Ethernet Fronthaul Transport of an Upper-Physical Layer Functional Split using Time-Aware Shaping

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Abstract

An Upper Physical layer functional Split (UPS) for an Ethernet fronthaul network is modeled, and the frame delay and Frame Delay Variation (FDV) limitations are investigated. The results show that contention in Ethernet switch ports can cause an increase in the delay and FDV beyond proposed specifications for the UPS and other time-sensitive traffic types such as I/Q-type traffic. Time Aware Shaping (TAS) can significantly reduce or even remove FDV for UPS traffic and I/Q-type traffic, but it is shown that TAS design aspects have to carefully consider the transmission pattern of the contending traffic in the Ethernet fronthaul network switches. Taking into account the transmission pattern of the UPS traffic, different time allocations within TAS window sections are proposed in conjunction with both receiver and transmitterside buffering. Further, it is proven that using TAS with higher link rates for example, 10 Gbps link rates or beyond makes it possible to transport the UPS and time sensitive traffic within its specification over fronthaul fiber spans, more than 10 kilometers length, and/or more hops as TAS can potentially eliminate any increase in the FDV of the UPS traffic.

Keywords

Mobile fronthaul, Ethernet fronthaul, time-sensitive networking, time-aware shaping, radio access network, functional splits

I. Introduction

The Cloud Radio Access Network (C-RAN) is a promising proposal for 5th generation mobile networks (5G) and beyond, bringing operational, management and energy cost savings for the operator and enhancing features such as joint processing of signals and network-wide interference mitigation [1]. Up to now, in a C-RAN, In-Phase and Quadrature (IQ) time-domain symbols have been transported between Baseband processing Units (BBUs) and Remote Radio Heads (RRHs) using industry standard specifications such as the Common Public Radio Interface (CPRI) [2]. IQ transport has excessive bit-rate requirements, exacerbated by multiple antenna techniques and increases in radio bandwidth [3,4]. Both eCPRI [5] and functional splitting between the Central Unit (CU), Distributed Units (DU) and Remote Units (RU) [6,7,8] have been introduced in the Radio Access Network (RAN) to overcome the excessive bit rate of CPRI and allow the transmission of flexible radio data.

The focus in this work is a split point between DU and RU which represents one of the lower-layer split (LLS) options, while the CU-DU split represents the higher-layer split (HLS) [9]. The LLS has been defined by the 3rd Generation Partnership Project (3GPP), whereas several options exist for the LLS, mainly within the Physical (PHY) layer of the RAN protocol stack [6].

The selection of this functional split option depends on several factors such as reduction of fronthaul bit-rate, and support of radio techniques such as multiple-input multiple-output (MIMO), massive and distributed MIMO and Coordinated Multipoint (CoMP) [10]. Using a new functional split in conjunction with Ethernet transport in the fronthaul has many advantages in comparison to use other transport technologies such as point to point, microwave links and Fibre Wireless Networks (FIWI), such as allowing for statistical multiplexing gains, and network virtualization, monitoring, orchestration and Software Defined Networking (SDN) [3,11,12]. In addition, the Ethernet network has the advantages of low cost deployment and the simplicity in its installation and maintenance. Point to point links can introduce more reliability in the network in terms of the delay and FDV, but with less ability to share and utilize the available resources. FIWI and microwave links have the advantage of flexibility and simplicity but with less reliability in terms of delay and FDV[13,14]. However, an Ethernet network may lead to a lack of synchronization [3,7,10], increased delay and delay variation due to contention [3,12], mapping inefficiency [15], and packet loss [16]. Synchronous Ethernet (SyncE) and Precision Time Protocol (PTP) are possible solutions for meeting the frequency and time/phase synchronization requirements [3]. Different scheduling

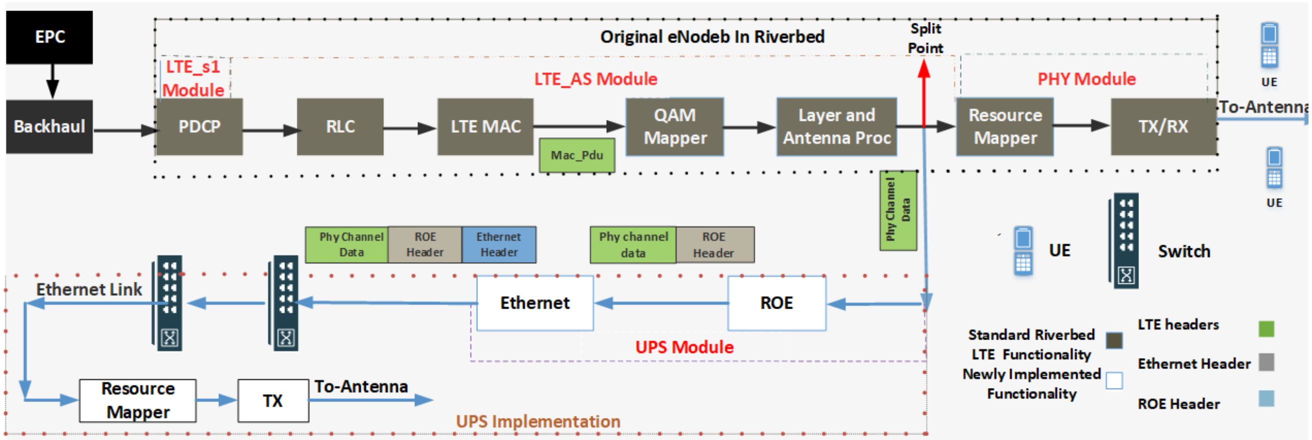

Fig. 1. Implementation of the UPS in the Ethernet fronthaul network. EPC, Evolved Packet Core; LTE_AS, LTE Access Stratum; Tx/Rx, Transmit/Receive; RoE, Radio-over-Ethernet; UE, User Equipment; PHY, Physical layer; PDU, Protocol Data Unit; QAM, Quadrature Amplitude Modulation.

regimes and standards have been proposed to improve the delay, FDV and packet loss in the Ethernet network due to the contention such as IEEE 802.1CM (Time Sensitive Networking for fronthaul) standards and profiles [24]. This will be discussed in detail later in this section. Among LLS options, the Upper Physical layer functional Split (UPS) is interesting as it is the closest split point to the antenna which can lead to statistical multiplexing gains. It also readily allows for joint processing techniques in the downlink and uplink and offers centralized aggregation for the transmission of 4G and 5G New Radio (NR) signals [18]. In previous work, a software-emulated Medium Access Control (MAC)-PHY split, which has similar traffic characteristics (traffic transmitted based on the air interface timings) and delay and FDV requirements profile to the UPS, was presented. This work focused on the latency performance [17], and the contribution of the encapsulation and packetization overhead on the Ethernet fronthaul data rate [18]. In [17], such a split was demonstrated to evaluate its delay performance in comparison to CoMP delay requirements at 4G data rates. In [15], the use of jumbo Ethernet frames (of around 4300 bytes) in a MAC-PHY split was found to cause significant frame delay variation (FDV). Therefore, the investigation in this work assumes frame sizes based on the received data from the upper layers, with a maximum frame size of 1518 bytes. In [18], some LLS options have been demonstrated and the results show that moving some functionality from the DU to the RU reduces the delay in the DU and increase the latency in the RU which contributes to the overall latency in the fronthaul network. The paper suggested as well that using some of the LLS options can lead to more interface and conversion delay than other options.

In this paper, we present, for the first time, a simulation model for UPS. This new model for UPS traffic transported over Ethernet has been implemented in the Opnet/Riverbed simulation platform. Table I summarizes the delay and FDV requirements for the UPS, as well as for an IQ transport-based fronthaul [15]. It should be noted that the UPS is equivalent to the option 7-2 split point (both splits are pre-resource mapper splits) and there is approximate agreement around the delay requirements for the UPS in the literature (range between 200 µs & 250 µs [15,18]).). As the requirements are very tight, so reducing delay and FDV induced by contention in an Ethernet fronthaul is important [20,22,23]. With this in mind, IEEE 802.1CM adopts a number of Time Sensitive Networking (TSN) profiles for use in a bridged Ethernet fronthaul [21,24]. Another promising TSN profile is Time Aware Shaping (TAS), based on IEEE802.1Qbv [25]. It should be noted that while TAS is one of the TSN standards, it is not one of 802.1CM standards.

In previous work, a detailed investigation of the performance of TAS for PTP and background traffic was presented [26,27]. The simulation model reported in [27] is used in this paper to investigate how TAS can efficiently reduce (or even eliminate) contention-induced FDV. Buffering, either at the transmitter [19], or receiver side [19,21], has been proposed as a means of reducing FDV in prior work as well.

In this work, the focus is the delay and FDV performance of the UPS traffic with TAS. The performance and limitations of TAS in the Ethernet fronthaul with different contention cases are investigated, considering different traffic types and their transmission patterns (bursty or random) and the use of buffering to eliminate FDV. While, transmitter-side buffering can be implemented with TAS, permitting alignment of the packet transmissions with the appropriate window [27], and is considered in this work, additional receiver-side buffering can be implemented to eliminate FDV. The UPS traffic is tested within both low- and high-priority sections in TAS to investigate the most efficient section allocation for this traffic in term of delay and FDV. Due to its transmission pattern being dependent on air interface timings, with tight delay and FDV requirements, there are advantages and disadvantages to each approach, which are thoroughly analyzed. This case has not been investigated in any prior work and can be used as a guide for the use of TAS with the UPS and other functional splits (splits that have tight delay and FDV requirements and traffic generated based on user data). Use cases for different link rates, lengths and numbers of hops in the switched Ethernet fronthaul are analyzed and studied.It should be noted that the UPS traffic has not been modelled in a simulation platform in any prior work in the literature.

The paper is organized as follows: in Section II, the implementation of the UPS in the Riverbed Modeler (previously OPNET) simulation platform, with the associated statistics functions to measure traffic characteristics, is described. Section III presents results for frame delay and FDV of

the UPS and IQ -type traffic with contention in an Ethernet fronthaul. Section IV describes the performance and limitations of TAS in the Ethernet fronthaul with different contention cases;
it further determines the best time window allocation for different traffic types based on their transmission pattern (bursty or random) and the use of buffering to eliminate FDV. Finally, the paper is concluded in Section V.

TABLE I
DELAY AND FDV REQUIREMENTS FOR DIFFERENT SPLIT POINTS [15]

Traffic Type	FDV (ns)	Normalized FDV	Delay (μs)	Normalized Delay
UPS	163	0.017	220 75 (w/ CoMP)	27.5
I/Q	16	0.002	220 75 (w/ CoMP)	27.5

Quoted value is used as an indicator. Exact value will depend on application being transported.

II. UPS Implementation In Riverbed Simulator

Riverbed Modeler is an event-based simulation platform that provides model suites for different network technologies, with Long-Term Evolution (LTE) being one of them. The eNodeB model, a node model within the LTE suite, is made up of three main modules associated with LTE functionality [28]. This distribution of the standard LTE functionality in Riverbed Modeler's eNodeB model and the implementation of the UPS are shown in Fig. 1. The PHY module performs part of the LTE PHY functions, such as power control. The LTE_AS module performs the pre-resource mapper functions in the LTE PHY, and LTE Medium Access Protocol (MAC), Radio Link Control (RLC) and some Packet Data Convergence Protocol (PDCP) functions. The remaining PDCP functions and handover are handled by the LTE_S1 module [28]. The LTE_S1 module receives the traffic from the Evolved Packet Core (EPC) through the backhaul. It should be noted that 5G models are not available in Riverbed Modeler or any similar event-based simulation platform. Due to the similarities in the 5G and 4G/LTE RAN protocol stacks, the LTE module has been modified for use as part of the 5G access network.

In the implementation of the UPS, all of the functionalities (from the resource mapper onward toward the antenna) existing in the Riverbed PHY module are moved to a newly implemented RRU, while the remaining LTE functionalities are handled by what is now a DU part of the eNodeB. As shown in Fig. 1, LTE physical channel data are copied from the original stream in this DU, and then encapsulated by a newly implemented Radio over Ethernet (RoE) sub-layer, with headers based on the RoE standard definitions [29]. The resulting RoE frames are then encapsulated in standard Ethernet frames and sent over the Ethernet fronthaul. As the RRU is not a complete Riverbed eNobeB implementation, the User Equipment (UE) remains connected to the original eNodeB model for the duration of the simulation; this guarantees generation of new traffic, while allowing for performance monitoring of the copied traffic flowing through the downlink section of the newly developed fronthaul. The focus is, thus, on the downlink of the fronthaul. No modification has been carried out to the traffic generation characteristics of the eNodeB; that is, traffic is generated in accordance to air interface timings as shown in Fig. 2. The new modeling in Riverbed consists of a modified LTE_AS module and a newly implemented UPS module, as will be described in the following.

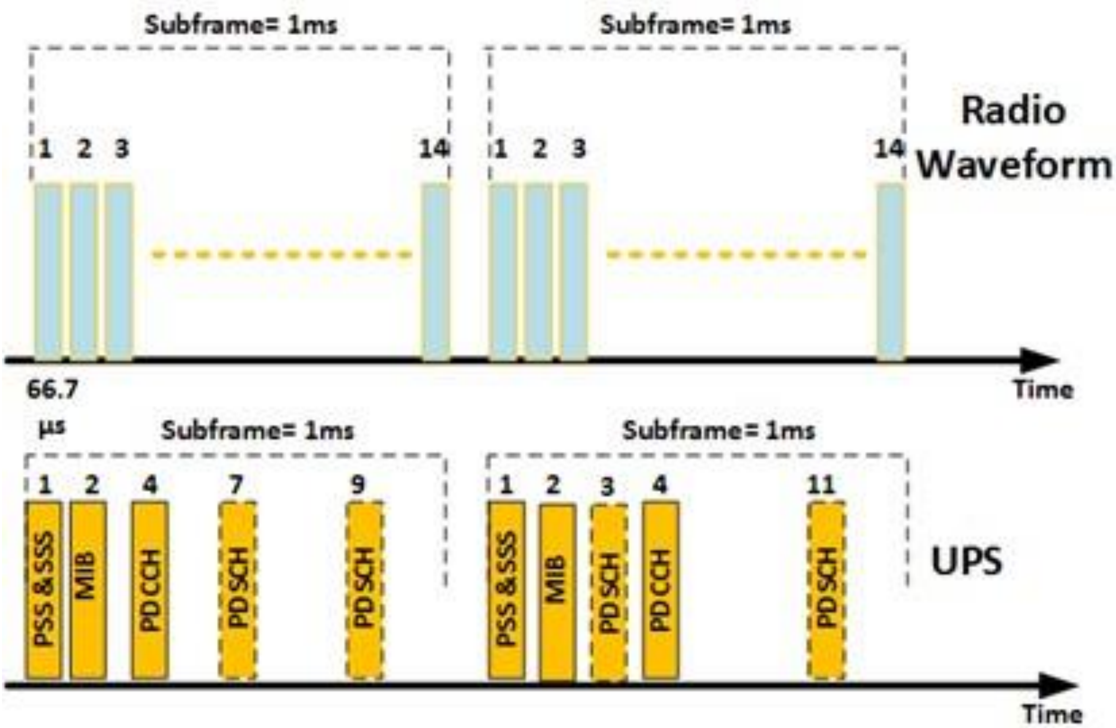

Fig. 2. UPS and Radio Waveform traffic transmission pattern,

A. LTE-AS Module

This module was modified in order to copy the physical channel data and send them to the UPS module. As the split point in interest is before the resource mapper (as shown in Fig. 1), one or more (depending on number of connected users) Physical Downlink Shared Channel (PDSCH) messages are sent every LTE subframe (1 ms duration). In addition, a number of physical control channel messages are sent. These include, Primary and Secondary Synchronization Signals (PSS & SSS) which are sent approximately every 0.5 ms (a slot duration), Master Information Block (MIB) which is sent once every 10 ms (a radio frame duration) and Physical Downlink Control Channel (PDCCH). The latter is sent only in subframes that include System Information (SI) and/or PDSCH messages. Additional control information, which has negligible effect on the overall data rate (e.g. format indicator channel), is, in Riverbed, either aggregated within the aforementioned control messages or sent directly to the UE through direct memory exchanges (i.e. not modelled as a message exchange).

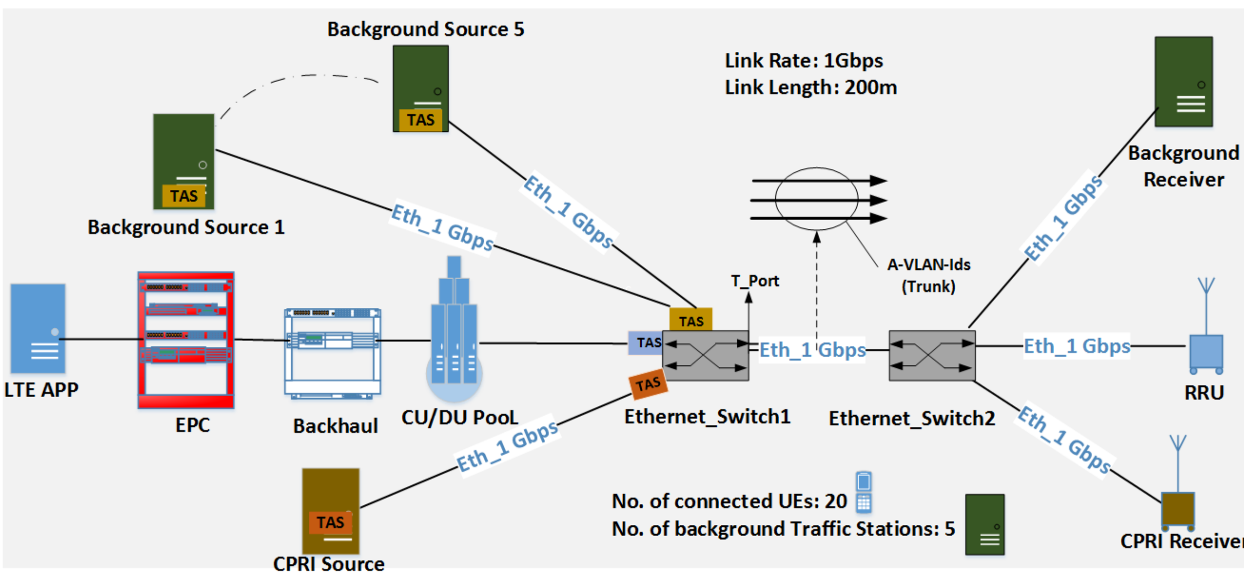

Fig. 3. The simulation set-up of the Ethernet fronthaul.

B. UPS Module

This new module handles two main functions (as depicted in Fig.1). The first is encapsulating the physical channel data into the implemented RoE frame, and setting some of the RoE header fields such as the packet type and flow identification (ID). The second function is the transport over standard Ethernet links as used in the modelled fronthaul. Here, a modification was necessary to the existing Riverbed Ethernet module functions as in these higher layer modules set the fields of the Ethernet header. In the new implementation, with a purely layer-2 fronthaul, all header fields are set directly within the UPS module.

C. Statistics Implementation in Riverbed Modeler

New statistics have been defined in Riverbed to measure Key Performance Indicators (KPIs) for the Ethernet fronthaul network. To define these statistics, they are registered in the simulation platform first and then the statistics rules are set to allow the simulator to collect data based on them. At the end of the simulation, collected meta data are written into a file that is extracted either as a CSV file or through the simulation interface. The newly registered statistics are frame size and frame ID. The frame ID statistic allows keeping track of the transmitted UPS frames from the DU and identifying any lost or out-of-order frames at the RRU. In addition, a time stamp is associated with each statistic and used to calculate the delay and FDV of the transmitted UPS frames. The extracted frame sizes are used in calculating the average, maximum and minimum frame sizes of UPS traffic.

III. Fronthaul Scenarios

In this section, a number of scenarios are implemented to show the effect of different combinations of traffic types on the performance of the UPS and IQ-type traffic. An overview of the simulation set-up including the different nodes (traffic transmitters and receivers) that will be used in the following scenarios is shown in Fig. 3. Precisely which nodes are used in each scenario will be specified in the following scenario subsections. It should be noted that low channel rate (1 GbE) and lower data rates, which need to be smaller than the channel rate, are employed to facilitate simulation of a loaded fronthaul. Normalization will be used in the presentation of results to enable projections for higher bit-rates, bandwidths and link lengths. LTE traffic is generated at the LTE application server, which sends traffic over the backhaul to the CU/DU. The DU generates the UPS traffic after encapsulating the received data with the RoE and Ethernet headers (as depicted in Fig, 1) and transmits the resulting Ethernet frames to the RRU through the Ethernet network. Twenty UEs are attached to the eNodeB (unless otherwise specified) with a per-UE data rate of 0.84 Mbps.

IQ-type traffic is modeled as bursts of constant-size 1000-byte Ethernet frames. The burst size is equivalent to the amount of traffic that is transmitted in one LTE subframe (1 ms), based on 5 MHz bandwidth and 6.25 sampling rate. "It should be noted that this is not a CPRI traffic rate (not one of the mentioned traffic rates in the CPRI standard [2]) . However, the generation and transmission of the traffic is in bursts, which can be expected with CPRI over Ethernet transport [15]".

As traffic is scaled to facilitate the simulations, it is the modelling of the general characteristics of the traffic which is of importance. In the following scenarios, the allocated capacity to the IQ-type traffic is 20% of the network capacity. The transmission pattern of IQ-type traffic is shown in Fig. 3. Bursty transmission with the radio waveform packetised with small inter-frame gap is presumed [2].

The Ethernet fronthaul network in the following scenario comprises of two GbE (gigabit-Ethernet) switches connected by a trunk, where contention can occur. Each network segment has been assigned a link length of 200m and the links in the network are 1 GbE (maximum network capacity). Note that the link rates in all of the following scenarios and results are used as an example of the possible link rates in the future Ethernet fronthaul. In order to have reasonable simulation times with loaded networks, the radio bandwidths, user rates and link rates need to be low. By examining at utilization and normalized delay, the results become scalable to any link rate or utilization. It should be noted that the switch schedulers are all byte-based schedulers. This type of switch's scheduler balances the number of transmitted frames from each input queue based on the total number of transmitted bytes per unit of time.

There are up to five background traffic servers in this network. The background traffic from each is configured to follow a uniform distribution, setting the inter-arrival of the frames to vary between +/- 50% of the average inter-arrival rate, and with a constant frame size of 1000 bytes. Traffic from the different sources is logically separated with Virtual Local Area Network Identifiers (VLAN IDs). Note that, applying to all scenarios, the delay and FDV values of the different traffic types are calculated based on the experienced delay and FDV by all transmitted frames of this traffic in the network. The number of transmitted frames in each scenario is 10000 frames. In addition, normalization is used in this paper, the values are also expressed as normalized delay and FDV assuming Gigabit Ethernet and 1000-byte frames (for 10 GbE, the normalized value would simply be multiplied by 10).

A. *Baseline (No Contention) scenario*

This scenario is used to measure the frame delay and FDV of the UPS and IQ-type traffic in a baseline case, when there is no contending traffic in the Ethernet fronthaul (i.e., the IQ and UPS traffic are transmitted separately, and the background traffic nodes are disabled). For the UPS baseline, two UEs are connected with a total application data rate of 1.68 Mbps. The resulting data rate over the fronthaul for UPS is 2.08 Mbps, due to the added overheads of the LTE, Ethernet and RoE processing; this data rate is approximately 23% higher than the backhaul traffic. In [30], an experimental implementation of a MAC-PHY split showed higher overheads, of approximately 35%, attributed to a fixed Transport Block (TB) size. Here the TB size can be more than twice as large, leading to a lower overhead for the transmitted traffic. The resulting overheads obtained here are in agreement with theoretical overhead values that are defined by the European Telecommunications Standards Institute (ETSI)/LTE [31], RoE [29] and Ethernet [32] standards. The average frame delay (Da) in the baseline scenario can be given as

$$D_a = 2(D_s + D_P + D_F), \quad (1)$$

where D_s is the serialization delay, D_p the propagation delay and D_F the processing (fabric) delay in the switch. The propagation delay in each section of the network is constant at 1 µs (200 m link length). Based on the average frame size, the serialization delay is approx. 2 µs. The fabric delay in both Ethernet switches is 5 µs. Fig. 4 shows the delay and FDV of the UPS and IQ-type traffic. These are normalized to the serialization delay of 1000 bytes over a 1 GbE link since the UPS traffic is made to contend with IQ-type 1000-byte frames. In the later scenarios, both types of traffic are made to contend with 1000-byte background traffic frames. The baseline FDV of the UPS traffic in this scenario is 1.6 µs and the delay is 11.04 µs. The FDV can be explained by the fact that the transmitted Ethernet frames from the DU have different sizes. The minimum Ethernet frame size is 74 bytes while the maximum is 1470 bytes. The average frame size that is transmitted by the DU is 255 bytes. Similarly, the baseline delay and FDV for I/Q-type traffic has been measured. The FDV is zero, due to the fixed frame size, and the delay is 23.04 µs (delay value based on (1)). It should be noted that the delay and FDV of both traffic in this scenario are considered the baseline of later scenarios and both the delay and FDV values are discounted when the delay and FDV values are analyzed in these scenarios.

B. *UPS Traffic with Statistically Distributed Background Traffic*

This scenario is used to show the effect on the frame delay and FDV of the UPS traffic when there is contention with uniformly distributed background traffic . In this scenario, five background traffic servers are enabled and configured with total average background traffic rates ranging between 100 Mbps and 600 Mbps.

Fig. 5 shows the delay and FDV results of the UPS traffic with increasing link utilization, due to contention in the Ethernet switch`s trunk port (shown as T_port in Fig. 3). The maximum increase in UPS delay is equivalent to the serialization of approximately five background traffic frames. The increase in FDV is less than the serialization of one background traffic frame on average, while the maximum increase in FDV is equivalent to the serialization of approximately four background frames.

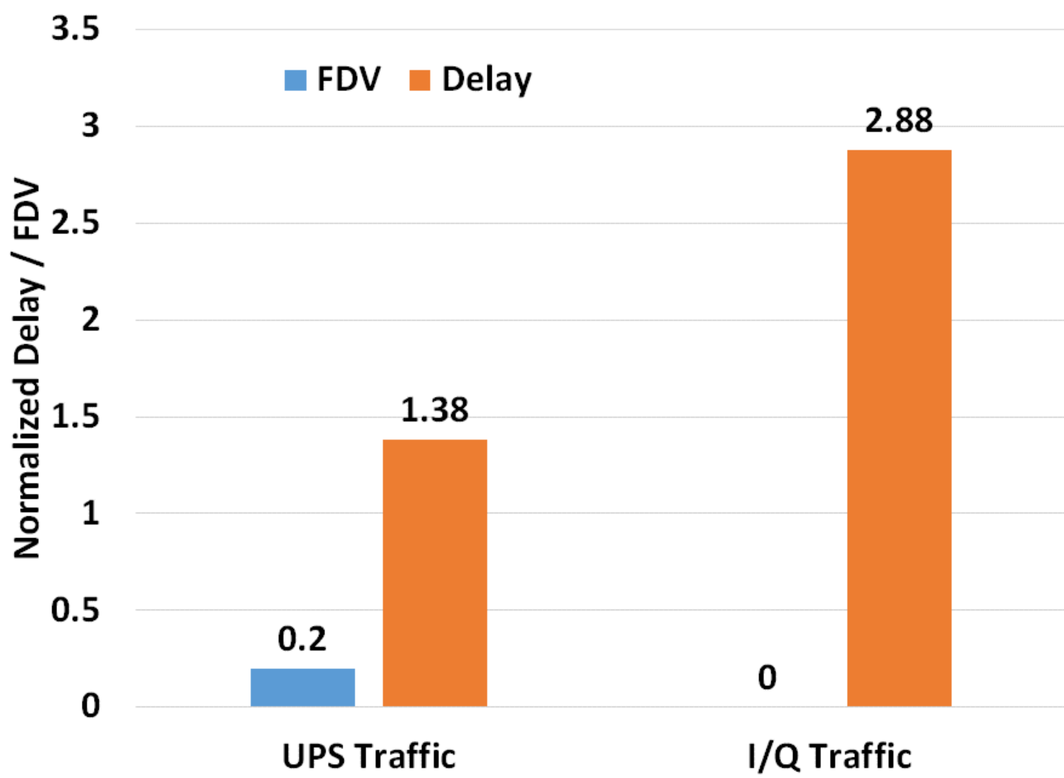

Fig. 4. Baseline delay and frame delay variation (FDV) of the UPS and I/Q-type traffic.

The results can be explained because the extra delay and FDV that can be encountered by the UPS frames, in the worst-case contention scenario, is from the serialization of five background traffic frames (one from each of the five background traffic stations). The average delay of the UPS traffic is significantly lower than this maximum since its data rate is low in comparison to the background traffic and the switch scheduler attempts to balance the number of transmitted frames from each input queue based on the total number of transmitted bytes per unit of time (i.e. byte-based scheduling is used).

As a special case, Fig.5 shows the FDV and delay results for the UPS with bursty background traffic. Each of the five servers generates a burst by buffering (in each server) the generated 1000-byte frames for part of a 1 ms and sending this burst at the start of the allocated time window. The number of Ethernet frames in a burst depends on the data rate. The results show that bursty traffic does not increase delay or FDV for the UPS traffic compared to the results with non-bursty traffic. This is also due to the aforementioned byte-based scheduling of the switch. If the switch scheduler did not balance the output data rate from the input queues based on the number of bytes transmitted, the average delay would be significantly higher since a UPS frame might have to wait for a full burst to be serialized out of the trunk port.

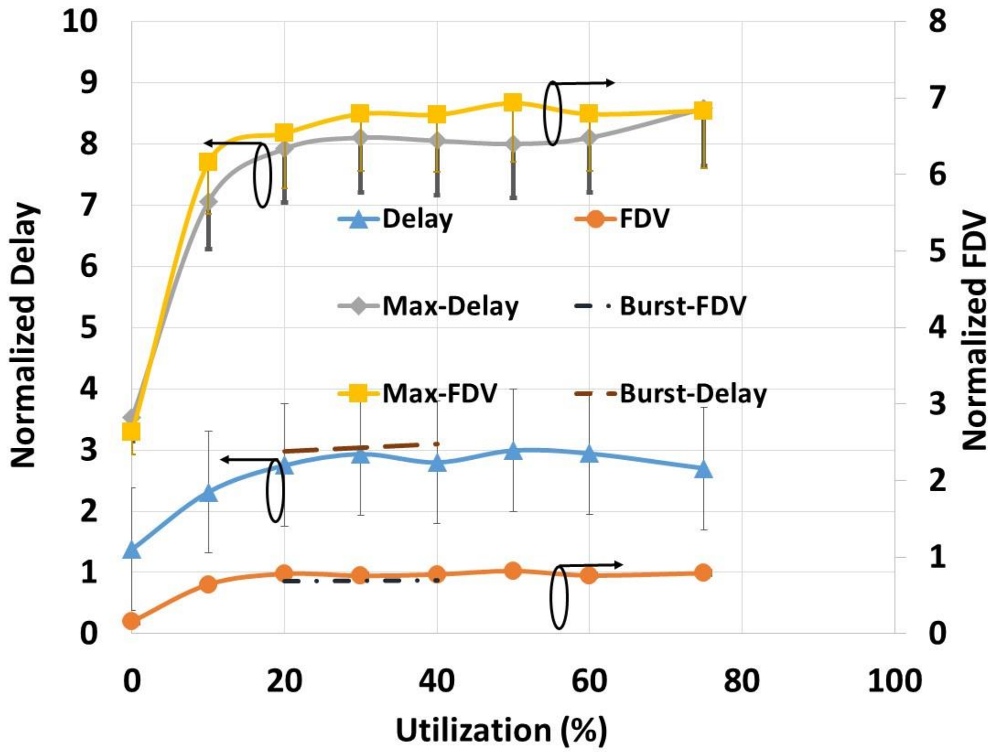

Fig. 5. UPS traffic delay and FDV for different background traffic data rates (scenario B). Special case of delay and FDV with bursty background traffic is presented.

C. Mixed Traffic

This scenario is used to show the effects that the group of five background traffic streams, IQ-type traffic and UPS traffic have on each other due to contention in the Ethernet fronthaul. Table II shows the data rates and the frame size for each traffic type in this scenario. These data rates are selected to represent an obvious contention case with average utilization of 40%, in the middle of the range shown previously in Fig.5.

The results in Fig. 6 show the effect of contention on the delay and FDV of the UPS and IQ-type traffic. Compared to the baseline, scenario A results of Fig. 4, the delay has increased by 8% on average for IQ-type traffic and by approximately 98% for the UPS traffic due to contention in the trunk port. The FDV is increased by approximately five times for the UPS traffic. The increase in delay of the UPS is equivalent to the serialization of less than two background or IQ-type traffic frames, while the increase in IQ-type traffic delay is equivalent to the serialization of less than one background or IQ-type traffic frame. The increase in the delay and FDV of the UPS traffic is higher than the increase with IQ-type traffic since the UPS traffic contends with high rate IQ and background traffic generated by a number of sources (one IQ source and five background traffic sources). In addition, the IQ-type traffic and background traffic frame sizes are four times that of the UPS (on average). The UPS delay and FDV are less than the serialization delay of six frames (there are five background traffic servers and one IQ server), which is the maximum possible delay and FDV for worst-case contention. The increase in the delay is significant for both traffic types but it is not significant enough to violate IQ-type and UPS traffic delay requirements. The increase in FDV is high enough to be considered a problem for the transmission of both traffic types since it violates FDV requirements with any link (>0.017 for UPS and >0.002 for CPRI).

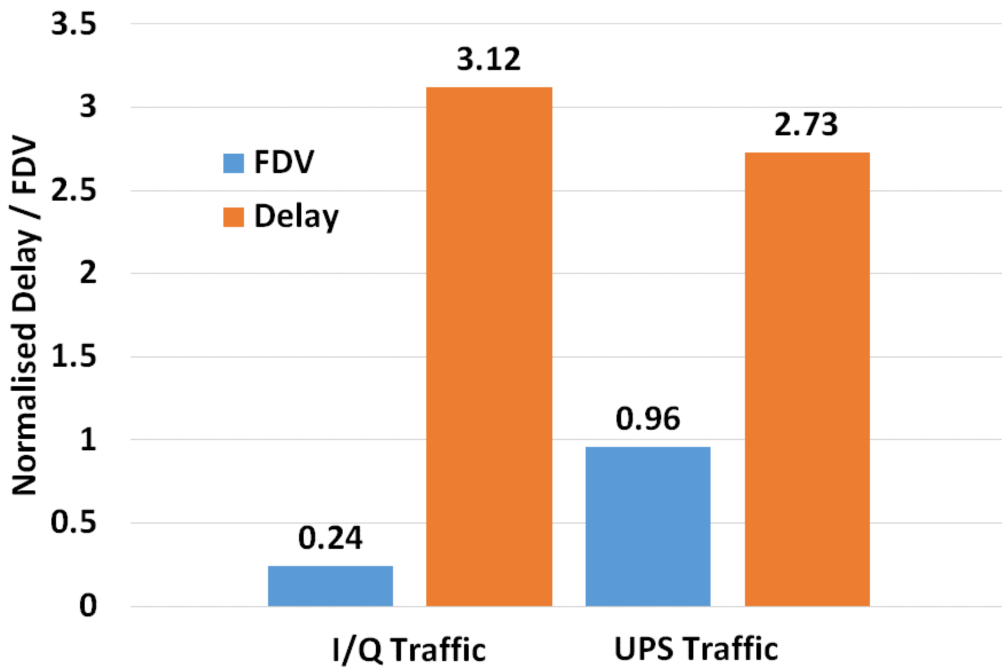

Fig. 6. UPS & I/Q traffic delay and FDV with the existence of background traffic (scenario C).

TABLE II
TRAFFIC SOURCE SETTINGS FOR SCENARIO C

Traffic Type	Average Data Rate (%)	Average Frame Size (Bytes)
UPS	16	276
Background	Dist (10,30)	1000 (fixed)
I/Q-type traffic	20	1000 (fixed)

IV. Time-Aware Shaper In The Ethernet Fronthaul

TAS divides the transmission time into sequential transmission windows (TWs) and each TW into sections and subsections [17]. The Protected Section (PS) is reserved for high priority streams while the Best Effort Section (BES) is used for lower priority streams. A Guard Period (GP) is inserted to prevent lower priority, best effort frames from overrunning into the PS. Traffic generated outside its allocated section must be queued and transmitted in the next TW.

The implementation of TAS in models of Ethernet switches and transmission servers was described in [27]. The locations in the network where TAS takes effect are shown in Fig. 3. Note that the TAS implementation includes transmitter-side buffering to align the transmission from the different end-stations with the port-gating in the switch module. To show the use, effectiveness and limitations of TAS at the different contention cases in the Ethernet fronthaul, the following scenarios are implemented.

A. UPS and Uniformly Distributed Background Traffic

In this case, as shown in Fig. 7.A, the UPS traffic is allocated 30% of the TW and the background traffic is allocated 62% of the TW (1 ms). The UPS traffic allocation allows it to be mostly transmitted within the window (the traffic is still transmitted according to the air interface timing, i.e., has variable transmission time and rate, but the window is aligned in this case to accommodate most of it). In this and the following scenarios, the GP is allocated 8% in order to: (i)prevent any 1000 byte frames in the best effort section from overrunning into the protected section; and (ii) accommodate low rate and high priority traffic such as PTP and control primitives for transmission without any contention (as stated in §II.A, such traffic is considered, but not modelled here). The results with this window assignment show that although TAS removes the FDV of the UPS traffic for a percentage of the frames (the frames that are transmitted immediately during the 300 µs PS), some frames arrive after the PS and are queued for transmission in the PS of the next TW. This queuing issue will be discussed in more detail in the following subsections. The queuing until the next TW would not take place if the DU generated all physical channel data (for a subframe) at a particular point in time of the subframe (instead of following air interface timings) and the allocated TAS window section aligned with the transmitted traffic. For the frames that are transmitted immediately through the PS of the same TW that they arrive in, the average delay with the different background traffic rates (same rates as in scenario B-Section III) is 11.3 μs while the FDV is 1.82 μs. These values are similar (given small statistical variations) to those obtained for scenario A in Section III and will be used as the baseline case for comparison in the following subsections.

B. Mixed Traffic

In this scenario, UPS, IQ-type and background traffic are transmitted over the Ethernet fronthaul network (with the same rates as in scenario C of Section III). Two section allocation cases are presented. The first case is shown in Fig. 7.B where UPS and I/Q-type traffic are each allocated 30% of the TW, the GP is allocated 8% and background traffic is allocated the remaining part of the TW (32%). IQ-type traffic is allocated this window size in order accommodate the burst of thirty frames of the IQ-type traffic within the LTE subframe duration. UPS is allocated 30% of the TW considering the transmission characteristics of the UPS traffic (transmitted based on the air interface timings). A second case is presented in Fig. 7.C where the UPS traffic is allocated 60% of the transmission time, IQ traffic is allocated 30%, the GP is allocated 8% but the background traffic is allocated only 2%.

Fig. 8 shows the delay and FDV of the UPS and I/Q traffic for the two different allocation cases. For the first case, the average delay and FDV of the UPS traffic is significantly increased in comparison to the baseline, since a percentage of frames (<17%) are generated outside the allocated section and are therefore queued for transmission to the next TW. The average delay of the UPS traffic is approximately eight times that of its baseline delay. Note that IQ traffic, although at a much higher data rate compared to the UPS traffic, is transmitted in a burst which allows it to fit within the allocated section, and no frames are delayed to the next TW.

The second allocation case is aimed at resolving the issue of UPS frames being queued for transmission to the next TW. Thus, UPS traffic is allocated a larger time section to allow more UPS traffic-carrying frames to be transmitted within the allocated window reducing the percentage of frames queued to the next TW. Now the delay and FDV of UPS traffic are close to their baseline values. While this solution achieves FDV and delay close to the baseline values for the UPS traffic, using such a large window section is not an efficient use of available network capacity (In this case, there is only 3.3% utilization of the UPS window which as a result leads to inefficient use of the available link capacity (more than 50% of the link capacity is not used in this case). In addition, only a small percentage of the background traffic can be transmitted in this case. Note that this will be an issue irrespective of the link rate employed.

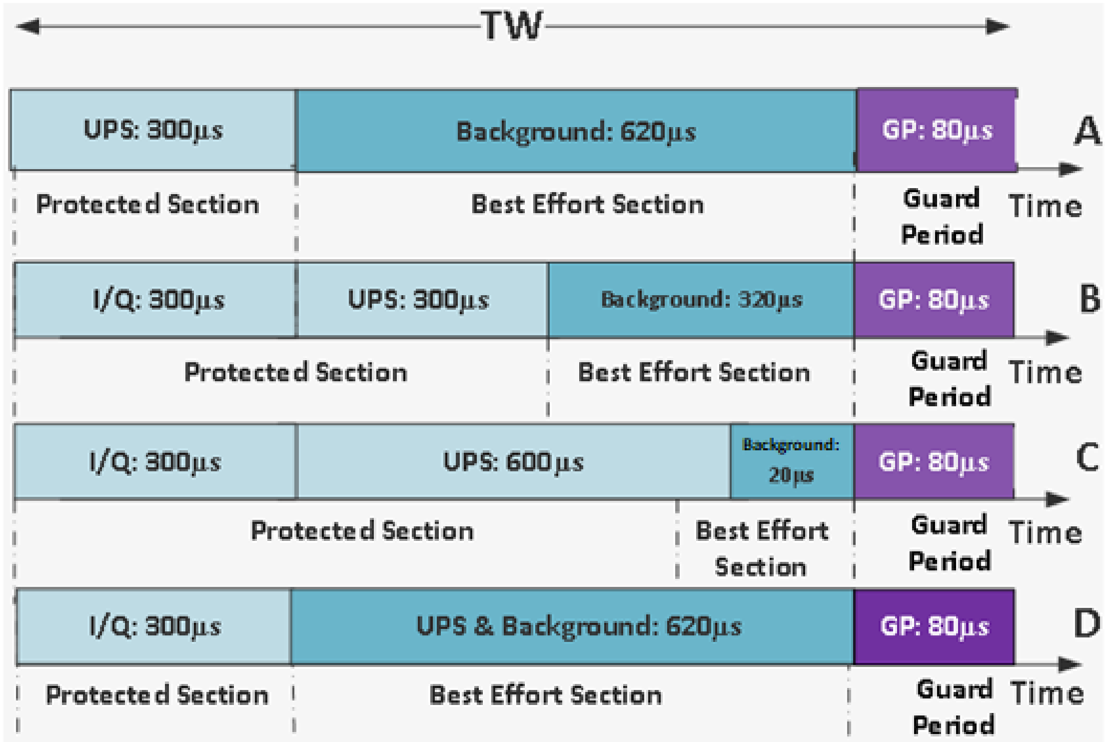

Fig. 7. TAS section allocations in: (A) UPS and background traffic scenario; (B) Mixed traffic scenario (case 1); (C) Mixed traffic scenario (case 2); (D) Mixed traffic scenario (case 3).

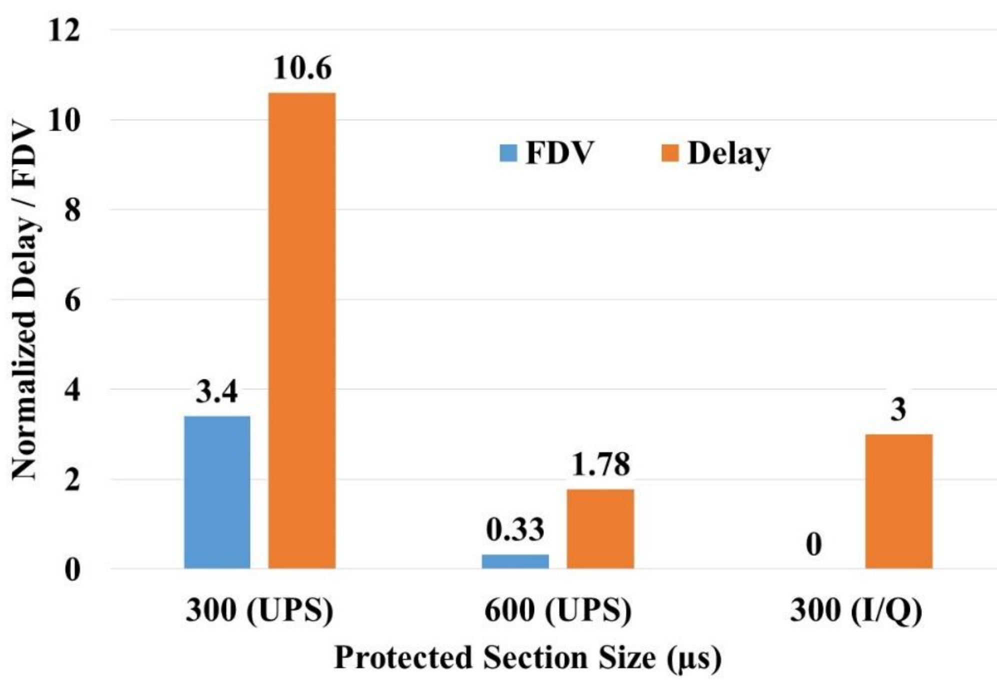

Fig. 8. Frame delay and FDV of I/Q-type and UPS traffic with TAS, for different window section allocations for the UPS traffic (300 µs and 600 µs) (scenario B).

C. Mixed Traffic with Alternative Time Section Allocation

To avoid allocating a larger time section for the UPS traffic with inefficient use for the available bandwidth and to solve the delay problem that has been discussed in section IV.B, in this scenario, the UPS traffic is moved to the BES, alongside the background traffic over a longer section window, as shown in Fig. 7.D. In this case, the UPS traffic uses 3% of the window capacity, which is equivalent to only just over 2% of the link capacity.

Fig. 9 shows the delay and FDV with different background traffic data rates corresponding to different utilizations of the BES. The results show that contention results in an FDV for the UPS traffic that violates the mentioned specifications in Table II , for all background traffic rates, while the delay remains within an acceptable level. The bursty traffic parameters used here are similar to those used for the bursty results in Fig. 5, to allow a direct comparison, however, the burst is created as a result of the TAS buffering (which allows transmission only during the allocated time section). As was also shown in Fig. 5, the effect of bursty background traffic on the UPS traffic is similar to that of non-bursty traffic. The increase in the average delay with 64% utilization (note that now this corresponds to the utilization of the TW section and not of the link rate, as was the case for the results of Fig. 5) is less than the serialization of two background traffic frames, whilst the increase in the average FDV is less than the serialization of one background traffic frame.

D. Buffering in the Ethernet Fronthaul

In order to receive the traffic at the end stations with FDV within the requirements given in Table I, a buffering mechanism can be applied at the end node (RRU). This requires such a node to play out the content of buffered frames according to air interface timings. To this end, the buffer, in addition to the buffering in TAS that used to buffer the traffic that received outside the allocated time window, needs to be designed so that contention-induced FDV is “absorbed”. Such an implementation requires accurate time information, for example, provided through the Timing and Synchronization standard (802.1 AS standard)) and frame time-stamps for use by the buffer play-out, such as those included in the RoE specification [27].

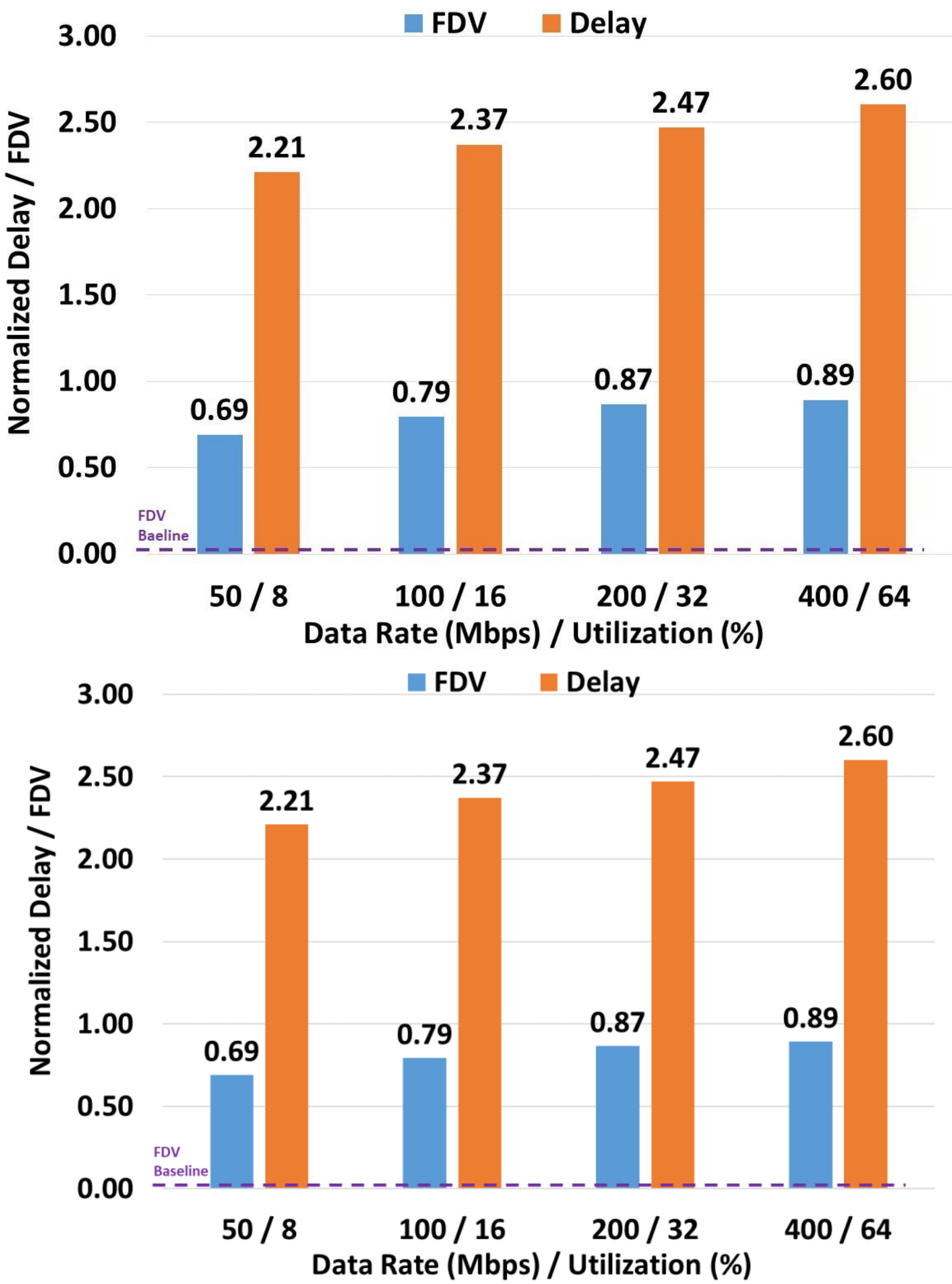

Fig. 9. Frame delay and FDV of UPS traffic with TAS when UPS is allocated to the BES for different background traffic data rates (scenario C). The traffic percentage corresponds to different utilizations of the BES window.

The size of the buffer *Bs* to absorb the FDV, is given as

$$B_s = B_D R_r, \quad (2)$$

where R_r is the link rate and the buffering delay B_D is given as

$$B_D = 2\ \sigma_f, \quad (3)$$

where σ_f is the FDV.

The factor of two in (3) is due to the fact that in dimensioning the buffer, the delay variations of the first and last frame of the UPS traffic are being considered. This approach is sensible provided that frames are received in-order in the RRU.

The overall average delay D_T, in the network can be given as

$$D_T = B_D + \overline{D}, \tag{4}$$

where $\overline{D}$ is the average delay in the network without buffering.

In Fig. 10.A, the Cumulative Distribution Function (CDF) of the UPS FDV is plotted for scenario C. In addition, the FDV of the baseline in scenario A is also plotted in Fig. 10.A for comparison. In scenario C, the maximum FDV with 32% utilization was 43 µs for a link rate of 1 Gbps. The buffer size required to absorb this maximum FDV is 86000 bits while the resulting end-to-end delay is 100.4 µs. This delay violates the delay specification of the UPS (i.e., it is larger than 75 µs). In order for the end-to-end delay to be less than the delay specification, the buffer can be designed so that it only absorbs a percentage of the FDV. However, this implies that a percentage of UPS traffic-carrying Ethernet frames will be dropped for the current radio subframe.

Fig.10.B shows a section (zoomed-in and annotated) of Fig.10. A. By using 97.4% of the UPS FDV's CDF, the buffer size at the receiver is reduced to a size of 48000 bits, resulting in an end-to-end delay smaller than 75 µs, for 32% utilization. For the case of 64% utilization, however, the increased contention causes a higher average delay and maximum FDV for the UPS frames, and reduces the ability to absorb the FDV of the UPS traffic to meet the delay specification. With 64% utilization, only 96% of frames can be received within the requirement. On the other hand, with 16% and 8% utilization, 98% and 99% of frames can be received within the proposed requirements, respectively.

Note that a significant percentage of the measured FDV is due to the baseline FDV variations. This is a result of the size variability of the transported frames, itself a result of variability in the traffic generation characteristics of the UPS-exposed control and user-plane traffic flows. The Ethernet mapping in this implementation is "overhead-optimized" and does not pad Ethernet frames to a fixed length. Padding would reduce (or eliminate) the baseline FDV but would lead to a reduction in achievable statistical multiplexing gains and an overall reduced efficiency in available capacity utilization.

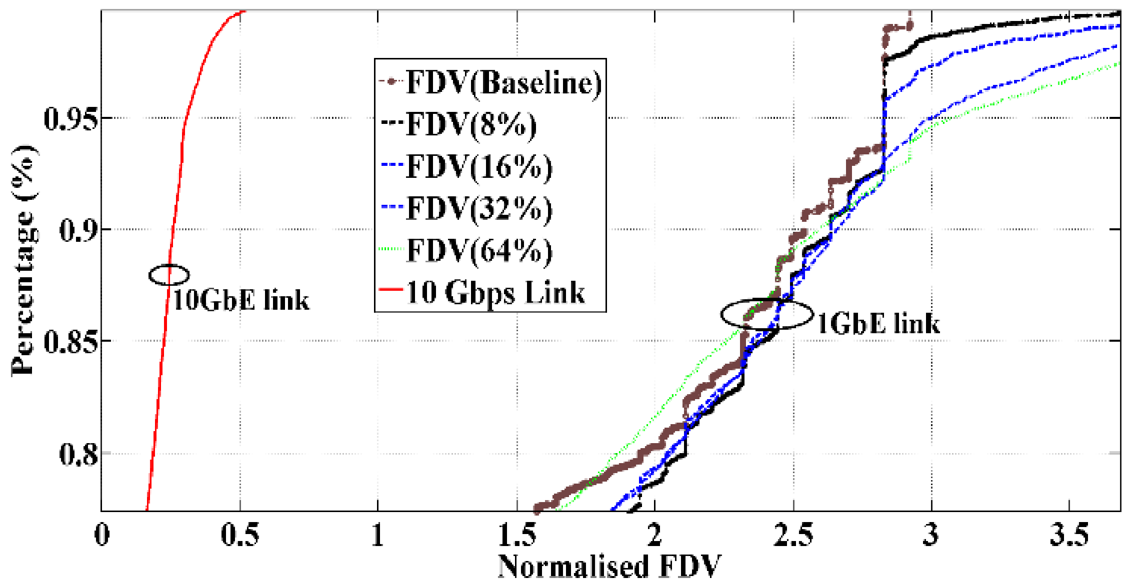

Fig. 10.A. CDF of the UPS FDV for different link utilizations.

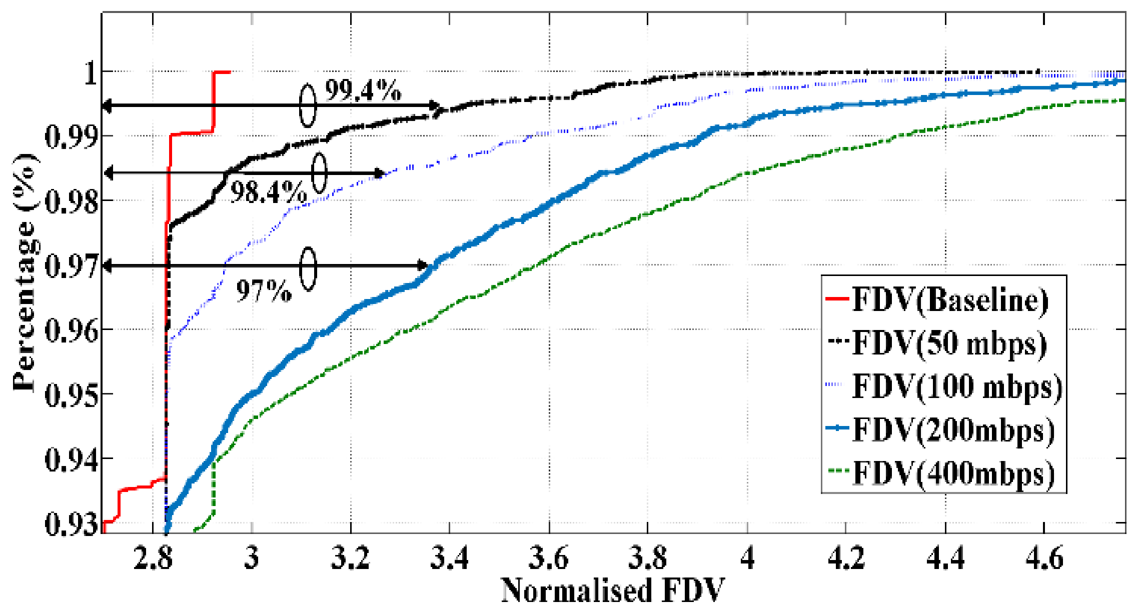

Fig. 10.B. Zoomed UPS FDV's CDF result.

Table III shows the achievable performance with 64% utilization considering different GbE technology link rates and fiber spans. The previous results up to this point have only considered short fiber spans of 200m length. With fiber link lengths less than 5 km, the percentage of frames that can be received within the requirements will be higher than 96%. With 14 km fiber links, only 60% of the traffic is received within the specification. However, with 10 Gbps links, 100% of traffic can be received within the specifications with a maximum 14 km fiber link length. The extrapolated CDF of the FDV for the UPS traffic with 64% utilization and 10 Gbps network link rate is plotted for comparison in Fig. 9.A. This result shows how important reduced serialization delays are with overhead-optimized mapping techniques such as that employed in this work.

While the previous results show the UPS delay and FDV with TAS over two hops (hops in the Ethernet fronthaul represent the number of switching units in the fronthaul network), it is important to investigate the UPS delay and FDV with TAS when the network consists of different numbers of hops. The Ethernet fronthaul network according to [33] might consist of up to five hops as shown in Fig.11. To investigate this case, the UPS FDV in the two hops case has been used to generate results for the multi-hop (five hops) scenario, by running a number of simulations with different seeds numbers. The FDV values of the UPS frames are randomly selected from the differently seeded runs and then shuffled with different seeds numbers for three times in order to generate three more FDV values for each frame. The behavior of the results has been verified with different seed numbers and the results showed a statistical reliability.

As a result of this method, the four contention points in the presented scenario in Fig.11 have the same contention profile of the previous two hops case (one contention point).

Note that, the presented five hops scenario results and discussion can scale and apply to any hops number of interests.

The results in Table IV show that using multiple hops and long link lengths causes a significant degradation in the delay and FDV performance of the UPS traffic. With 5 hops and 13 km fronthaul, less than 80% of the traffic can be transmitted according to the delay and FDV specifications, while with 5 hops and 7 km fronthaul, 100% of the UPS traffic can be transmitted within the delay and FDV specifications.

With a multiple hops scenario, the network complexity in terms of the time section allocation and queuing management can increase significantly. In such a case, an SDN controller and/or Global Scheduler (GS) could adjust allocated time windows for each traffic flow and control the transmitter- and/or receiver-based queuing to manage the delay and FDV experienced by each flow.

TABLE III

PERCENTAGE OF TRAFFIC FRAMES RECEIVED WITHIN SPECIFICATIONS FOR DIFFERENT ETHERNET LINK LENGTHS AND LINK RATES (1 GBPS & 10 GBPS) FOR 64% UTILIZATION.

Link Length (km)	Traffic Percentage With 1 Gbps	Traffic Percentage With 10 Gbps
0	97%	100%
0.2	96%	100%
1	95%	100%
5	93%	100%
14	60%	100%

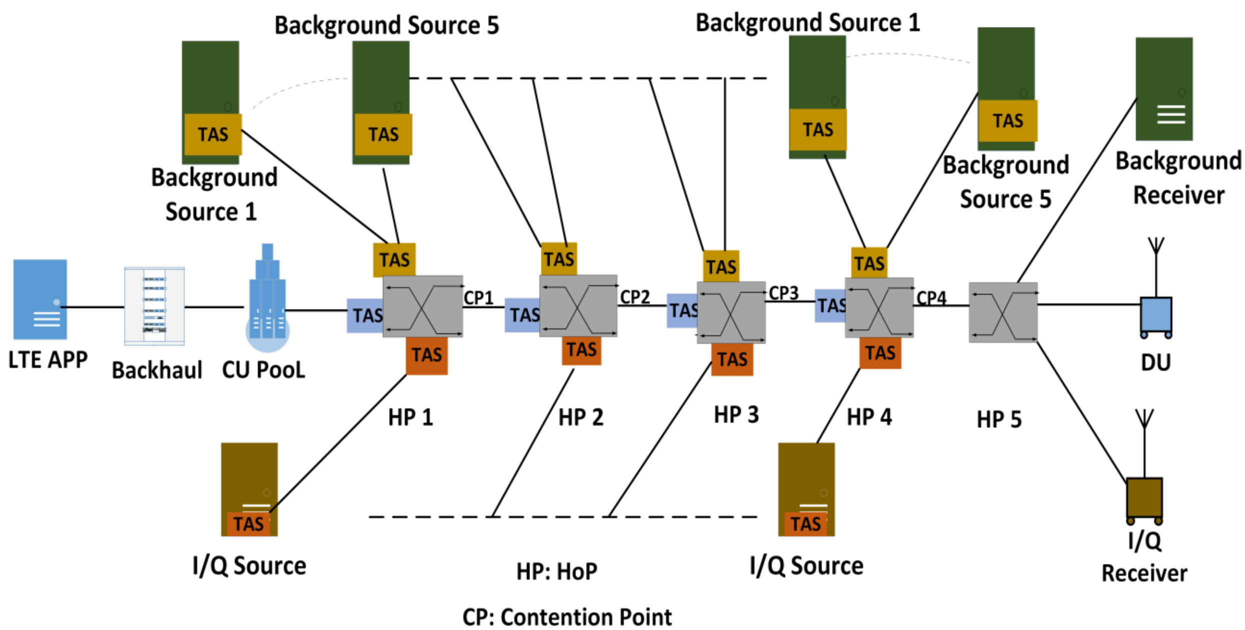

Fig.11. Ethernet fronthaul with TAS and five hops.

TABLE IV

PERCENTAGE TRAFFIC WITHIN SPECIFICATIONS WITH DIFFERENT ETHERNET LINKS LENGTHS (13, 10 &7 KM) AND NUMBER OF HOPS FOR 64% UTILIZATION. LINK RATE IS 10 GBPS.

Link Length (km)	No of Contention points (no)	No of Hops (no)	Traffic Percentage With 10 Gbps (%)
13	1	2	100%
	2	3	99%
	3	4	83.5%
	4	5	76.3%
10	1	2	100%
	2	3	100%
	3	4	99%
	4	5	97%
7	1	2	100%
	2	3	100%
	3	4	100%
	4	5	100%

V. Conclusion

A simulation model, implemented in Riverbed Modeler, for a DU-RRU UPS and an Ethernet fronthaul with mixed traffic and scheduling based on TAS has been presented. This is the first UPS functional split model with TAS and Ethernet fronthaul with mixed traffic types implemented in a standard simulation package for any LLS or HLS. Contention in the Ethernet fronthaul is shown to lead to the violation of the FDV specifications of UPS and I/Q-type traffic. In addition to contention-induced FDV, an overhead-optimized mapping approach, while leading to potentially higher statistical multiplexing gains, results in a finite (non-zero) baseline FDV, a result of variability in the traffic generation characteristics of the UPS traffic

TAS can remove the FDV for both traffic types when they are allocated to the PS. However, variability in the UPS traffic generation timings can cause frames to arrive outside their TAS time section and be buffered for transmission to the next TW, violating delay specifications or requiring a large PS with inefficient use of the available time section capacity. This issue will persist even if higher link rates are employed in the network. The problem can be solved by either changing the traffic generation characteristic of the UPS traffic to a bursty one, for example, by requiring a DU to generate all physical channel data (for a subframe) at a particular point in time of the subframe (instead of following air interface timings), or by allocating the UPS traffic to a longer BES. The former will require an implementation of the radio access network protocols with increased complexity, while the latter can mitigate the delay problem, but causes an increase in FDV due to contention with other traffic in the BES. Buffering is proposed at the receiver side to "absorb" the contention-induced FDV in such cases. The buffer should be designed carefully so as not to violate the end-to-end delay requirements of the UPS while guaranteeing that most frames are received within FDV and delay specifications.

In future work, the allocation of parts of the UPS traffic, such as control traffic, to the protected section while other parts such as the data traffic, are transmitted in the best effort (shared) section can be investigated

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