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*Article*

# C-RAN Traffic Aggregation on Latency-controlled Ethernet links

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**Abstract:** Centralized/Cloud Radio Access Networks (C-RAN) are deployed in converged fixed-mobile networks to exploit the flexibility coming from joint application of Network Function Virtualization (NFV) and Software Defined Networking (SDN). In this context, optical links connecting C-RAN nodes, possibly based on the Ethernet standards, may carry traffic with different requirements in terms of latency and throughput. This paper considers the problem of traffic aggregation on C-RAN optical Ethernet links with latency control for fronthaul traffic and throughput capability for backhaul traffic. Integrated hybrid nework technique is applied to show how time transparency can be enforced for Ethernet encapsulated Common Public Radio Interface (CPRI) traffic while allowing statistical multiplexing of backhaul traffic. Simulation results show the effectiveness of segmentation of backhaul traffic to allow exploitation of the available bandwidth even with high capacity CPRI options.

**Keywords:** hybrid optical networks; Ethernet; fronthaul; backhaul; C-RAN; convergence.

## 1. Introduction

Centralized/Cloud Radio Access Network (C-RAN) is a promising technique enhancing mobile network performance and flexibility [1]. Enhancing survivability and power saving are the two main key design in this architecture [2]. C-RAN is based on the splitting of functionalities which are possibly remotized for the purpose of centralization of the higher layer baseband processing related to multiple Remote Radio Heads (RRHs), by the introduction of the fronthaul network segment [3]. In addition, this approach takes significant advantage of Network Function Virtualization (NFV) and Software Defined Networking (SDN) control and management to add flexibility and adaptability to 5G transport Networks [4] and to allow migration of functionalities over the nodes of C-RAN for optimization purposes.

In recent proposal [1], the highly demanding traffic, generated by the above functional splits, is carried together with packet-based backhaul (BH) traffic over a common optical infrastructure on different wavelength channels of the same fiber links [5]. This solution can be designed to meet the latency requirements of fronthaul (FH) traffic but may limit the system scalability and lead to low resource utilization with consequently high deployment costs. Hence, techniques for improving the optical channel utilization while meeting the strict performance requirements of FH traffic are needed and investigated in this paper. Ethernet-based links can be adopted to implement FH and standardization bodies are recently very active on the definition of the requirements to support FH traffic on this widely deployed interfaces. Delay requirements are identified as quite challenging being the Ethernet not originally designed for delay-sensitive aplications, such as fronthauling [6].

In this work an integrated hybrid architecture is reviewed and extended with pre-emption to be applied to C-RAN optical transport network. An integrated Ethernet-based interface, where FH and BH traffic are multiplexed to achieve high utilization of the wavelength resource, is proposed and evaluated to meet the delay requirement of FH traffic, while offering throughput capability to BH traffic.

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A converged fronthaul/backhaul scenario, as depicted in figure 1, is considered for evaluating the additional BH throughput that can be obtained as a consequence of the application of the mechanism to wavelength channels. In figure 1 a sample C-RAN topology is shown where Integrated Hybrid Nodes (IHN) are interconnected by optical links, possibly forming a mesh or other topologies. IHN are assumed to be equipped with Ethernet interfaces, which ensure high backward compatibility and low cost. Remote Radio Heads (RRH) are connected to IHNs which host baseband unit (BBU) functionalities. The set of BBUs available in a IHN form the BBU Hotel. These functionalities can be virtualized in a C-RAN and moved throughout the network to optimize the access service. The management of migration of virtual BBU functionalities is performed by the SDN control/management plane, not shown in the figure. As a consequence of different possible locations for BBU Hotels in IHNs, FH and BH traffic can be present on each link of the C-RAN. FH traffic is assumed according to the CPRI standard as encapsulated in Ethernet frames. The traffic characteristics of the CPRI traffic as generated by the different standardization options are taken into account and managed by a suitably extended integrated hybrid mechanism. As a consequence of the deterministic behavior of the encapsulated CPRI traffic, the benefits of introducing a fragmentation policy on the BH traffic is also considered.

The paper is organized as follows. In section 2 research in this context is described. In section 3 the application of the integrated hybrid concept in C-RAN is described. Section 4 describes how to insert BH traffic in the FH stream while preserving time transparency. In section 5 evaluation of the proposed architecture is presented. Conclusions and open aspects are drawn in section 6.

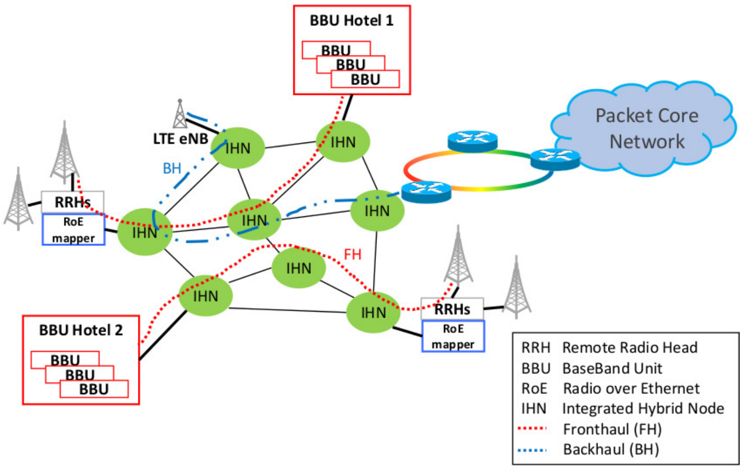


**Figure 1.** Converged fronthaul/backhaul scenario.

## 2. Related works

Any transport network has among its main targets to serve different kinds of applications while being able to handle Quality of Service (QoS) requirements. These aspects are widely investigated in literature to design networks with enhanced flexibility and scalability, which are turned recently to be the key enablers for cost-efficient 5G deployments [7],[8]. The C-RAN concept jointly takes advantage of NFV/SDN [9] and different splitting options for 5G network design optimization [10]. As a consequence the traffic on transport network links can have different QoS requirements, being it related to different sections of splitting [11].

Ethernet interfaces are of increasingly interest to implement packet-based multiplexing of FH and BH traffic for the widely adoption of this standard in transport networks [12]. Ethernet as a packet based technology suffers of statistical multiplexing delay, which is typically not bounded and variable. This is a key issue to be solved to design integrated interfaces for different levels of service [13].

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The packet-based integrated hybrid optical network with ultra-low Packet Delay Variation (PDV) services and statistically multiplexed traffic, was firstly proposed in [14]. A hybrid packet/circuit node is defined in order to add the ability to the network to manage priority and non-priority traffic. As introduced in the paper, the traffic in the network can be divided into two categories. The traffic with fixed delay and zero packet loss which will be routed through the optical network. This types of traffic are given absolute priority and since it is QoS sensitive, their delivery must be guaranteed. The other traffic category is less delay sensitive and is in the packet format which will be transported through packet switches. This separation of different priority of traffic in the network is accomplished by employing Statistical Multiplexing (SM). This type of hybrid network is demonstrated to offer improved performance at a lower cost, compared to a pure circuit- or pure packet switched networks.

Integrated Hybrid Optical Networks (IHONs) is a further evolution of the primary concept of hybrid node which was introduced in [15]. This new node architecture merges the circuit and packet network in the same wavelength to enable the circuit quality transport of demanding services with higher granularity than wavelengths and enabling statistical multiplexing for the throughput efficiency of packet networks. They used the same principle of dividing the traffic between priority and non-priority as mentioned before and demonstrate experimentally that priority traffic will have absolute transfer guarantees with no packet loss, low packet delay, and ultra-low PDV. Any capacity not utilized by the priority traffic is identified as idle time gaps which can be used by lower priority traffic. Implementation based on Ethernet has been demonstrated in C-RAN [16], assuming CPRI traffic transparently transported by a wavelength and using the leftover capacity for BH traffic. However, to prevent the FH traffic from PDV caused by BH traffic insertion, IHON adds a fixed delay, corresponding to the maximum duration of a BH frame, to all FH packets.

An extension of the IHON concept was proposed and evaluated in [17] for possible application in data center by considering three different QoS levels and the possibility of pre-emption for priority traffic. The priority scheduling of three different service profiles was investigated to maximize data center traffic throughput while guaranteeing time transparency for delay-sensitive services and zero loss/fixed delay for guaranteed connections.

The idea to use the integrated hybrid concept in C-RAN requires consideration of C-RAN traffic characteristics. In C-RAN the interconnection between RRH and BBU Hotel is based on CPRI [18].

CPRI is nowadays the most common protocol to transport data in the FH segment of C-RAN between radio sites and baseband hotels/mobile edge computing. Being it a Time Division Multiplexing (TDM)-based protocol, it poses strict capacity, latency and latency variation requirements on the transport network. Recently, packet-based functional splitting protocols, such as eCPRI [18], have been released, while splits proposed by 3GPP [19] are on their way of standardization. However, so far, the majority of the proposed splits concern the radio physical layer and do not relax the strict delay requirements on the FH transport.

The utilization of Ethernet in this architecture is considered as a way for improving reconfigurability and efficiency in terms of both capital and operational expenditures. Since C-RAN is mainly dimensioned based on the peak traffic, it requires large capital expenditures. Moreover implementing custom-made CPRI switches which enable reconfigurability to C-RAN adds extra cost to the network. In the work referenced in [20], authors focus on a FH solution encapsulating CPRI frames into Ethernet frames and implementing dynamic CPRI line bit rate reconfiguration. In their study, CPRI over Ethernet encapsulation/decapsulation is assumed to be performed at both the RRH and BBU Hotel. The encapsulation is performed as a size-based burst assembly and the minimum granularity of CPRI data to be encapsulated into an Ethernet frame is the CPRI basic frame. Performance evaluation results show that dynamic CPRI link bit rate reconfiguration is achieved within about one millisecond after rate reconfiguration triggering. However, if size-based encapsulation is utilized, the time to perform encapsulation varies as a function of the CPRI link bit rate, thus causing encapsulation delay jitter. In [21], the authors provide an analysis of the impact of different parameters (e.g., BH packet size) on latency and latency variation of a converged FH and BH Ethernet-based network. This analysis is

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conducted on a real field trial and a discussion of the challenges when dealing with design of ultra low latency traffic aggregators is also reported. The capability of the integrated hybrid approach to support the high data rate required by CPRI have been demonstrated in recent experiment [22]. Mapping of Ethernet encapsulated CPRI traffic in integrated hybrid networks is the step beyond the state of the art that this paper addresses. Some evaluations of the additional BH throughput achieved by the integrated hybrid approach aggregating FH and BH according to extension of the IHON principle were presented in [23]. Limitations of throughput for high capacity CPRI option were outlined. In this paper further extension of the mechanism based on BH traffic fragmentation is proposed to achieve better throughput for BH Traffic.

## 3. Integrated hybrid optical network in C-RAN

Figure 1 shows a sample network topology implementing a C-RAN. The BBU serving a RRH can be activated in different hotels for resource optimization, service continuity or energy efficiency, thus possibly requiring dynamic association between RRHs and BBUs. This dynamic association is though to be managed by a suitable SDN conrol/management plane. Moreover, traditional base stations (e.g., LTE eNB) may also be present in the same area, requiring connection to the core network. As a consequence, both FH and BH traffic need to be transferred on each optical network segment. A solution to deploy such a scenario can be to assign dedicated wavelength channels to each kind of traffic, either FH or BH, so that FH links can be designed to meet strict delay requirements and BH traffic is statistically multiplexed on separated channels. The integrated hybrid multiplexing scheme IHON, was firstly proposed to implement statistical multiplexing of the GST (Guaranteed Service Traffic) and SM (Statistical Multiplexed) in Ethernet packet-based nodes [14]. In IHON a small fixed delay ($\Delta$) is added to guaranteed traffic (GST) so that statistically multiplexed (SM) traffic can be inserted in GST gaps, with minimum delay and zero PDV (figure 2), as it was experimentally proved in [15]. With the aim to minimize the delay of GST traffic, IHON can be extended to allow GST traffic pre-emption on SM traffic and the effectiveness of this mechanism was analyzed in [17] .

Here, the integrated hybrid concept with pre-emption, is applied to a network segment of a C-RAN where FH traffic, i.e. CPRI flow encapsulated in Ethernet frames [24], is identified as GST, with zero PDV, while BH traffic is dealt with pre-emption as SM traffic. During the transmission of a FH frame, incoming BH packets are stored in a buffer until an output channel is free. A scheduler (represented by the block S in figure 2) senses the input channels to detect FH frames and is in charge of deciding when to start and interrupt the transmission of BH packets on the output channels. IHON eliminates PDV of the FH traffic because the fixed delay $\Delta$ enables a time-window which gives sufficient time for processing and decision of BH packet preemption. This goes beyond, e.g., the IEEE 802.1Qbu pre-emption [25] recommended in the IEEE 802.1CM standard [26]for FH, where FH packets may experience anyway PDV corresponding to the service time of 155 *Byte*.

## 4. Traffic mapping and aggregation using the integrated hybrid approach

CPRIoE traffic characterization has been analyzed in [24] and [27]. A list of parameters used in this study is reported in Tab.1, while an example of IH node output line is provided in figure 3. RRHs generate CPRI flows at different rates ($R_{CPRI}$) set by the standard [18]. Each flow is composed of CPRI basic frames with fixed duration $T_{CPRI} = 260\ ns$, equal for all CPRI options. A certain number of CPRI basic frames ($N_F$) are encapsulated in an Ethernet frame forming the CPRIoE payload of length:

$$L_F = N_F * R_{CPRI} * T_{CPRI}. \quad (1)$$

CPRIoE frames are then sent by RRHs towards IHON switches, where they are delayed by $\Delta$. Also conventional BH traffic reaches the switches, loading the output channels with parameter $\rho_B$. In order to avoid collision between different frames on the output line, a guard time $T_{guard}$ is applied

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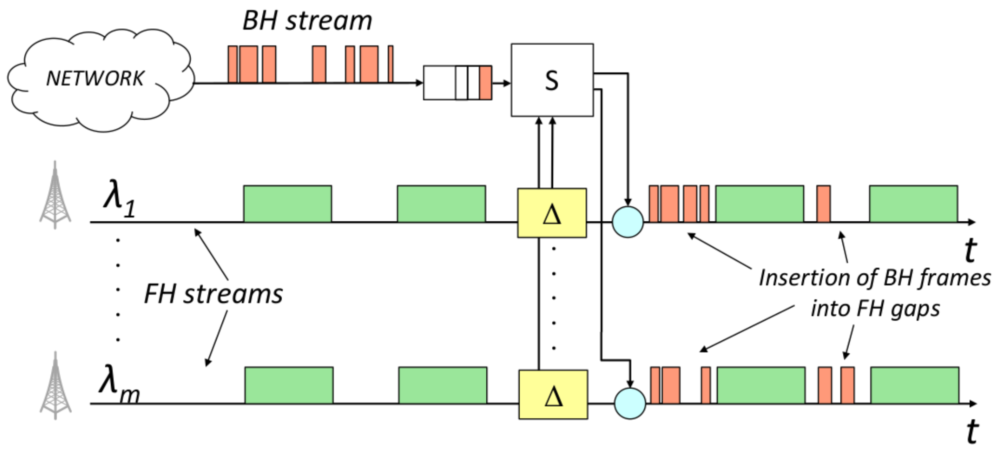


**Figure 2.** IHN multiplexing scheme

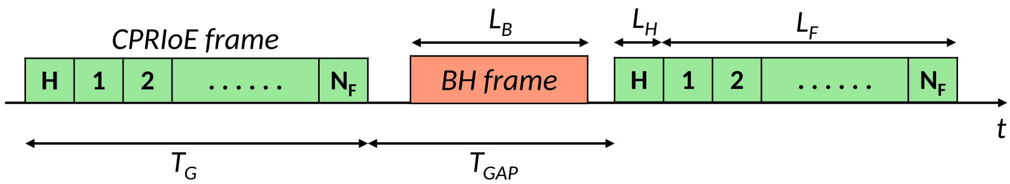


**Figure 3.** CPRIoE parameters applied to hybrid node.

during which the transmission of any data is not permitted. IHON switches have $m$ output channels, each characterized by a rate $R_W$, and accommodates CPRIoE frames of duration:

$$T_G = \frac{L_H + L_F}{R_W} \tag{2}$$

where $L_H$ is the header of CPRIoE frames assumed to be 44 *Byte* [24].

Depending on $N_F$ and $R_{CPRI}$, the gap duration $T_{GAP}$ is selected according to:

$$T_{GAP} = \frac{L_F}{R_{CPRI}} - T_G. \tag{3}$$

**Table 1.** List of parameters used to describe CPRIoE and hybrid nodes.

| Parameter | Description |
|---|---|
| $N_F$ | Number of CPRI basic frames forming a CPRIoE payload. |
| $L_F$ | Payload length for CPRIoE frame. |
| $R_W$ | Output channel rate. |
| $T_G$ | CPRIoE duration. |
| $T_{GAP}$ | Gap duration. |
| $\Delta$ | Fixed delay to avoid collision. |
| $\rho_B$ | Offered BH load per channel. |
| $L_B$ | Average length of BH frames. |
| $T_{guard}$ | Guard time. |
| $T_{CPRI}$ | CPRI basic frame duration. |
| $R_{CPRI}$ | CPRI flow generation rate. |
| $L_H$ | Length of CPRIoE header. |
| $m$ | Number of channels in the switch output interface. |

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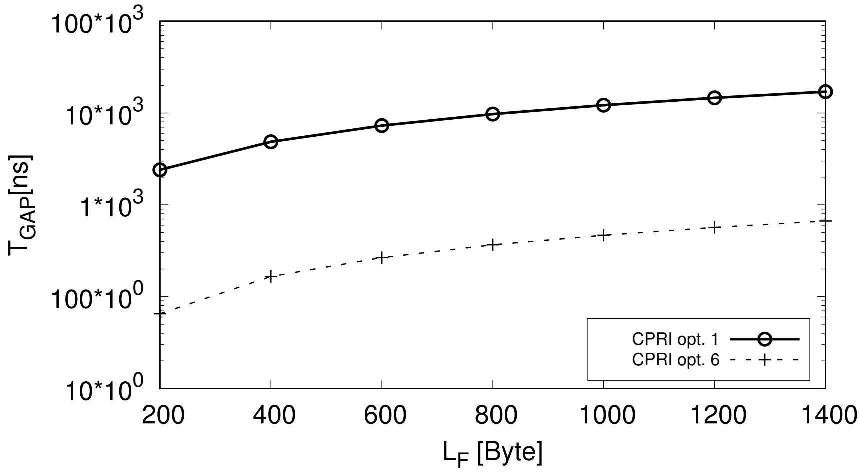


**Figure 4.** $T_{GAP}$ as a function of different values of payload length $L_F$ for CPRI opt. 1 and 6 on a 10 $Gbps$ line.

By looking at (3), it is possible to notice that, depending on $R_{CPRI}$, different values for $T_{GAP}$ can be obtained for the same length of CPRIoE packets $L_F$. An example of $T_{GAP}$ using CPRI opt. 1 and 6 for a line rate of $R_W = 10\ Gbps$ is depicted in figure 4.

This time gap is used in the hybrid multiplexing scheme in order to aggregate BH traffic on the same transport channel. To this end, two different policies are here considered:

- A BH packet is transmitted when a gap is available and it is possibly pre-empted upon arrival of a new GST burst, in case BH packet duration is longer than the gap itself. In case of pre-emption the BH packet is lost. This policy is indicated as P policy, with insertion of an entire packet into the by-pass GST flow.
- A BH packet waits for a gap and in case the BH packet is longer than the gap it is fragmented into as many fragments as needed to fit the gap. This avoid the need of pre-emption but introduces some overhead to manage fragmentation and additional functionalities. This policy is indicated as S policy, where packets are divided into $N_S$ segments of suitable size for their insertion into the GST flow.

## 5. Numerical Results

To evaluate the benefits introduced by the proposed mechanism, an event-driven simulator in C++ language has been developed. One RRH generates a CPRI flow according to two different options with rates $R_{CPRI} = 614.4\ Mbps$ (option 1) and 6.144 $Gbps$ (option 6). The IHON fixed delay $\Delta = 99.2\ ns$ is assumed, which corresponds to the smallest fragment (124 $Byte$) that can be preempted [26]. A time guard of 10 $ns$ between frames is applied. A single output channel ($m = 1$) with rate $R_W = 10\ Gbps$ is considered. The number of CPRI basic frames in a guaranteed burst $N_F$ is varied over the intervals $[1, 70]$ and $[1, 7]$, for CPRI option 1 and 6, respectively [24], so that the payload length $L_F$ varies accordingly. A set of simulations varying the average BH packet length $L_B$ is obtained with a load $\rho_B$ such that a BH packet is always ready for transmission on the output channel. The length of BH frames is considered to be exponentially distributed with parameter $L_B$.

Figure 5 shows the success probability of the BH traffic, defined as the ratio between the packets not interrupted and the total packets in service, as a function of $L_F$, for both CPRI options, varying $L_B$. In both cases, the success probability increases with $L_F$, due to the resulting larger $T_{gap}$. Option 6 shows lower performance than option 1 due to the smaller size of the gap, especially when $L_F$ is low, so suggesting to use larger $N_F$ in this case. However, increasing $N_F$ increases the encapsulation delay, that may impact the maximum reach of FH connection.

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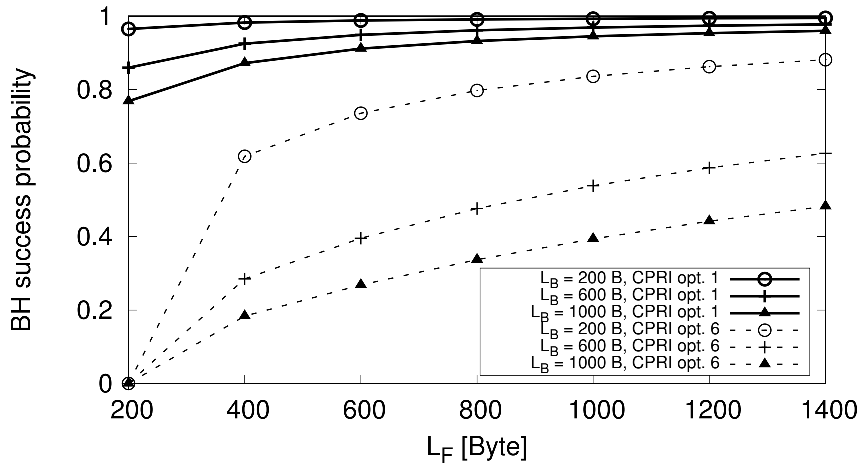


**Figure 5.** BH success probability as a function of payload length $L_F$ for different BH packet length $L_B$ using CPRI opt. 1 and 6.

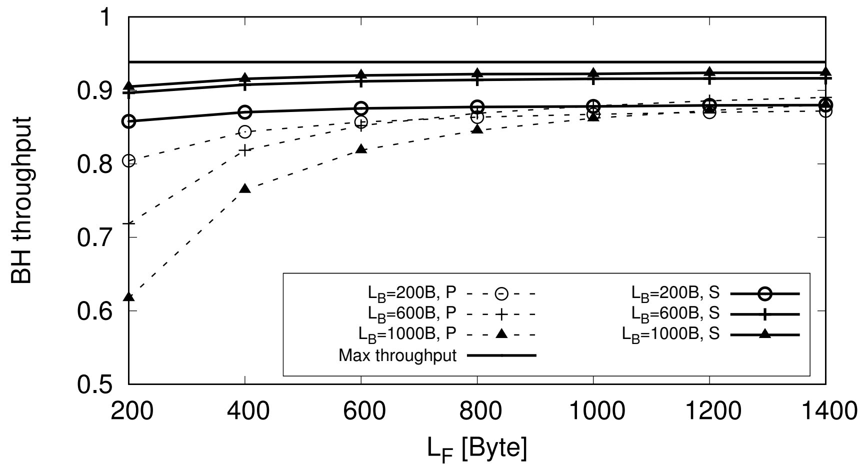


**Figure 6.** BH throughput, normalized to the output link capacity, as a function of payload length $L_F$ for different BH packet length $L_B$ using CPRI opt. 1. Solid lines for the case with segmentation (S), dashed lines for the no-segmentation case(P).

Figure 6 reports the BH throughput, normalized to the output line rate ($10Gbps$), as a function of $L_F$ for option 1 varying $L_B$. The figure also reports the maximum normalized capacity left by FH traffic. The value of throughput in the case of the P policy reaches 8.9 $Gbps$ only for high values of $L_F$ with quite limited influence of $L_B$. The S policy, instead, is able to better exploit the available capacity for any value of $L_F$, except for the influence of the transmission guard times inserted. The same evaluation obtained for option 6 in figure 7 shows a remarkable effect of the shorter gaps in the FH flow, that prevents also the F policy to fully exploit the available capacity for low values of $L_F$, due to the high numbers of segments needed and related inserted transmission guard time.

Figure 8 reports the overhead introduced by the P and S policies calculated as the ratio of the number of bytes for Ethernet headers and the the total number of bytes transmitted as BH traffic for option 1. The same evaluation is presented in figure 9 for option 6. The effect of the S policy is more evident with option 6 where, due to the smaller gaps in the FH flow, multiple segments are typically required to transmit each BH packet. In any case the additional overhead is quite limited when increasing $L_F$. It is interesting to analyze the average number of segments to transmit a BH packets in option 1 and option 6, as shown in figure 10 for the S policy. Option 1 allows transmission

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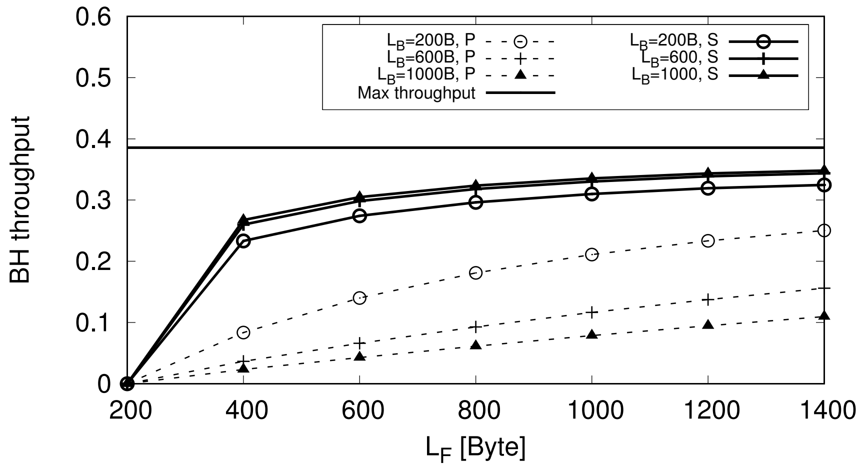


**Figure 7.** BH throughput, normalized to the output link capacity, as a function of payload length $L_F$ for different BH packet length $L_B$ using CPRI opt. 6. Solid lines for the case with segmentation (S), dashed lines for the no-segmentation case (P).

of a packet as a single segment in most cases for any $L_F$. In option 6, instead, reasonable values of $L_F$ seem to be not less than 1000 bytes which give an average number of segments less than 3 for any $L_B$, with a resulting overhead around 10%, which is reasonable as well. However, working with high $L_F$ increases the encapsulation delay, which in the worst case is 18.3$\mu s$ for CPRI option 1 and 1.83$\mu s$ for CPRI option 6.

## 6. Conclusions

This paper has explored the feasibility of the integrated hybrid network concept with pre-emption applied to C-RAN for transporting FH traffic with timing transparency combined with pre-emptable BH traffic within the same optical Ethernet channel. Performance evaluations have been presented for different CPRI options, finding the amount of BH traffic taking advantage of unused FH capacity. Remarkable BH throughput is shown especially for CPRI option 1. Scheduling BH packets only when gaps in the FH traffic of suitable size for the BH packets are present, is an IHON characteristic. CPRI option 6 limits BH throughput because the smaller packet gaps in the FH traffic makes fitting of the BH traffic more difficult. Further investigations will include the introduction of controlled traffic mechanisms for adapting the BH traffic for better fitting the unused bandwidth in a FH multi-channel configuration.

**Author Contributions:** Carla Raffaelli has supervised and written the paper. Federico Tonini has developed the simulator in C++ and obtained results and contributed to paper writing. Bahare Masood Khorsandi has contributed to writing the paper, plotting figures and discussing results. Raimena Veisslari and Steinar Bjornstad have reviewed the paper

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**Conflicts of Interest:** The authors declare no conflict of interest.

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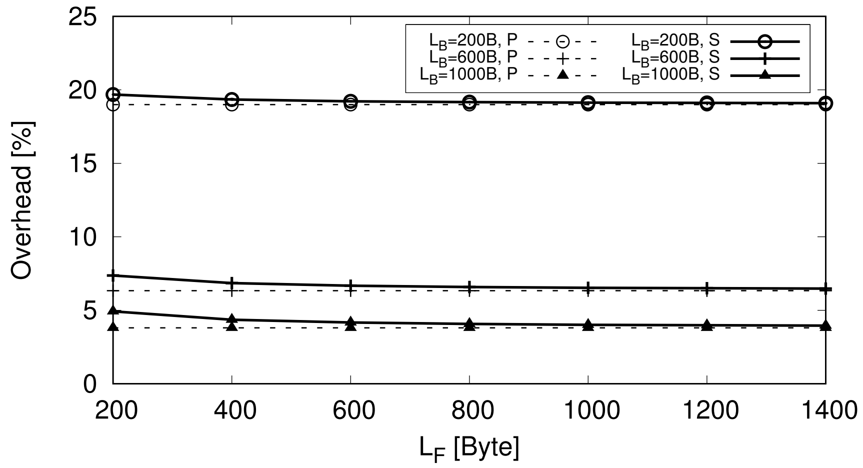


**Figure 8.** Overhead for BH packets as a function of payload length $L_F$ for different BH packet length $L_B$ using CPRI opt. 1. Solid lines for the case with segmentation (S), dashed lines for the no-segmentation case (P).

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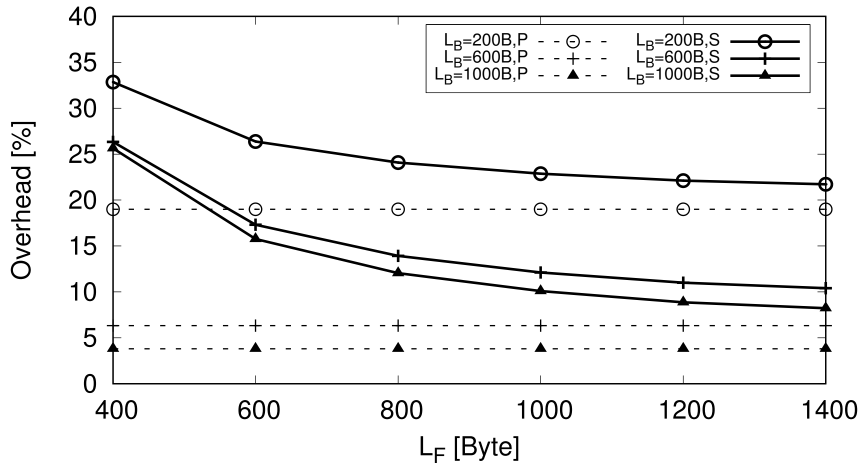


**Figure 9.** Overhead for BH packets as a function of payload length $L_F$ for different BH packet length $L_B$ using CPRI opt. 6. Solid lines for the case with segmentation (S), dashed lines for the no-segmentation case (P).

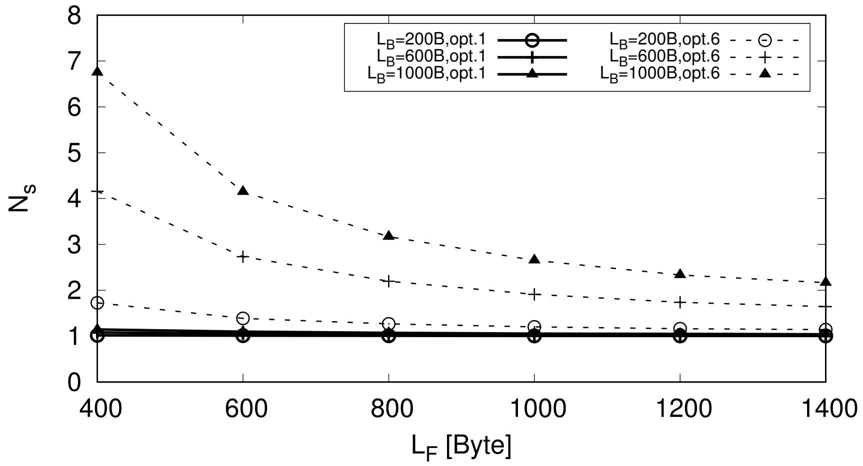


**Figure 10.** Average number of segments ($N_S$) required to send a BH packet as a function of payload length $L_F$ for different BH packet length $L_B$ using CPRI opt. 1 and 6.


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