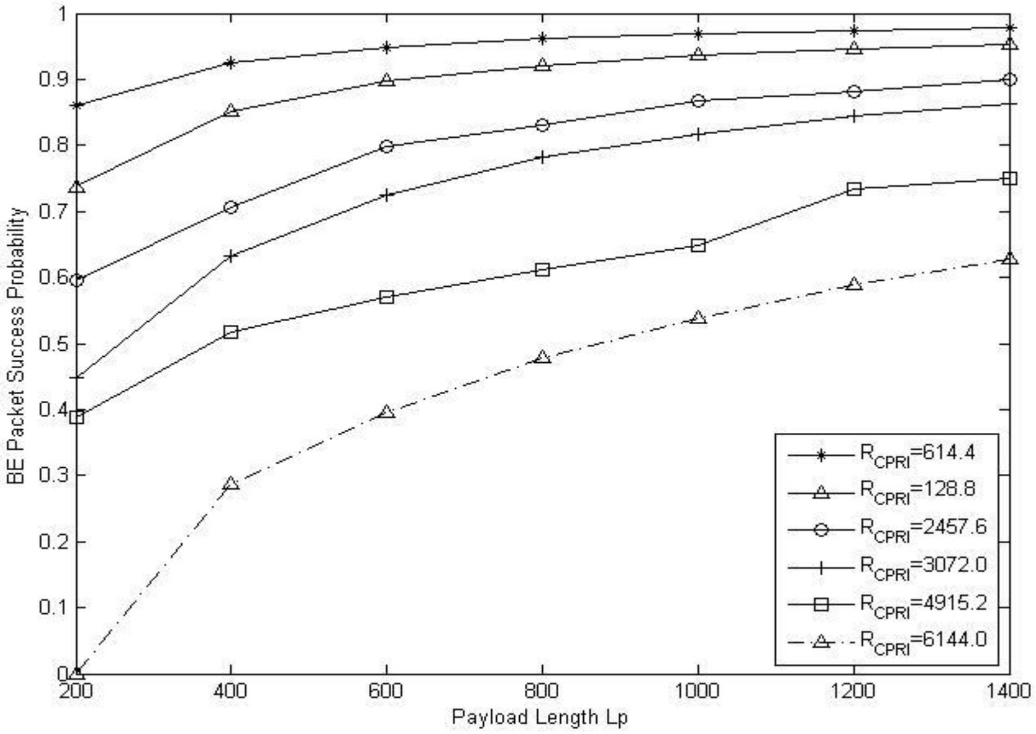


Fig. 19. Average BE traffic success probability (per channel), as a function of L_P, ρ_B *=2.0, and M=2, for the different CPRI line rates*

This is the same scenario when we test the BE throughput. We achieve a lower throughput for CPRI option 6 compared to Option 1; this is because of the narrow gaps resulting from the encapsulation at the higher rate. In option 1, there are larger gaps created hence more packets can be serviced in the gap, so higher BE success probability compared to Option 6, same applies to BE throughput under same conditions.

From the simulation results we can see that for higher Payload at the Ethernet link we get higher BE success probability. We also witness that we can achieve a higher BE success probability in case we use a lower CPRI line rate compared to a higher CPRI line rate.

From the simulations we can conclude that, payload (L_P) and service time (θ_B) determines the length/size of the gap which controls the performance of the system. Therefore, BE success probability and BE throughput depends on choice of the N_B at the input and this will influence the model performance. As such, we can conclude that the system model designed improves the performance of the aggregated hybrid switch by reducing the number of wavelengths needed in transmitting packets when CPRIoE and conventional packet based Backhaul traffic are transmitted over the same link.

5) Conclusion

The thesis presents a novel concept in hybrid network solution. It allows for CPRI over Ethernet (CPRIoE) and conventional packet based Backhaul traffic to be transported over the same link. From the simulation and results it has been shown that the implementation of the system model is feasible for use in future networks. In addition, a collision avoidance mechanism is proposed and tested by the simulation, thereby demonstrating the feasibility of this approach. In comparison to earlier hybrid architecture, better resource utilization at lower cost is achieved because of the reduction on the number of wavelengths needed to implement this architecture. Additionally, the proposed system does not allow for jitter. Guaranteed Service traffic (GST) that is of high performance and reliability is required when dealing with high demand traffic [24]. Future applications such as real time tele visualization or future applications like remotely controlled surgery will require this kind of GST packets. The implementation of the model of this type of service is feasible in an aggregated hybrid switch network which is requires high throughput efficiency. From the simulation it has been shown that high GST such as the traffic in transit transferred over WDM can be saved in this type of packet switch [22]. This permits for a high efficiency and low-cost performance network. Moreover, the thesis has shown that aggregation of hybrid switching, and packet scheduling can be combined to offer guaranteed service [24]. The network can minimize the number of wavelengths needed for packet switches when compared to a pure switched network. As such, a hybrid network can offer an improved performance at a reduced cost. In future, full service packet switched network that offer quality such as circuit switched network should be implemented.

References

[1] X. Liu and F. Effenberger, "Emerging optical access network technologies for 5G wireless," *Journal of Optical Communications and Networking,* vol. 8, pp. B70-B79, 2016.

[2] A. M. Mousa, "Prospective of fifth generation mobile communications," *International Journal of Next-Generation Networks (IJNGN),* vol. 4, pp. 1-30, 2012.

[3] K.-i. Sato and H. Hasegawa, "Optical networking technologies that will create future bandwidth-abundant networks," *Journal of Optical Communications and Networking,* vol. 1, pp. A81-A93, 2009.

[4] I. Chih-Lin, J. Huang, R. Duan, C. Cui, J. X. Jiang, and L. Li, "Recent progress on C-RAN centralization and cloudification," *IEEE Access,* vol. 2, pp. 1030-1039, 2014.

[5] P. Chanclou, A. Pizzinat, F. Le Clech, T.-L. Reedeker, Y. Lagadec, F. Saliou, *et al.*, "Optical fiber solution for mobile fronthaul to achieve cloud radio access network," in *Future Network and Mobile Summit (FutureNetworkSummit), 2013*, 2013, pp. 1-11.

[6] V. Jungnickel, K. Habel, M. Parker, S. Walker, C. Bock, J. F. Riera, *et al.*, "Software-defined open architecture for front-and backhaul in 5G mobile networks," in *Transparent Optical Networks (ICTON), 2014 16th International Conference on*, 2014, pp. 1-4.

[7] C. Kachris, K. Kanonakis, and I. Tomkos, "Optical interconnection networks in data centers: recent trends and future challenges," *IEEE Communications Magazine,* vol. 51, pp. 39-45, 2013.

[8] D. Chitimalla, K. Kondepu, L. Valcarenghi, M. Tornatore, and B. Mukherjee, "5G fronthaul-latency and jitter studies of CPRI over Ethernet," *IEEE/OSA Journal of Optical Communications and Networking,* vol. 9, pp. 172-182, 2017.

[9] A. Pizzinat, P. Chanclou, F. Saliou, and T. Diallo, "Things you should know about fronthaul," *Journal of Lightwave Technology,* vol. 33, pp. 1077-1083, 2015.

[10] N. J. Gomes, P. Chanclou, P. Turnbull, A. Magee, and V. Jungnickel, "Fronthaul evolution: From CPRI to ethernet," *Optical Fiber Technology,* vol. 26, pp. 50-58, 2015.

[11] C. Specification, "V6. 1 (2014-07-01)," *Interface Specification Common Public Radio Interface (CPRI),* 2014.

[12] L. Valcarenghi, K. Kondepu, and P. Castoldi, "Analytical and experimental evaluation of CPRI over Ethernet dynamic rate reconfiguration," in *Communications (ICC), 2016 IEEE International Conference on*, 2016, pp. 1-6.

[13] J. Perelló, S. Spadaro, S. Ricciardi, D. Careglio, S. Peng, R. Nejabati*, et al.*, "All-optical packet/circuit switching-based data center network for enhanced scalability, latency, and throughput," *IEEE Network,* vol. 27, pp. 14-22, 2013.

[14] I. T. F. Neri, J. S. P. X. M. Bruin, and S. S. Lopez, "Optical Network Design and Modeling."

[15] C. Kachris and I. Tomkos, "A survey on optical interconnects for data centers," *IEEE Communications Surveys & Tutorials,* vol. 14, pp. 1021-1036, 2012.

[16] C. Gunther, "What's New in the World of IEEE 802.1 TSN."

[17] M. Savi, H. Øverby, N. Stol, and C. Raffaelli, "Sharing wavelength converters in optical switching fabrics: When, how, and which kind of?," in *Optical Network Design and Modeling (ONDM), 2013 17th International Conference on,* 2013, pp. 149-154.

[18] N. Stol, C. Raffaelli, M. Savi, and G. Cincotti, "Optical codes for packet detection in the opmigua switch architecture," in *Photonics in Switching,* 2010, p. JTuB27.

[19] A. Kimsas, S. Bjornstad, H. Overby, and N. Stol, "Improving performance in the OpMiGua hybrid network employing the network layer packet redundancy scheme," *IET communications,* vol. 4, pp. 334-342, 2010.

[20] S. Bjornstad, D. R. Hjelme, and N. Stol, "A packet-switched hybrid optical network with service guarantees," *IEEE Journal on Selected Areas in Communications,* vol. 24, 2006.

[21] C. Raffaelli, M. Savi, and A. Stavdas, "Multistage shared-per-wavelength optical packet switch: Heuristic scheduling algorithm and performance," *Journal of Lightwave Technology,* vol. 27, pp. 538-551, 2009.

[22] N. Stol, M. Savi, and C. Raffaelli, "3-level integrated hybrid optical network (3LIHON) to meet future QoS requirements," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE,* 2011, pp. 1-6.

[23] W. Cerroni and C. Raffaelli, "Analytical model of quality of service scheduling for optical aggregation in data centers," *Photonic Network Communications,* vol. 28, pp. 264-275, 2014.

[24] R. Veisllari, S. Bjornstad, and K. Bozorgebrahimi, "Integrated packet/circuit hybrid network field trial with production traffic," *IEEE/OSA Journal of Optical Communications and Networking,* vol. 5, pp. A257-A266, 2013.