Delay analysis of mixed fronthaul and backhaul traffic under strict priority queueing discipline in a 5G packet transport network

Apurva Gowda, José Alberto Hernández, David Larrabeiti*and Leonid Kazovsky†

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Abstract

Virtualization of the base station for the purpose of centralization is being actively studied and researched as a candidate for 5G mobile networks. Proposed as Cloud Radio Access Network (C-RAN) by China Mobile, the technology is expected to facilitate easy operation and maintenance. However, the base stations traffic, referred to here as fronthaul traffic, has stringent delay requirements. In this paper, we explore the possibility of multiplexing fronthaul traffic and traditional backhaul traffic as it traverses over the metropolitan network while keeping the average fronthaul queueing delay and jitter under control. We analyse and simulate the cases of a single fronthaul flow and multiple fronthaul flows arriving at the packet switch assuming strict priority for the fronthaul queue. We also propose a fronthaul frame aggregation strategy to improve the packet overhead efficiency while keeping the average fronthaul queueing delay and jitter constant regardless of the percentage of fronthaul traffic. We show that for the two cases, the criteria for aggregation is different but the optimal number of basic frames to aggregate is between 3-10 frames assuming the CPRI protocol.

Keywords: 5G; CPRI; fronthaul/backhaul integration; Strict Priority

1 Introduction

In 2011, China Mobile introduced the concept of Cloud RAN where Base stations are split between a Remote Radio Unit (RRU) located at the antenna site and a Baseband Unit (BBU) centralized and possibly virtualized at data centers [?]. For the operators, the most advantageous split in terms of capital

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and operating expenditure would be to virtualize the base station in servers at a data center and use the existing network infrastructure to transport the fronthaul data to the RRU. [?, ?] propose SDN based architectures to realize such a network. However, such a split poses new challenges at the transport level since fronthaul and backhaul traffic needs to be multiplexed while adhering to fronthaul traffic demands such as strict synchronization, bounded latency and jitter between BBU and RRUs [?, ?]. A popular method of multiplexing being studied is to encapsulate the fronthaul traffic in Ethernet packets for easy deployment in existing network infrastructure [?].

Currently, Common Public Radio Interface (CPRI) is the most widely used specification for the transport of the digitized radio samples over a fiber [?]. Basic Frames (BFs) are exchanged between BBU and RRH at a constant bit rate: 1 Basic Frame every 260.146 ns. Depending on the number of carriers, MIMO option and LTE bandwidth, the size of BFs varies from 20 bytes (CPRI option 1) to 320 Bytes (CPRI option 7). However, CPRI has a fixed data rate that does not scale well with the number of antennas or bandwidth of the wireless technology. Thus, new protocols with different functional splits that have data dependent bit rates are being studied [?, ?]. An example of a new protocol being developed is the Next Generation Fronthaul Interface (NGFI) [?]. The IEEE 1904 Task Force, created in 2015 [?], is at present seeking for mechanisms to encapsulate one or multiple BFs in a single Ethernet Frame (IEEE 1904.3 Radio over Ethernet), in an attempt to carry them across (the one way end-to-end delay excluding propagation delay for CPRI and NGFI is 5us and 100us, respectively [?, ?]) we revisit classical Quality of Service (QoS) mechanisms and study their suitability in 5G scenarios. In this paper, we evaluate, through analysis and simulations, the effect on queueing delay at a packet switch when fronthaul and backhaul traffic is mixed assuming a strict queueing discipline. We start with the simple case of a single periodic fronthaul flow mixed with the backhaul traffic and then progress to analyze multiple CPRI flows. We further provide a mechanism to aggregate multiple Basic Frames in a single Ethernet packet to keep overhead low while keeping queueing delay and jitter under control. We show that aggregating multiple BFs per packet reduces overhead but increases queueing delay and jitter of the backhaul and, in the case of multiple flows, fronthaul substantially. However, the number of BFs per packet can be set such that the both the fronthaul and backhaul queueing delay and jitter remain relatively constant regardless of the total load and/or percentage of the fronthaul traffic. In the case of multiple flows, the fronthaul packet size can be calculated based on the total load and statistical properties of the backhaul traffic. The paper is organized as follows: Section **??** analyses the queueing delay for the case of a single fronthaul flow and presents the aggregation strategy, Section **??** presents a similar analysis assuming multiple fronthaul flows arriving at the packet switch and we finally conclude in Section **??**.

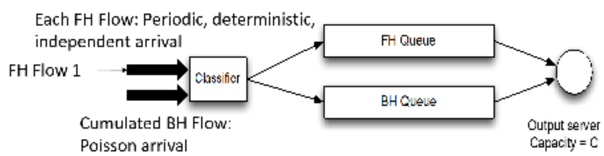


Figure 1: Queueing model black diagram: Single CPRI flow

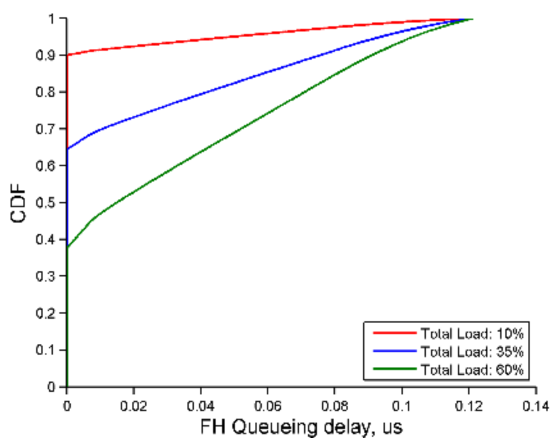


Figure 2: CDF of the fronthaul queueing delay for a single CPRI flow at the packet switch

2 Single Periodic Fronthaul Flow

In this section, the case where a single periodic fronthaul flow, such as a CPRI flow, arrives at the packet switch is analysed. As illustrated in Fig. **??**, a packet switch with two input ports competing for a single service unit at the output port is assumed. Further, the packet switch is assumed to have two separate queues: one for fronthaul and another for backhaul traffic, as shown in Fig. **??**. A strict priority and a non-preemptive policy has been assumed for the fronthaul queue i.e. fronthaul traffic is assumed to be packetised and marked as high-priority traffic. In other words, when the server completes the service time of a packet, the fronthaul queue is checked first no matter how long the backhaul queue has been waiting for service. Though there exist other queueing disciplines, such as Deficit Round Robin [**?**], that give some preference to backhaul traffic with respect to fronthaul, we do not consider them due to the tight delay requirements of the fronthaul traffic [**?**].

Since strict priority has been assumed for the fronthaul queue and a fronthaul load < 1, the maximum queueing delay experienced by the fronthaul traffic is the largest service time of a backhaul packet which depends on the switch service rate, R_{eth}, and the largest packet size.

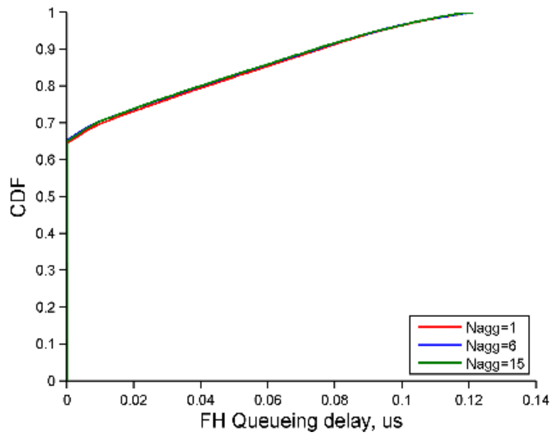


Figure 3: CDF of fronthaul delay when aggregating 1, 6 and 15 CPRI Option 5 basic frames.

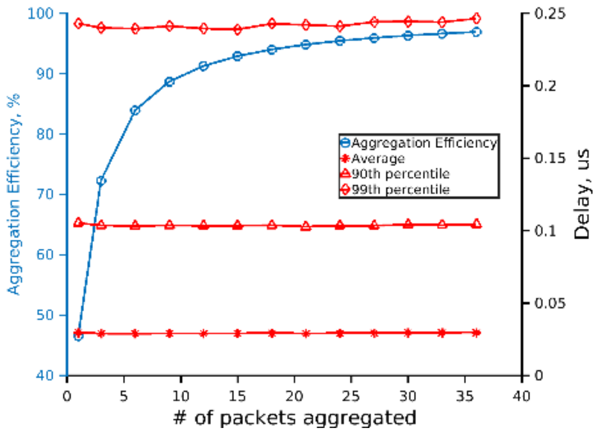
To illustrate the behaviour, the queueing model depicted in Fig. **??** is simulated in MATLAB. As mentioned above, the fronthaul flow is assumed to follow the CPRI protocol [**?**] which is reviewed in Appendix **??**. In the simulation, a CPRI Option 5 flow which generates frames of size 106 bytes at a frequency of $f_c = 3.84 \times 1e6$ frame/s is considered. The backhaul packet sizes are assumed to follow the AMS-IX distribution [**?**] (briefly explained in Appendix **??**) with the arrivals Poisson distributed. The service rate of the switch, R_{eth}, is set to$100 Gbps$. Also, the CPRI frames are assumed to be encapsulated into Ethernet packets with 46 bytes of overhead. Fig. **??** shows the cdf of the queueing delay of the fronthaul packets. As expected, the maximum delay is the maximum backhaul service time i.e.$^{1514\times 8}/_{R_{eth}}$, regardless of the load.

The overhead efficiency of the fronthaul packet considered in the simulation is about 78%. Basic frame aggregation is a simple, and thus, an attractive strategy to improve the overhead efficiency. Aggregating the frames increases the overhead efficiency, as

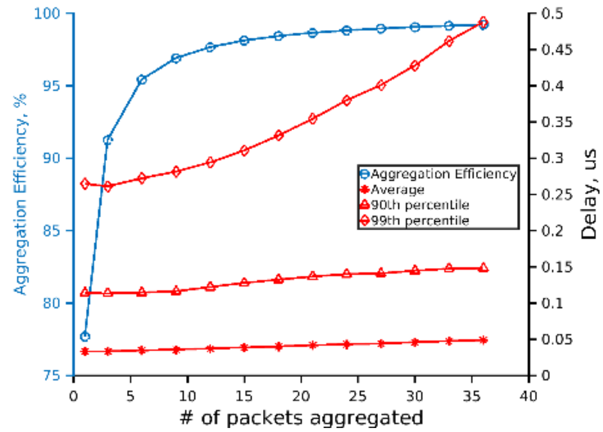
$$\text{Overhead Efficiency,}\eta_{OH} = \frac{N_{agg}S}{(46 + N_{agg}S)} \times 100\ \%$$

Here, S is the number of bits per frame and N_{agg} is the number of frames that are aggregated. Aggregating the frames also reduces the arrival rate of the fronthaul packets by a factor of N_{agg}. Since the packet size increase is offset by a lower packet arrival rate, distribution of the fronthaul queueing delay at practical loads is largely unaffected and the maximum is still the largest service time of a backhaul packet as can be seen in Fig. **??** which shows the CDF of the fronthaul queueing delay for $N_{agg} = \{1, 6, 15\}$ assuming a backhaul load of 35%.

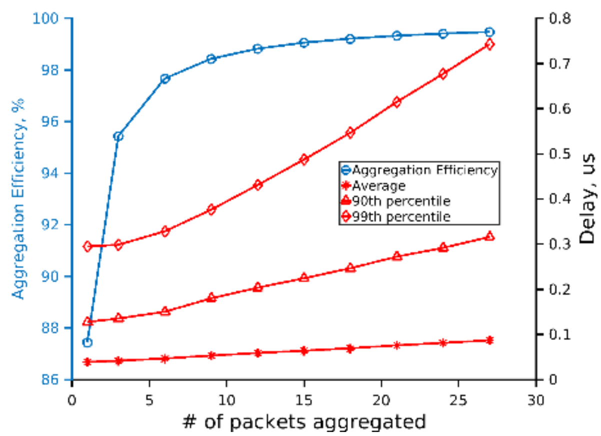
However, the packets in the backhaul queue have to wait longer as the fron-



(a) CPRI Option 2

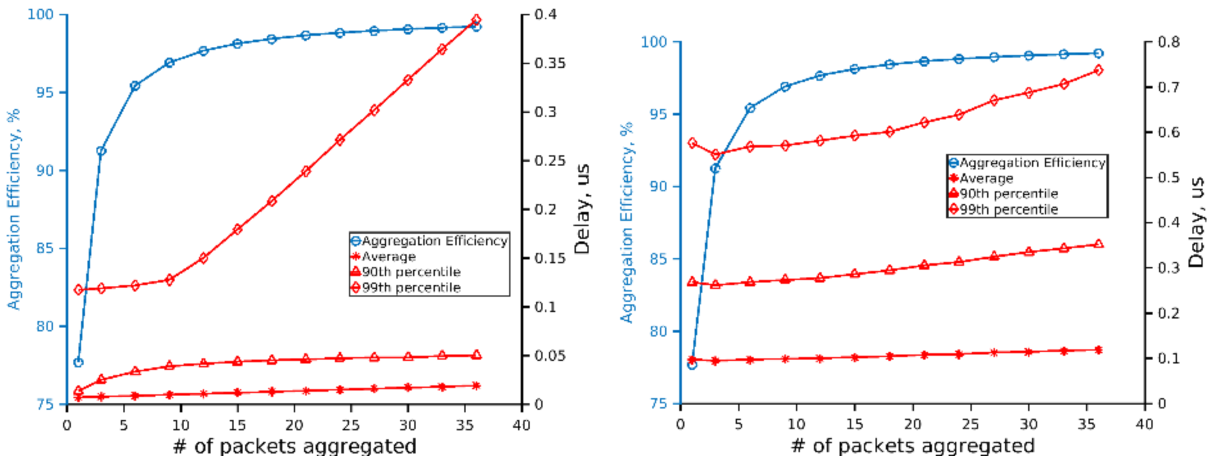


(b) CPRI Option 5



(c) CPRI Option 7

Figure 4: Overhead efficiency and backhaul delay statistics vs. number of basic frames aggregated,N_{agg} for CPRI Options 2, 5 & 7 and backhaul load of 35%



(a) Backhaul load = 10% (b) Backhaul load = 60%

Figure 5: Overhead efficiency and backhaul delay statistics vs. number of basic frames aggregated,N_{agg} for backhaul loads of 10% and 60% and CPRI Option 5

thaul packet size increases. Fig. **??** shows the overhead efficiency and backhaul delay statistics obtained from the simulator for the different CPRI Options 2, 5 and 7 assuming a medium backhaul load (35%). Similarly, Fig. **??** shows the overhead efficiency and backhaul delay statistics for the low (10%) and high (60%) backhaul loads assuming CPRI option 5. For all three CPRI options, as well as low, medium and high loads, the mean and the 90th percentile remain relatively flat as N_{agg} is increased, however, the 99th percentile increases after the efficiency curve passes it's knee point. Fig **??** also indicates that at low loads, aggregating too many packets results in a high rate of increase in the 99th percentile after the knee of the efficiency curve, i.e. where the returns diminish. The knee of the curves occurs between 3-10 packets. From these simulations, we see that aggregating 3-10 packets not only achieves $>90\%$ overhead efficiency of the packet but also does not significantly affect the backhaul queueing delay.

A more stringent limit may arise from the delay due to aggregation. For example, in the case of CPRI, the first frame has to wait at least ${}^{N_{agg}}/_{f_C}$ s. Depending on the maximum delay allowed by the fronthaul protocol, this sets a limit to the maximum number of frames that can be aggregated which may be the limiting criteria.

3 Multiple Fronthaul flows

The packet switch queue model is assumed to be the same as in the single fronthaul flow case but, in this analysis, multiple fronthaul flows arrive at the

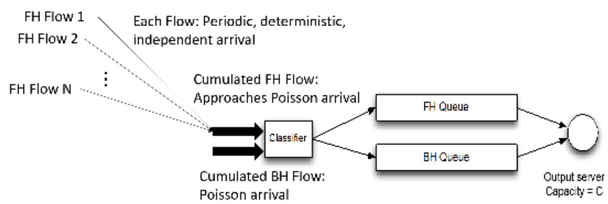


Figure 6: Queueing model black diagram: Multiple CPRI Flows

packet switch as depicted in Fig. **??**. Classical queueing theory based on the M/G/1 queue model is used to analyse the system. As in the single fronthaul flow case, the fronthaul queue is given strict priority and a non-preemptive policy.

3.1 M/G/1 with priorities and numerical example

The fronthaul and backhaul traffic arrival is assumed to follow the Poisson distribution. Though each fronthaul traffic flow generates packets periodically, an aggregate of multiple fronthaul flows is assumed to arrive at the server and thus the fronthaul packet arrival can be assumed to follow a Poisson distribution. The service time distribution of the backhaul traffic is dependent on the distribution of the packet size which is assumed to be the AMS-IX distribution [**?**]. Following the classical analysis of M/G/1 queues with priorities [**?**, **?**], the average waiting time in the queue for packets with two different priorities follow:

$$E\left[W_q^{FH}\right] = \frac{E\left[R\right]}{1-\rho_{FH}} \tag{1}$$

$$E\left[W_q^{BH}\right] = \frac{E\left[R\right]}{\left(1-\rho_{FH}\right)\left(1-\rho\right)} \tag{2}$$

where $E\left(R\right)$ is the average residual life of a packet in the server's service unit, ρ_{FH} is the fronthaul load and ρ_{BH} is the backhaul load with $\rho = \rho_{BH}+\rho_{FH} < 1$ for the stability of the queue. It can be shown that the average residual life is given by [**?**, **?**],

$$E\left[R\right] = \frac{1}{2}\left(\lambda_{BH}E\left[X_{BH}^2\right] + \lambda_{FH}E\left[X_{FH}^2\right]\right) \tag{3}$$

where λ_{FH} and $E\left[X_{FH}^2\right]$ refer to the fronthaul packet arrival rate and second moment of the packet service time respectively, and λ_{BH} and $E\left[X_{BH}^2\right]$ represent the same parameters for the backhaul traffic.

The respective packet arrival rates can be calculated from their loads and average packet sizes,

$$\lambda_{BH} = \frac{\rho_{BH}}{E\left[X_{BH}\right]};\ \lambda_{FH} = \frac{\rho_{FH}}{E\left[X_{FH}\right]} \tag{4}$$

Here $E[X_{BH}]$ and $E[X_{FH}]$ are the average backhaul and fronthaul packet sizes, respectively.

Numerical Example

Assume that the output port of the packet switch is working at a rate of 100Gbps. Let the total offered traffic $\rho = 0.4$ (i.e. 40%) of which 25% is fronthaul traffic while the rest is backhaul traffic. This implies $\rho_{FH} = 0.1$ and $\rho_{BH} = 0.3$. As mentioned, the backhaul packet size follows the AMS-IX distribution (Appendix **??**). The fronthaul packets are assumed to carry CPRI Option 2 basic frames which has 40 bytes of IQ samples and control word [**?**]. Since the minimum Ethernet packet size is 64 bytes, the fronthaul packets are assumed to be of that size.

The first and second moments of fronthaul and backhaul traffic are:

$$E[X_{BH}] = 60.746\ ns; \quad E\left[X_{BH}^2\right] = 6236.8\ ns^2$$

$$E[X_{FH}] = 5.12\ ns; \quad E\left[X_{FH}^2\right] = 26.2144\ ns^2$$

With these values, we can compute the packet arrival rate for each type of traffic:

$$\lambda_{FH} = \frac{0.4 \times 0.25}{5.12\ ns} = 19.5313\ Mpacket/s$$

$$\lambda_{BH} = \frac{0.4 \times 0.75}{27.23\ ns} = 4.9386\ Mpacket/s$$

The average residual life of a packet in the server at the arrival time of a given packet is:

$$E[R] = 15.6565\ ns$$

Finally, the average waiting time in queue for fronthaul and backhaul packets are $E\left[W_q^{FH}\right] = 17.3962\ ns$ and $E\left[W_q^{BH}\right] = 28.9936\ ns$. In this example, the average fronthaul waiting time is well within the end-to-end delay for CPRI.

To validate the analysis, the multiple fronthaul flow case in a switch depicted in Fig. **??** is simulated in MATLAB following the M/G/1 queue model i.e. Poisson arrival for both fronthaul and backhaul traffic and AMS-IX distribution for the backhaul packet size. Fig. **??** shows the simulations vs. calculations of the average queueing delay for different total loads at the server assuming 50:50 split between fronthaul and backhaul traffic and a fronthaul packet size of 64 bytes. The calculated values agree with the simulated values. Also, due to the prioritization of the fronthaul traffic, the increase in it's queueing delay w.r.t total load is not significant (max. of 30ns).

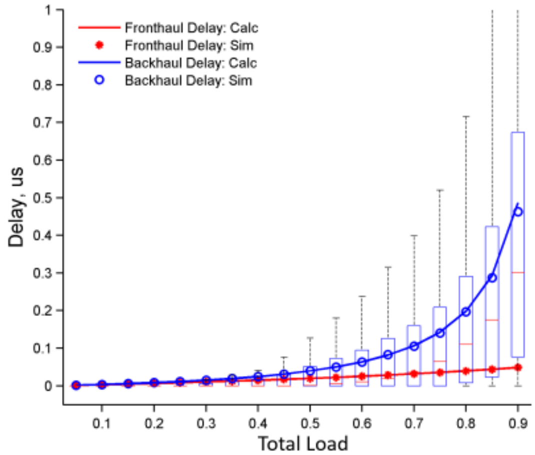


Figure 7: Average queueing delay for backhaul and fronthaul traffic: simulations vs. calculations; Also shown is the box plot with the median 25th and 75th percentile

3.2 Basic Frame Aggregation Strategy

A point of note is that, since for the multiple flow case the fronthaul queueing delay is affected by the percentage of fronthaul load, the fronthaul queueing delay becomes the limiting criteria for aggregation.

Eq. **??** and **??** show that given a total load, the residual life and the percentage of fronthaul traffic determines the average waiting time in the queue. Eq. **??** can be re-written as below

$$E\left[R\right] = \frac{1}{2}\left(\rho_{BH}\frac{E\left[X_{BH}^{2}\right]}{E\left[X_{BH}\right]} + \rho_{FH}\frac{E\left[X_{FH}^{2}\right]}{E\left[X_{FH}\right]}\right) \tag{5}$$

From close examination of Eq. **??**, it can be seen that the average size of the backhaul packet relative to that of the fronthaul packet determines the behaviour of the average residual life of a packet in the server with respect to the percentage of fronthaul traffic. If the fronthaul packet size is large compared to the backhaul packet size, the queueing delay increases as the percentage of fronthaul traffic increases. Similarly if the backhaul packet size is larger, the queueing delay decreases as the percentage of fronthaul traffic.

We propose an aggregation strategy that, given a certain total load, keeps both the fronthaul and backhaul average queuing delay constant regardless of the percentage of the fronthaul traffic. The number of basic frames that need to be aggregated is calculated based on the first and second moments of the backhaul traffic such that $E\left[W_q^{FH}\right] = C$ and $E\left[W_q^{BH}\right] = {}^{C}/_{(1\ \ \rho)}$. The packet size of each fronthaul flow is deterministic, thus, $E\left[X_{FH}^{2}\right] = \left(E\left[X_{FH}\right]\right)^{2}$. With

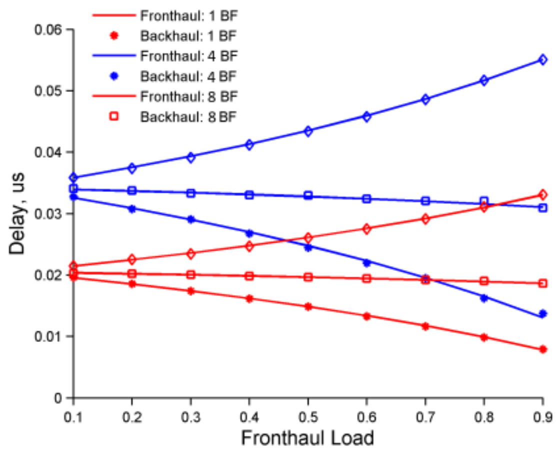


Figure 8: Average queueing delay for different frame aggregation sizes (from equations)

some manipulations, we can show that if $(E[X_{FH}])^{*} = (1 \quad \rho)\frac{E[X_{BH}^2]}{E[X_{BH}]}$, then

$$E\left[W_q^{FH}\right] = \frac{1}{2}\rho\frac{E\left[X_{BH}^2\right]}{E\left[X_{BH}\right]} \tag{6}$$

$$E\left[W_q^{BH}\right] = \frac{1}{2}\frac{\rho}{(1 \quad \rho)}\frac{E\left[X_{BH}^2\right]}{E\left[X_{BH}\right]} \tag{7}$$

A feedback protocol can be designed to relay the statistics of the backhaul packet sizes and total load at a server to the BBUs and the RRUs which in turn can decide the aggregation sizes. As mentioned in the case of single CPRI flow, during aggregation, the first frame has to wait at least N_{agg}/f_c *seconds*, where N_{agg} is the number of fronthaul frames that are aggregated and f_c is the frequency at which the frames are generated which sets a limit to the maximum number of frames that can be aggregated.

Assuming the AMS-IX distribution as before with a total load of 0.4 and $R_{eth} = 100Gbps$, $(E[X_{FH}])^{*} = 61.6022\ ns$ which at 100Gbps amounts to approximately 770 bytes. Assuming a 46 byte overhead for the Ethernet header, this amounts to 18 basic frames for CPRI option 2, 4 basic frames for CPRI option 5 and 2 basic frames for CPRI Option 7. Regardless of the relative percentage of fronthaul and backhaul traffic, the average queueing delay for a total load of 0.4 is 20.5027ns and 34.1712ns for the fronthaul and backhaul traffic respectively.

However, CPRI delay requirements limit the maximum delay contribution to $5\mu s$. If we allow 25% for the aggregation delay, N_{agg} is limited to 4 frames. Thus, CPRI option 2 is limited to aggregating 4 frames, while CPRI options 5 & 7 meet the delay requirement.

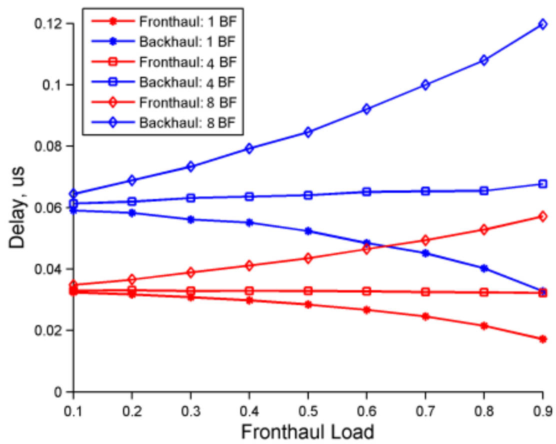


Figure 9: 95th percentile of the queueing delay for different percentages of fronthaul traffic (from simulations)

Fig. **??** shows the variation of average queueing delay for different percentages of fronthaul traffic given a certain total load. The average queuing delay for different number of frame aggregations assuming a total load of 40%, a service rate of 100Gbps and CPRI Option 5 is plotted. We consider a short Ethernet packet with only one basic frame of size 206 bytes, a medium sized Ethernet packet with 4 basic frames of size 686 bytes and a large Ethernet packet with 8 basic frames of size 1326 bytes. It can be seen that for CPRI Option 5, aggregating 4 frames leads to a constant average queueing delay regardless of the % of fronthaul traffic as per the calculations. As expected, if $E\left[X_{FH}\right] < \left(E\left[X_{FH}\right]\right)^*$, the queueing delay decreases as the percentage of fronthaul traffic increases. For large fronthaul packet sizes, the average queueing delay increases drastically as the percentage of fronthaul traffic increases.

Fig. **??** shows the standard deviation of the fronthaul and backhaul delay which demonstrates the change in jitter for different frame sizes as the fronthaul traffic increases. The jitter, much like the average, remains constant when $E\left[X_{FH}\right] = \left(E\left[X_{FH}\right]\right)^*$ and decreases as the fronthaul traffic increases as long as $E\left[X_{FH}\right] < \left(E\left[X_{FH}\right]\right)^*$.

Since the arrival of the fronthaul packets may not truly be Poisson, we simulate the case of multiple periodic CPRI option 5 flows arriving at the packet switch to validate the assumption. Fig. **??** shows the average queueing delay vs. different percentages of fronthaul traffic assuming 1 and 8 basic frames are aggregated. It can be seen that the Poisson assumption is an upper bound which implies the optimal aggregation is also an upper bound. Since aggregating less number of frames reduces the residual life, using the upper bound in practice will not negatively affect the fronthaul queueing delay.

In practice, the exact requirements to achieve constant delay cannot be met. Thus, the deviation from the constant delay as the aggregate packet size varies

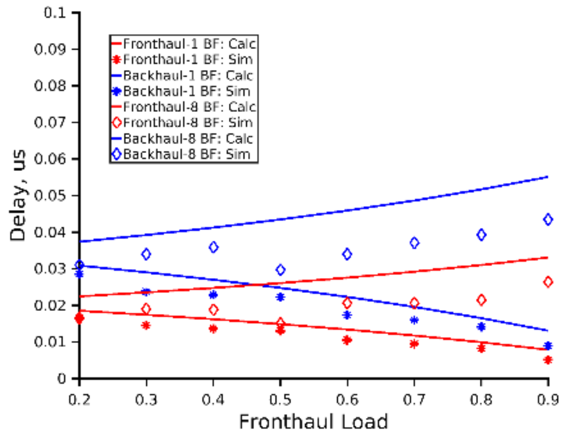


Figure 10: Average queueing delay vs. percentage of fronthaul load assuming 40% total load and CPRI option 5 (Need to fix the legend, but solid line is Poisson calculation and points are the real CPRI flows from simulations)

from $(E[X_{FH}])^*$ is analysed. Let $\delta = \frac{E[X_{FH}]}{(E[X_{FH}])^*}$, which represents the factor deviation from the optimum value, then

$$\begin{aligned} \%\text{ deviation} &= \frac{E\left[W_q^{FH}\right] \quad E\left[W_q^{FH}\right]\big)^*}{E\left[W_q^{FH}\right]\big)^*} \times 100 \\ &= \left(\frac{\rho_{FH}\delta(1 \quad \rho) + \rho_{BH}}{\rho(1 \quad \rho_{FH})} \quad 1\right) \times 100 \qquad (8) \end{aligned}$$

With Eq. **??**, operators can control the deviation from the expected average queuing delay based on the total load and percentage of fronthaul traffic.

Fig. **??** shows the % deviation in delay vs. the factor of deviation from the optimal aggregation value for CPRI Option 5, total load of 40% of which 25% is fronthaul traffic. The negative sign indicates that the delay is lower, which is intuitive - we have reduced the average residual life by reducing the aggregate fronthaul packet size. For a 25% larger packet size, the increase in delay is about 4%.

4 Conclusions

In this paper, we explore the possibility of multiplexing fronthaul and backhaul traffic in a metropolitan network for future 5G Crosshaul networks. In our analysis, we assume strict priority for the fronthaul queue due to the stringent delay requirements. In the case of a single periodic fronthaul flow at the packet switch, the maximum delay is set by the largest service time of a backhaul

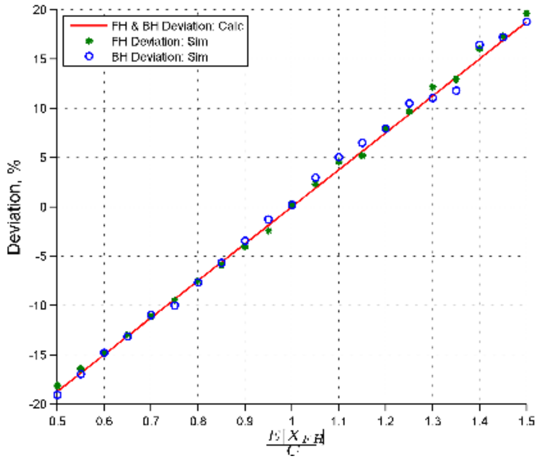


Figure 11: Percentage deviation in delay vs. the factor of deviation from the optimal aggregation value

packet. Aggregating multiple fronthaul frames does not affect the maximum fronthaul queueing delay, however, it does affect the backhaul queueing delay. Our simulations show that aggregating 3-10 CPRI basic frames not only achieves $> 90\%$ overhead efficiency of the packet but also does not significantly affect the average backhaul queueing delay or the jitter.

In the case of multiple fronthaul flows, the fronthaul queueing delay is affected by the total fronthaul load, thus, this becomes the main criteria for choosing the number of frames to aggregate. We show that the average queueing delay and jitter can be controlled by deciding the number of basic frames to aggregate based on the total load, the first and second moments of the backhaul traffic. Depending on the CPRI option, the number of frames to aggregate varies from 2-18. We also analyse the increase in fronthaul delay when the aggregate packet size larger than the optimal packet size which allows operators to control the delay in practice.

However, a more stringent limit on the number of frames to aggregate is the aggregation delay. For CPRI, if we allow 25% of the allowable latency for the aggregation delay, the number of frames is limited to 4 frames.

5 Appendix: CPRI Protocol Specifications

For all CPRI options, a 'Basic Frame' (BF) is generated every $T_c = {}^1/_{f_c}$ seconds where f_c is the nominal chip rate set based on the OFDM sampling rate for 2.5 MHz LTE signal (remark that $f_c = 3.84MHz$, and $T_c = 260.41667$ ns) [**?**]. One BF contains 15 words of IQ data and 1 word of Control & Management. The length of the BF depends on the CPRI option which defines the line rate and

Table 1: Length of BF for all CPRI options

CPRI Option	CPRI data rate (Mb/s)	Length S of BF (bits)
1	614.4	160
2	1228.8	320
3	2457.6	640
4	3072	800
5	4915.2	1280
6	6144	1600
7	9830.4	2560
7A	8110.08	2112
8	10137.6	2640
9	12165.12	3168

Table 2: Ethernet Frame Size PMF

Frame Size (bytes)	PMF
0-63	0
64-127	0.3962
128-255	0.0512
256-511	0.0291
511-1023	0.0301
1024-1513	0.2839
1514	0.2096
>1514	0

the accordingly the word length. Table **??** shows the number of bits per BF for all CPRI options. Thus, all CPRI options generate 1 BF every $T_c$at a constant bit rate, while the size of the BF, $S = {}^{CPRI\ Line\ Rate}/_{f_c}$.

6 Appendix: AMS-IX Ethernet Frame Size Distribution

The backhaul frame size distribution is based on the statistics available at AMS-IX website[**?**]. AMS-IX (Amsterdam Internet Exchange) is a neutral and independent Internet Exchange based in Amsterdam, the Netherlands. The statistics are updated from real traces taken from this high-aggregation traffic exchange. In our simulations, we use the yearly average percentages which we normalize to obtain the PMF. The distribution within a packet range is assumed to be uniform. The PMF used is given in Table **??**.

Acknowledgments

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