A Traffic Pattern Adaptive Mechanism to Bound Packet Delay and Delay Variation in 5G Fronthaul

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***Abstract*— A novel packet-based adaptive mechanism for bounding delay and delay variation in 5G Ethernet fronthaul is proposed. The mechanism enables aggregation of asynchronous traffic from fronthaul links using a traffic pattern adaptation algorithm. Traffic of a first stream is added in time-gaps of a second stream. For bounding and balancing the packet delay and delay variation between the streams, the size of the required time-gap before insertion is made adaptive. Simulation results demonstrate that through suitable tuning of the algorithm parameters, packet delay and delay variation below 10 microseconds can be achieved.**

Keywords—5G; delay; delay variation; Ethernet; IHON; mobile fronthaul; TSN;

I. INTRODUCTION

5G transport network has been evolving toward centralized eNB processing unit (CU) and remote RF front-ends units (RU), inter-connected via the so-called fronthaul, requiring low latency time-sensitive transport. In this context, Ethernet-based fronthaul is seen as a key enabler for the 5G transport, and is constantly developing new mechanisms to meet the network requirements including a reliable time-sensitive network with strict timing and synchronization, significantly improved deterministic delays, and scalability to larger network deployments.

The most latency critical requirement comes from the data transfers / messages inside the eNB related to the Hybrid Automatic Repeat Request (HARQ) loops of the air interface. Fig. 1 shows an example of the HARQ loop and the delay constraints for various functional splits as defined in 3GPP TR 38.801 [1]. In this view, some of the baseband functions are performed in the distributed unit (DU) while the others are performed in the CU, depending on the selected option. The interface between CU and DU is commonly referred to as midhaul. The split L2 (or Option 2 in Fig. 1), between the RLC/MAC and PDCP, is delay tolerant as it is outside of the HARQ loop. On the contrary, the L1-L2 split is within the HARQ loop and becomes time sensitive. This is mainly due to transactional delay-constrained IQ data and control (CTRL) messages exchanged between the L1 and L2 needing to be completed within a certain time limit. Furthermore, the bandwidth requirements of the L1-L2 split depends on the information rate. This is different for the split within the L1 fronthaul (3GPP Option 7 and related sub-options) where bandwidth requirement is much higher. This is also the most time critical part of all split options, where the delay and delay variations are highly constrained. The delay budget for one-way transport is generally agreed by standards to be set to 100µs [2].

Splitting the L1 processing delay/delay variation (including switching, queueing/scheduling, sync accuracy, etc.) can become a major source of constraint to the baseband processing time. As illustrated in Fig. 2, the larger the Ethernet fronthaul delay, the higher the demand for expedited baseband processing. This motivates the need for Ethernet-based time-sensitive mechanisms for minimizing and bounding the delay of the transport network. While mechanisms based on synchronization of the network may enable fixed and low delay, the synchronization increases the complexity of the network. Hence, for balancing the complexity and cost, novel features are required for reducing Ethernet fronthaul delay and delay variation.

In this paper, we propose a novel mechanism for bounding the delay and delay variation without requiring synchronization. The mechanism's design goal is to enable deterministic and low delay, relaxing the required baseband processing delay budget. This work is an extension and builds on our previous work [3] on Integrated Hybrid (as in packet/circuit) Optical Networks (IHON) [4] applied to Ethernet-based fronthaul transport. The outline of the paper is as follows: in Section II we discuss our previous work and set the context for the novel proposed mechanism explained in Section III. Section IV presents the simulation results, while Section V concludes the paper.

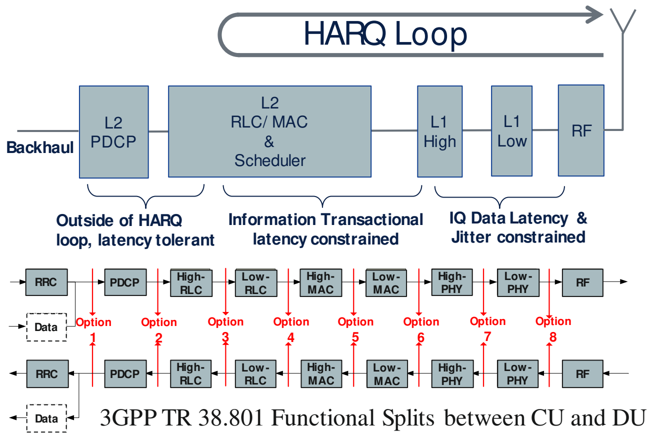

Fig. 1. HARQ Loop and Fronthaul Functional Splits.

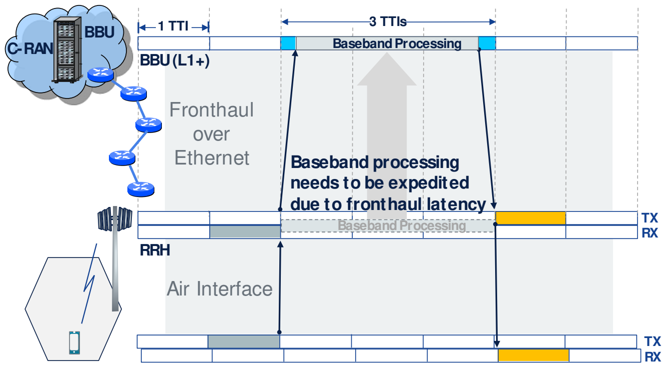

Fig. 2. Fronthaul over Ethernet and Baseband Processing Trade-off.

II. Earlier Works On Mechanisms For Bounding Delay In Packet-Switched Fronthaul

A. Standardization on controlled-delay Ethernet

Ethernet has been lacking deterministic quality of service (QoS) characteristics for many time sensitive applications. IEEE 802.1 is a Working Group (WG) of the IEEE 802 project of the IEEE Standards Association. As indicated in [5], Time Sensitive Networking (TSN) is one of the core activities of the IEEE 802.1 Working Group. TSN's target applications, real-time networks, require a guaranteed bounded end-to-end delay and packet delay variation (packet jitter) for critical data, which is ideal for industrial control, automotive applications, and 5G networks. TSN standards related to controlled-delay Ethernet bridging are 802.1Qav (Credit Based Shaper), 802.1Qbu (Frame Preemption), 802,1Qbv (Time-Aware Shaper), 802.1Qch Cyclic Queuing and Forwarding (CQF), 802.1CM (Time-Sensitive Networking for Fronthaul) [2], and P802.1Qcr (Asynchronous Traffic Shaping). Instead of throwing away late packets or grossly over-provisioning the network to accomplish bounded delay, these TSN standards strive to make use of queuing/reservation disciplines that strictly limit inter-flow interference and provide predictable gap/burst behavior to achieve bounded delay with zero packet loss. Additionally, reserving buffer space and bandwidth resources before the critical flow starts, and using extra buffers to accommodate known delay variations (e.g., forwarding delay) are key features to achieve bounded delay. These bounded-delay TSN standards basically enable no-tail distribution of average end-to-end delay and delay variation. In previous work [6], we have elaborated on these TSN standards and the context of Ethernet-based fronthaul networks in details.

B. Earlier works on IHON and deterministic delay mechanisms

Integrated hybrid optical networks (IHON) [4] apply two key mechanisms. The first concerns the deterministic aggregation and add/drop of multiple equal and high priority services with low and fixed delay, referred to as Guaranteed Service Transport (GST). The second instead provides deterministic QoS (priority) differentiation for maximizing the throughput by inserting lower priority Statistically Multiplexed (SM) traffic on the wavelength channels carrying GST traffic, without affecting the latter. The deterministic QoS differentiator bypasses the GST traffic from ingress wavelength port to egress wavelength port with a fixed delay, equal to the service time of a maximum sized SM packet. A monitoring block identifies available time-gaps in the GST stream, referred to as Time-Window (TW). Packets in the SM class are inserted whenever their service time fits the available TW. Thus, the SM insertion is transparent to the GST service and does not influence its QoS. Furthermore, since all GST packets experience the same fixed delay, the scheduler does not add any packet delay variation.

These IHON mechanisms have been further developed and implemented for Ethernet networks, referred to as Fusion. Previous experimental works have demonstrated 10Gb/s and 100Gb/s Ethernet (GE) services with QoS characteristics that fit the fronthaul requirements [7].

In recent work [3], which we extend and enhance in this paper, we have proposed a novel low and bounded delay mechanism, referred to as **Time-Window with Timeout** (TWT), for a multi-node Ethernet network. Multiple aggregated fronthaul services (e.g. L1 splits) enter the node's 100Gb/s Ethernet ingress port, while additional fronthaul traffic is added locally towards the egress port. Two key differences to earlier works with GST aggregation and add/drop [4] are: (*i*) the proposed mechanisms are asynchronous and (*ii*) tolerant to physical layer induced Packet Delay Variation (PDV). The block diagram of the simulated IHON node applying the mechanism is illustrated in Fig. 3. The fronthaul services which are aggregated at upstream nodes (left), arrive at the ingress port of the 100GE path and are identified as bypass (BP) traffic. The BP traffic is assumed to be carried by a network which introduces delay and PDV, as a result of aggregation and queuing of packets at each node. The local fronthaul traffic (referred to as ADD) is then added using different TW schemes and combined with the BP traffic to the egress 100Gb/s Ethernet port.

The mechanisms parameter space is explored through simulations for balancing the delay and PDV interference between the ADD and BP traffic:

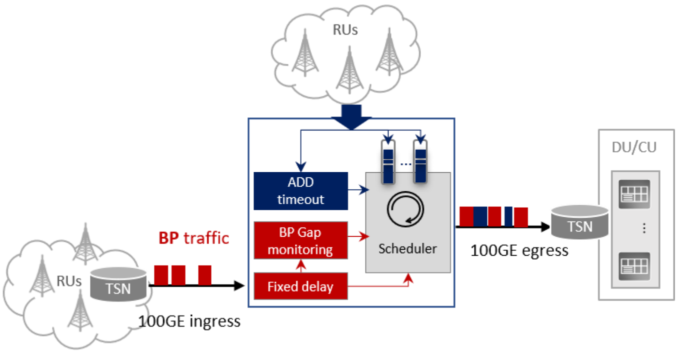

Fig. 3. TWT mechanisms block diagram in a three node Ethernet fronthaul network, illustrated at the middle node in the upstream path direction (from RUs to CUs). BP (red) traffic arriving at the 100GE ingress of the middle node pass through a fixed delay used for identifying the traffic time gaps. ADD (blue) traffic is inserted within these time gaps at the 100GE egress.

- BP traffic is forwarded with a fixed delay while the ADD traffic is inserted in the available TW if the packets fit. This gives the baseline reference performance (delay and PDV of ADD) of the previous deterministic priority of IHON, where the BP is GST and ADD is SM, i.e. ADD traffic is opportunistic and has no guarantees.
- ADD traffic is always inserted, even if the TW is too small for the ADD packets. Thus, this is the opposite operation of the previous baseline.
- ADD traffic is always inserted after a Timeout equal to different N x MTU (Maximum Transmission Unit) service times; bounding the delay and PDV of the ADD traffic and exploring its influence on adding delay and PDV to BP.

Differently from [3], the new Adaptive Time-Window mechanism, described in the next section, actively adapts the TW required for inserting the ADD traffic into the BP stream as time passes and no suitable gaps are found, with the goal of further reducing the influence of the ADD traffic on BP.

III. The Novel Mechanism Adapting The Time-Window To The Delay Bound

The adaptive TW-based mechanism proposed here reduces the window as the waiting time of ADD packet increases with a factor k. The partially relaxed TW size constraint is a tradeoff with accepting some additional PDV on the BP traffic. This typically happens when an ADD packet is too large with respect to the gaps, and cannot, within a specified time, find a suitable time gap in the BP stream to be inserted. When a gap is found according to the eventually adjusted TW, the ADD packet is inserted, possibly causing PDV on the BP stream if the gap on the BP stream is smaller than the actual size of the ADD packet.

The procedure is illustrated in the flow diagram in Fig. 4. The proposed scheduling technique starts from a new ADD burst with a duration ADD_burst that needs to be inserted. The algorithm looks for a gap in the BP stream.

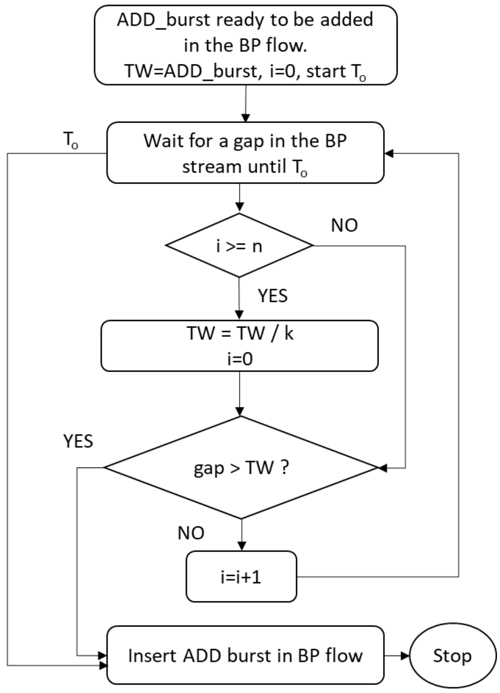

Fig. 4. Flow diagram of the adaptive window mechanism.

As soon as a gap is detected, the algorithm checks the number of gaps i, whose length is smaller than the current window size TW. If it is greater than or equal to n (i.e., a gap size larger than TW is not found after n gaps), the window is decreased by a factor k such that the new window is updated as:

$$TW = TW / k \tag{1}$$

Otherwise, the algorithm does not perform the window reduction and immediately checks if the gap is larger than TW, so that the waiting packet can be inserted. If the gap is not of suitable size, the algorithm repeats until the timeout To expires, and the ADD packet is inserted in the next gap of the BP flow, independently of the TW size. This adaptive window mechanism is expected to more flexibly control delay and PDV of both BP and ADD traffic. This is important also to make the effects of the scheduling less dependent on the traffic pattern.

IV. Simulation Results

The proposed mechanism has been simulated with an ad-hoc simulator with the following assumptions:

- Remote units generate fixed MTU sized packets. The MTU transmission time is assumed to be 121.76 ns, which corresponds to a packet of 1522 byte sent over a 100Gbit/s channel.
- The BP traffic has a constant burst size equal to 5 MTUs and negative exponential distribution of OFF time, calculated such that the average traffic load is ρ_{BP}=0.5. The fixed delay (see Fig. 3), experienced by

BP traffic passing through the switch is equal to 6 MTUs (size of ADD burst). The negative exponential assumption for the OFF time is introduced to take the effect of the network (i.e. physical layers) on packet delay and PDV into account [8].

- The ADD traffic has constant ON and OFF time for each simulation with the burst size equal to 6 MTUs and OFF time calculated to obtain the given total traffic load ρ_{TOT}.

Simulation results are obtained to evaluate the maximum delay and PDV varying the number of gaps n till the TW is decreased, the decreasing factor k, and the total traffic load ρ_{TOT}, which is the sum of ρ_{BP} and the load of the ADD traffic ρ_{ADD}. In addition, two boundary cases are simulated for comparison with earlier schemes [3]:

(1) no timeout applied (To=∞) to ADD traffic insertion, i.e. ADD traffic is only inserted if the TW is equal or less than the BP gap, i.e. BP has absolute priority and its QoS is not influenced by ADD;

(2) with timeout To=0 when ADD traffic has absolute priority and is always inserted first.

To focus on the effects of n and k, in the following simulation results no timeout is applied, or, equivalently, that the time out value applied to ADD traffic insertion is assumed To=∞. As a consequence, ADD traffic is only inserted if the value of TW is equal or less than the BP gap. All the results are averaged over 10 simulation runs, each with 10^8 arrivals to the system.

In Fig. 5 the maximum delay for the ADD traffic is reported, using the adaptive window mechanism with no timeout. The sudden increase of the maximum delay of each group of curves is related to the status of the ADD transmission queue, which tends to fill up and contains multiple bursts waiting for transmission. This happens because the idle time gaps in the BP stream are not all usable/filled by ADD traffic, as a consequence of the characteristics of the scheduler which leaves some gaps empty. This load value $\rho_{MAX,}$ where the delay steeply increases, is the system saturation point and the maximum achievable throughput. Thus, in order to bound the ADD maximum delay to 10μs, the maximum total offered load ρ_{TOT} must be set to be less or equal to ρ_{MAX}. We can notice that the latter varies with n and k, and, in particular, it is higher for low values of n. The behavior with n=0, which represents the case in which the initial window is decreased before looking for the gap, provides the lowest delay solution for the ADD traffic and the maximum load. The behavior with n=5 is shown to be very close to the behavior found in [3] with To=∞ (upper dotted black line). The case k=1, which is the case when the TW is never reduced, is equivalent to the To=∞ case.

Fig. 6 shows the maximum delay for BP traffic under the same conditions of Fig. 5. The maximum delay of BP traffic is constant with load and varies with k around the duration of 2 ADD bursts (1.46 μs), while the minimum BP delay is equal to the applied fixed delay, in this case 1 ADD burst (0.73 μs). Note that the BP average PDV is thus 1 ADD burst. The value of k has impact on max BP delay at very small or high values of k (1 or 8). In comparison with results for To=0 and To=∞, all values stay in between (with k=1 coinciding with To=∞). Thus, the influence of the mechanism on the BP QoS is limited, and it is possible to bound the BP delay for any load while focusing

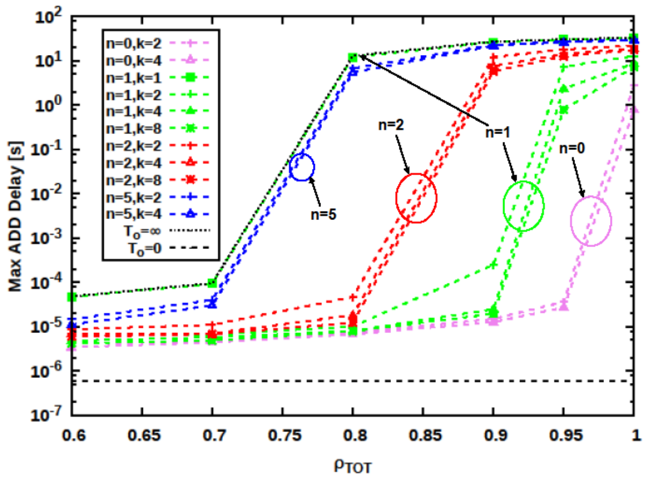

Fig. 5. Maximum delay of ADD traffic as a function of the carried load, varying the number of gaps to wait, n, and the factor k which reduces the window size. The curves for the mechanism with the time out only, To=0 and To=∞, are reported for comparison.

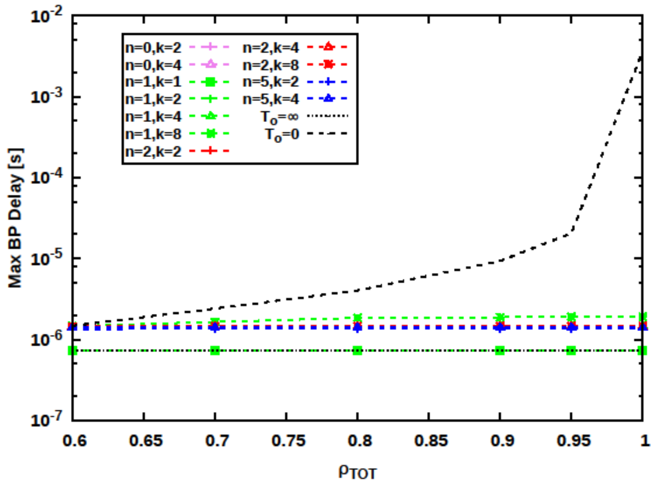

Fig. 6. Trade-off Maximum delay of BP traffic as a function of the carried load, varying the number of gaps to wait, n, and the factor k which reduces the window size. The curves for the mechanism with the time out only, To=0 and To=∞, are reported for comparison.

on optimizing the parameters for minimizing the ADD bounded delay and PDV.

Fig. 7 reports in more detail the maximum delay experienced by both ADD and BP streams, when n=1 and ρ_{TOT}=0.9, for different values of k. It can be noticed that for k=1 the delay of the ADD traffic is in the order of seconds, as for the case To=∞ (see Fig. 5). For larger values of k, the ADD delay decreases, while the BP delay slightly increases. This is due to the fact that TW is reduced by larger values, thus ADD packets can be injected in the BP stream even in case of small gaps. When k=4, the ADD delay is limited to 25μs, while for BP it is less than 2μs. Further increasing k slowly brings the ADD and BP delays closer. Note that while the path insertion delay is higher for ADD, at the next node this traffic is identified as BP and

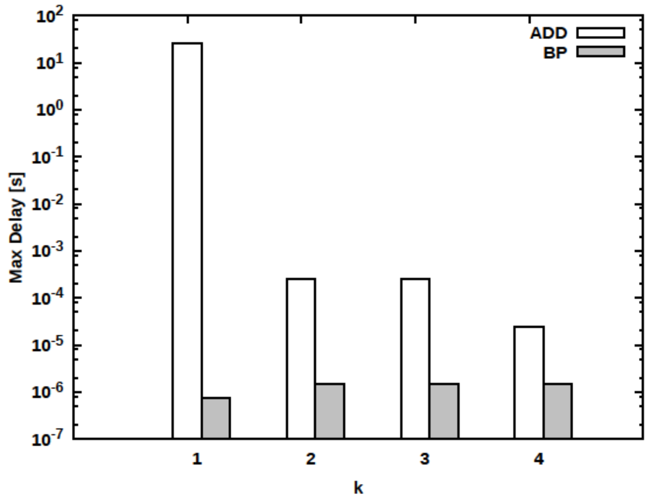

Fig. 7. Maximum delay experienced by ADD and BP streams for different values of factor k when n=1 and ρ_{TOT}=0.9.

will experience a lower delay through the path once it is inserted. Hence it is also important to have a low and bounded BP delay to simplify the dimensioning of the end-to-end fronthaul path for the available delay budget, i.e. the maximum allowed delay and PDV in the network. E.g. for a path with N nodes, the maximum path delay is equal to the sum of the maximum ADD delay plus the maximum BP delay multiplied by the number of traversed nodes N-1.

Fig. 8 shows the maximum PDV introduced by the adaptive window mechanism on BP and ADD traffic for different carried loads in the case n=k=2. In this figure, the BP,IN case corresponds to the maximum PDV experienced by the BP traffic at the input, due to the assumption on the negative exponential distribution of the BP OFF periods. It is possible to observe that the maximum PDV for both ADD and BP is bounded. For the BP flow, the maximum PDV is around 11μs, while for the ADD is around 8μs. As explained in more details in [6], the PDV is important for dimensioning the playout buffer at the receiver side for smoothing/removing the packet jitter and sending out the packets for further processing as they were originally sent. Thus, the fastest packet in the path (minimum delay) has to be delayed equal to maximum PDV time by being buffered and played out/transmitted such that its end-to-end delay is equal to the slowest packet (maximum delay) in the path. A small and bounded PDV is thus desired as it requires a small and fixed buffer size, especially important at the RU side for simplifying and lowering the cost of the antenna site.

V. Conclusion

This paper has proposed a novel window-based mechanism to bound delay and PDV of aggregated traffic on 5G fronthaul. Results have been obtained by simulations to show the bounding effectiveness of the mechanism, which is simpler to implement with respect to only timer-based approaches and results are shown to be even more effective. Results also demonstrating the effect of the parameters on the maximum load that can be achieved to avoid saturating condition on the ADD channel. In addition, stability of the bounding over the whole

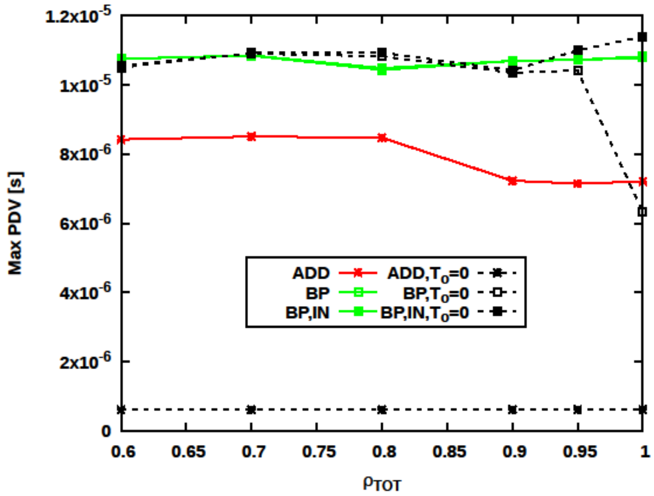

Fig. 8. Maximum PDV as a function of the carried load for BP and ADD traffic, n=2 and k=2 in comparison with results obtained with To=0 (worst case for BP, best case for ADD).

interval of carried load is also achieved. Implementation of the mechanism in real traffic condition is expected to support these conclusions by practical experiments.

Acknowledgment

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References

[1] 3GPP TR38.801 Radio access architecture and interfaces, http://www.3gpp.org/ftp/specs/archive/38_series/38.801.

[2] IEEE 802.1CM-2018 - IEEE Standard for Local and metropolitan area networks - Time-Sensitive Networking for Fronthaul, https://standards.ieee.org/standard/802_1CM-2018.html.

[3] S. Bjørnstad, R. Veisllari, D. Chen, F. Tonini, C. Raffaelli, "Minimizing Delay and Packet Delay Variation in Switched 5G Transport Networks", to appear in Journal of Optical Communications and Networking (https://www.osapublishing.org/jocn/home.cfm).

[4] R. Veisllari, S. Bjornstad, J. P. Braute, K. Bozorgebrahimi and C. Raffaelli, "Field-trial demonstration of cost efficient sub-wavelength service through integrated packet/circuit hybrid network [invited]," in IEEE/OSA Journal of Optical Communications and Networking, vol. 7, no. 3, pp. A379-A387, March 2015.

[5] D. Wright, "The history of the IEEE 802 standard," IEEE Communications Standards Magazine, vol. 2, no. 2, pp. 4–4, Jun. 2018.

[6] S. Bjomstad, D. Chen, and R. Veisllari, "Handling delay in 5G ethernet mobile fronthaul networks," in Proc. IEEE European Conf. on Networks and Commun. (EuCNC), Jun. 2018, pp. 1–9.

[7] R. Veisllari, S. Bjornstad, J.P. Braute, "Experimental Demonstration of 100 Gb/s Optical Network Transport and Aggregation for Ethernet Fronthaul with Low and Bounded Delay", in Proc. of the Optical Fiber Communications Conference and Exposition (OFC), San Diego, CA, USA, 11–15 March 2018.

[8] G. Perez, J. Hernandez, and D. Larrabeiti, "Fronthaul Network Modeling and Dimensioning Meeting Ultra-Low Latency Requirements for 5G," J. of Opt. Comm. and Net., vol. 10, no. 6, pp. 573-581, June 2018.