

Tradeoffs in optical packet and circuit transport of fronthaul traffic: the time for SBVT ?

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Abstract— This paper provides a short overview of 5G fronthaul transport and analyses the opportunity of using a new generation of SBVT (Sliceable Bandwidth Variable Transceivers), for this purpose.

Keywords—fronthaul, C-RAN, sliceable bandwidth variable transceiver (SBVT), xhaul

I. INTRODUCTION

After over a 10-year period of intense research and standardisation effort in the design of fronthaul traffic transport [1], a number of tradeoffs, advantages and limitations of the studied technologies have been identified. The transport of narrow bandwidth channels has been proven to be viable in LTE-A [2], but the more challenging 5G new radio requirements seem very hard to meet with standard packet-based approaches. In this paper, we revise such requirements (section II). Then we describe the limitations and try to quantify the problems that Ethernet-based networks need to solve to cope with the transport of this traffic in section III. As opposed to the worst-case delay design proposed by the IEEE802.1CM standard, we review the use of very high packet delay percentiles for extreme cases, where the link length needs to be extended at the cost of an acceptable frame loss ratio. Even with this latency engineering schemes the disadvantages of packet switching remain. A discussion on the impact of the receiver buffer required to emulate a circuit and assemble the OFDM symbols reveals additional relevant latency penalties of fronthaul packet switching that delays radio processing. All this seems to suggest that the research on cost-efficient optical circuit-based technologies may still yield an advantageous option over the packet ones. To analyse this possibility, in section IV we compare different circuit and packet switching technologies and study the opportunity of adopting SBVT (Sliceable Bandwidth Variable Transceivers) in the context of increasing data rates, low latency and jitter requirements as demanded by 5G.

II. C-RAN TRAFFIC

Cloud Radio Access Network (C-RAN) introduces the idea of cloud processing of radio signals, as one step beyond Distributed RAN [1]. In Distributed RAN the radio processing functions are split and distributed in two or three locations across the network. RF signals received by Remote Radio Heads (RRHs) or Remote Units (RU) are downconverted, digitalised and transported to a pool of remote Baseband Units (BBUs) or

Distributed Unit/Central Unit (DU) over the fronthaul (FH) network. Conversely, the DU must synthesize the baseband signal to be upconverted and radiated by the antennas; this signal is transmitted over the fronthaul network to the RU.

This approach distributes the functionality of the base station and the actual remote radio head in the field becomes simpler. Furthermore, it enables signal processor sharing by the massive deployment of antennas expected for 5G and beyond. Figure 1 shows the main splits considered by 3GPP and the usual distribution of functionalities among RU, DU and CU (Central Unit).

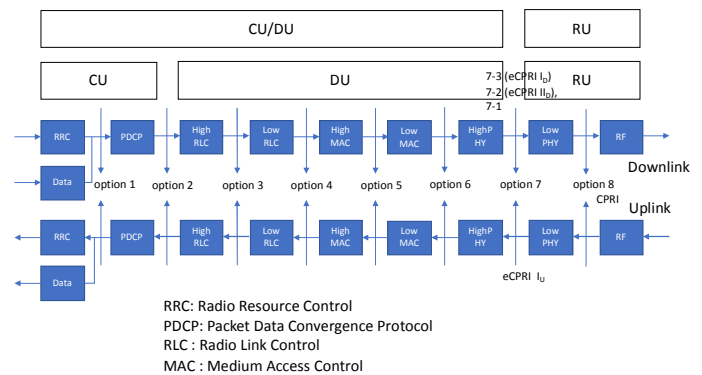


Fig. 1. 3GPP TR38.801 options for functional splits of radio processing

This approach has been used in some LTE-A deployments, where fiber is available for 20MHz channels, but the transport of fronthaul has become much more challenging for 5G new radio. In December 2017, 3GPP published TS38.1047 Release 15 as the specification of the New Radio air interface for 5G. This Technical Specification defined two frequency ranges: FR1 (under 6 GHz) with component bandwidths ranging 5-100 MHz and sub-carrier spacings 15/30/60 KHz; and FR2 (24-86 GHz) with component bandwidths ranging 50-400 MHz, and sub-carrier spacings 60/120 KHz. In addition, 8 possible functional split options were further defined in TR38.801 as depicted in Figure 1. This generates a wide range of fronthaul traffic patterns. However the most relevant split options are Option 2 (F1 interface that processes up to RLC (Radio Link Control) layer) and Option 7 (intra-PHY, being option 7-2 equivalent to eCPRI split $I_0=II_D$). Option 8 corresponds to the CPRI (Common Packet Radio Interface [2]) interface (designed for

direct optical fiber connection between a Radio Element and the Radio Element Controller), which generates a load-independent CBR (Constant Bit Rate) traffic pattern. The pattern is a deterministic periodic sequence of OFDM symbols of duration T_s . In this paper, we focus on fronthaul transport (low-layer splits) given the interest in maximising the utilisation radio processing resources.

A more efficient implementation than option 8 is achieved with split option 7, where the Low PHY box performs the removal of the cyclic prefix, FFT and Resource Block de-mapping in the uplink (split I_U in eCPRI), and modulation, layer mapping and precoding in the downlink (split II_D in eCPRI). This leads to a traffic volume that is proportional to the user traffic in the cell. However, for a stable utilisation η the traffic can be assumed to produce a deterministic fronthaul pattern given by:

$$R_{\text{Split } I_U} = N_{sc} \cdot U_{sc} \cdot \eta \cdot T_s^{-1} \cdot 2 \cdot N_{\text{bits}} \cdot N_{\text{ant}} \quad (1)$$

Where N_{sc} is the number of subcarriers, U_{sc} is the percentage of usable subcarriers (not used as guard bands), η the utilisation, N_{bits} is the amount of bits per samples and N_{ant} the number of active MIMO layers matches the number of antennas of the gNB. Table I provides sample rate and burst sizes for split I_U traffic with 5G New Radio numerology assuming $\eta=100\%$ utilisation, usable subcarriers $U_{sc}=95\%$, $N_{\text{bits}}=15$ bits/sample.

TABLE I. RATE AND BURST SIZE FOR SPLIT I_U TRAFFIC WITH 5G NEW RADIO NUMEROLOGY FOR 100% UTILIZATION

B [MHz]	Δf [KHz]	#SCs	T_s [μ s]	#Antennas	R [Gbps] per RF Channel	Burst Size (bytes)
20	15	1267	66.7	2	1.14	9503
50	15	3167	66.7	2	2.85	23753
100	60	1584	16.7	32	91.24	190080
100	60	1584	16.7	256	729.91	1520640
200	120	1584	8.3	32	182.48	190080
200	120	1584	8.3	256	1459.81	1520640
400	120	3167	8.3	32	364.84	380040
400	120	3167	8.3	256	2918.71	3040320

This means very high rates for the numerology of 5G new radio. As it can be seen the impact mm-wave (broader radio channels) and the use of massive MIMO as the way to circumvent the challenge of using high frequencies, has a multiplicative effect that may lead to rates of up to 3 Tb/s. The burst sizes, if we consider its transport over packet switching technologies, are challenging too. As described, the Evolved Universal Terrestrial Radio Access (E-UTRA) specifications 3GPP TS 36.211 and the New Radio (NR) access technology for 5G 3GPP TS 38.211 make use of Orthogonal Frequency Division Multiplexing (OFDM). The specifications define the time intervals for data transmission based on the OFDM symbol time, which is the smallest E-UTRA or NR frame with a meaning. This frame becomes a large burst of data (as big as 3MB according to our table for 400MHz and 256 antenna elements) to be transmitted over a burst of packets.

The transport of new radio traffic to be processed deep into the MAN (in order to achieve high degree of sharing of radio processors) is further complicated by the real time and synchronisation requirements of this traffic. On the one hand, there is a 100μ s deadline to deliver signals for MAC processing, set by IEEE 802.1CM and eCPRI, which is due to the HARQ timers of the retransmission scheme of LTE and 5G. On the other hand, the evolution of the air interface requires processing coming not just from one centralised MIMO antenna array, but the combination of signals from antennas scattered over a large area. The following figures try to illustrate this evolution. Fig. 2 shows a C-RAN deployment for 5G. The processing at the DU may imply the synchronisation of one or two flows, if CoMP-JT (coordinated multipoint with joint transmission) [3] is used to deal with inter-cell interference and increase transmission capacity.

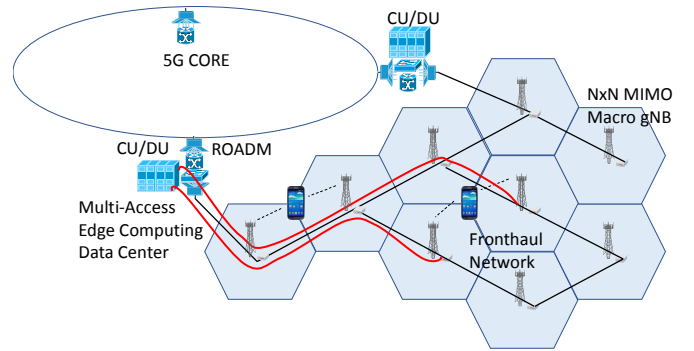


Fig. 2. Macro-cell based fronthaul network

If the densification process follows the small cell approach, the needs for synchronising flows is similar, but more frequent, understanding that the user equipment (UE) may attach to a macro gNB and a couple of small cells within, in order to perform soft handovers between them (Fig.3).

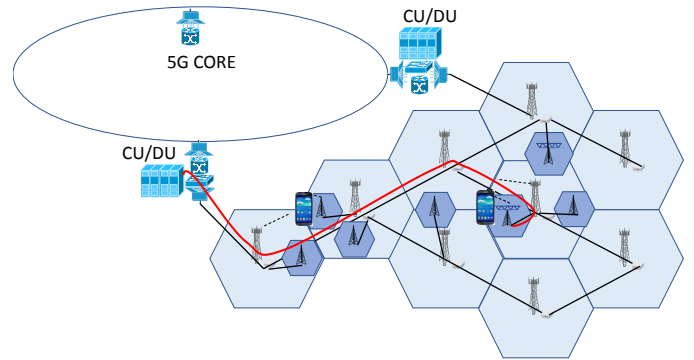


Fig. 3. Small-cell-based fronthaul network densification

However, the evolution beyond 5G to a cell free user-centric approach makes the synchronisation and processing challenge a matter of future research. In this case, the notion of cell disappears and the UE signal is received and processed by $N \gg 2$ antenna elements to perform distributed MIMO (Fig. 4). Moreover, it should be noted that those fronthaul flows may need to be transported from antennas attached to very distant access networks from one another.

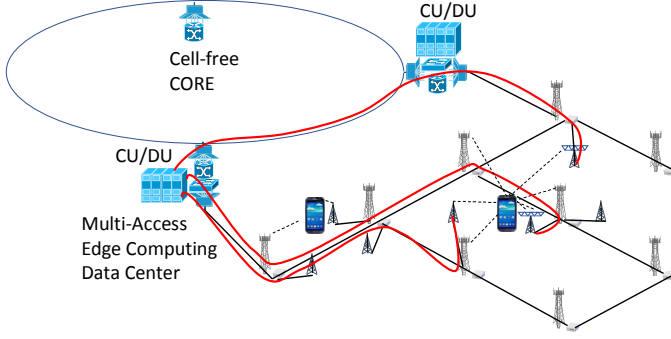


Fig. 4. Beyond-5G cell-free fronthaul network fixed network path diversity

III. PACKET-BASED C-RAN TRAFFIC TRANSPORT

Despite the large bitrates and real-time requirements implied by the full development of 5G and beyond, a lot of research and standardisation effort has been set on the transport of fronthaul traffic over packet-switched networks. The interest on a cost-effective technology for fronthaul transmission and multiplexing has led to the development of eCPRI [4] and IEEE802.1CM [5]. This latter standard published in 2018 includes important recommendations for Ethernet-based fronthaul transport. The standard itself includes specific QoS target parameters like the end-to-end latency budgets and the maximum Frame Loss Ratio (FLR) for each type of fronthaul traffic. The most urgent traffic class is called HPF (High Priority Fronthaul) and has a 100 μ sec ingress-switch-to-egress-switch budget for HPF frames, and a maximum FLR of 10^{-7} . In successive amendments under study (802.1CMde) three target latency classes are under consideration: 100, 200 and 300 μ sec for high priority user data, which seem to provide more budget for the network transport, as suggested in 3GPP TR 38.801 V14.0.0 (2017-03).

IEEE802.1CM also suggests four time/frequency distribution schemes based on SyncE and Precision Time Protocol (PTP) to fulfill the time synchronization requirements of the Categories listed by [6] to implement 3GPP features as summarised in table II.

TABLE II. 3GPP TIMING ACCURACY CATEGORIES IDENTIFIED BY eCPRI

Category	Time Error at UNI (when Time Slave Clock is not integrated in eRE)	Typical Application	Time Alignment error at antenna port of RRH
A+	20 ns	MIMO or transmission diversity at each frequency	65 ns
A	70 ns	Intra-band contiguous carrier aggregation,	130 ns
B	200 ns	Intra-band non-contiguous carrier aggregation	260 ns
C	1100 ns	3GPP LTE TDD	3000 ns

Given that existing timed-gate approaches for Time Sensitive Networking could not guarantee such tight end-to-end latency budgets the approach proposed by 802.1CM to deal with latency in Ethernet networks is to allocate maximum priority to HPF traffic and use worst-case latency calculation of frames. The main target was to let network designers compute the available distance DU-RU. However, that worst-case calculation can be very high and constrain the practical reach of a network setting. The use of split I_U and the reduction of the symbol period derived by the longer sub-carrier spacings (60 and 120 KHz) of 5G new radio numerology has alleviated the burstiness of fronthaul sources to a great extent, but the maximum queuing times are still relatively high. For instance, the aggregation of 4 fronthaul flows for 100MHz channel (3rd entry in table I) with 400G Ethernet switches causes a maximum queuing delay of 15 μ s. This means an additional de-jitter buffer of 15 μ s on reception to guarantee a continuous flow of OFDM symbols. The use of a jitter-less technology would provide six additional Km of reach which is significant for many deployments.

In [7] we proposed an scheme to use very high delay percentiles instead of the theoretical maximum for network design, in contexts where enhancing the reach is important, under the assumption that most FLR can be assumed to be due to frames arriving after their deadlines (the percentile).

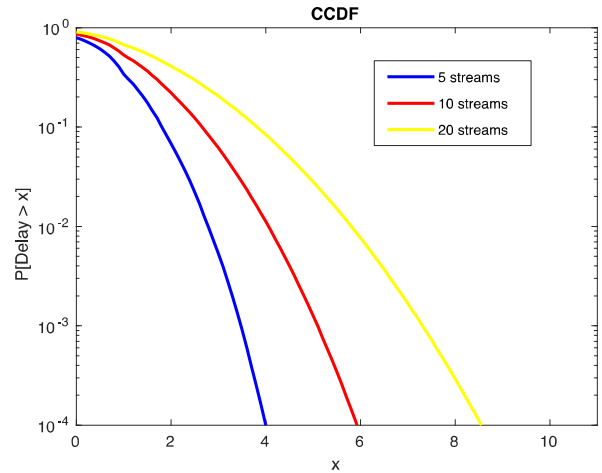


Fig. 5. Complementary Cumulative Distribution Function (CCDF) for the latency of frames from n deterministic fronthaul flows made up of back-to-back frame bursts

However, despite the fact that under static conditions the traffic sources can be considered D/D/1, the only accurate available tool to model nD/D/1 is [8], and no multi-hop traffic model exists in the state of the art. The impact of adding multiple D/D/1 sources on latency is very relevant as Fig. 5 shows. The figure shows the CCDF of the queuing latency of frames in a generic scenario where deterministic flows are merged on a single aggregator. Assuming a random alignment of the flows ranging from 0 to T and normalizing the problem parameters so that T=1, the plotted curves are obtained. With 5 fronthaul streams, the probability of a frame waiting in queue longer than 4 time units is 10^{-4} , whereas that probability is 0.9 for 20 streams.

Trying this concept with different parameters we can check how much distance can be gained for using the 99.9999999 percentile rather than the maximum. This can be as large as 6Km at high loads for a 50MHz system on 100Gb/s links (Fig.6), but the gain is reduced as the channel bandwidth grows and symbol period is reduced according to table II (Fig.7).

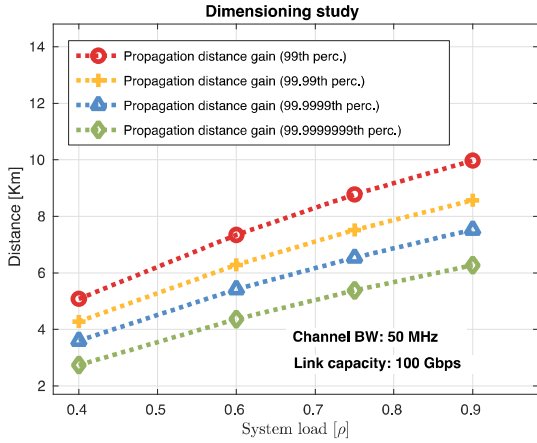


Fig. 6. Distance gain for using a high percentile latency limit rather than the maximum in a 50MHz/100Gb/s one-hop fronthaul system

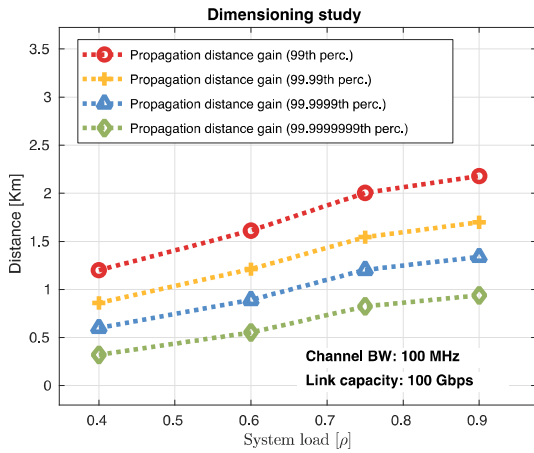


Fig. 7. Distance gain for using a high percentile latency limit rather than the maximum in a 100MHz/100Gb/s one-hop fronthaul system

IV. CIRCUIT VS PACKET TRANSPORT TRADE-OFFS

The previous section has shown the technical penalty implied by packet-switched transport of fronthaul traffic. Even if packet switching is not optimal from the latency, jitter and synchronisation perspective, there are a number of advantages of this approach, being cost the most relevant one. A number of standard alternatives have been studied in the past, including access technologies like PON (Passive Optical Networks) and transport technologies like OTN (Optical Transport Networks). However, we would like to highlight the potential of a new type of devices being studied for MANs: the SBVTs (Sliceable-Bandwidth Variable Transceivers) [9],[10],[11]. In all cases Ethernet is the technology of choice inside the data center segment (CU/DU), as the only way to distribute the traffic to the pool of baseband processors. The following table tries to outline the trade-offs of several technologies in fronthaul transport.

TABLE III. PACKET AND CIRCUIT TECHNOLOGIES SUITABLE TO BE USED FOR FRONTHAUL TRANSPORT

	Ethernet	SBVTs	OTN	TWDM-PON	WDM-PON
Latency	High	Low	Low	Medium in CBR service	Low
Jitter	High	Low	Low	Low in CBR service	Low
Capacity	Medium 400G	High 2T	Medium 100G	Low 40G	Low 25G
Aggreg./Distrib. of traffic	Electr.	Electr./photonic	Electr./photonic	Electr.	Electr.
Range	IEEE 802.3CN 80Km	80Km	Long haul with 3R reg.	20Km	40Km
MAN wide	yes	yes	yes	no	no
SDN control	Configuration of VLANs	yes	may	configuration	configuration
OAM	standard	Not yet	standard	standard	standard
Energy effic.	Low	High	Low	High	High
Complexity	\$	\$\$	\$\$\$	\$	\$\$
Clock support	SyncE, PTP	May embed	mode	no	May SyncE
Protection	Electr.	Electr./photonic	Electr./photonic	no	no
Rate adaptab.	Limited	Flexible nx50G and finer	Fixed	yes	limited

Optical access technologies are cost-effective solutions but clearly lack capacity to support fronthaul rates, range and protection mechanisms. These facts make them suitable for small cell fronthaul scenarios, where the operation of cells is not critical. In TDMA PON, such as GPON, EPON or 10G-PON (XG-PON), the uplink access latency has an implicit budget of 1ms. EPON has some advantage over GPON to reduce this latency due to its variable framing size. On the other hand, GPON provides the possibility to allocate periodic time slot to services, what makes it possible to use the uplink capacity every 125 μ sec if so configured. Transmission interruptions, such as the 250- μ sec quiet period for ONU activation and ranging is also a handicap for seamless operation that needs to be addressed. TWDM PON, such as NG-PON2, which is actually an overlay of four XG-PON systems at different frequencies, and hence it has the same limitations as TDM PON. Finally, WDM-PON is the most suitable PON technology for fronthaul, given the advantages: it provides a point-to-point dedicated connectivity service for each base station in the PON and a longer reach than splitter-based TDM or TWDM-PON. However, it does not have any embedded protection mechanism either, their capacity is not enough for 5G new radio rates and does not provide MAN wide connectivity.

TDM circuits provided by Optical Transport technologies based on WDM like OTN may use bit-synchronous mapping modes suitable to transport a clock reference, but it is a complex and expensive technology designed for core networks difficult to scale to massive deployments near the access with numerous access and add/drop points. Furthermore, its evolution to support beyond-100G rates is currently under development. Its fast recovery features (both electronic ODU-based and optical channel based) and the possibility to use photonic layer aggregation are positive features that deserve mentioning.

Ethernet and other packet switching technologies like MPLS-TP or IP-MPLS are common approaches expected to support eCPRI. From them, Ethernet standardisation has evolved more quickly as the 802.1CM standard shows and the Terabit Ethernet project has produced mid-range interface specifications for the physical layer that tend to support 40 and 80Km at 400Gb/s (IEEE 802.3cn, November 2019), hence aiming at technology suitable for fronthaul. The objective is competing in the packet switching domain, with the expensive transponders used in WDM and OTN. The adaptability of port rates is limited to the negotiation phase to pre-defined values. This means that the energy efficiency potential is lower than other schemes like SBVT where wavelengths are turned on and off on demand [12].

Finally, in this paper we draw the attention on the suitability of a special type of devices that may become a cost-effective alternative for fronthaul traffic transport [9],[10]. SBVTs enable a modular approach to flexible bandwidth provisioning and specific designs can provide up to 2Tb/s on a single integrated chip (which can be exploited in the edge gNBs); fully exploiting the modularity over the spectrum resource, up to 8Tb/s can be achieved, which can be further enhanced by exploiting the polarization and spatial dimension [10]. SBVTs may be used as a flexible alternative to Ethernet transceivers pluggable to routers and/or Ethernet switches. SBVTs have a number of advantages over fixed Ethernet transceivers like: a) the possibility to configure a flexible rate [12]; b) the capability to set up circuits to many endpoints simultaneously (this makes it possible to distribute traffic to different switches and configure protection schemes with a single transceiver) [12]; c) the potential to work in a bus setting in drop-and-waste configurations (under study); d) the potential to create low jitter circuits as alternative to multi-hop Ethernet packet queuing [13]; e) the capability to support jumbo frames (in Ethernet, the practical frame size is limited to 2000 bytes for backward compatibility) that may match the size of fronthaul OFDM symbol bursts (the jitter induced by segmented transport is extremely relevant); f) the ability to use only the wavelengths necessary to carry the traffic of that end point [12]; g) an SDN-based control plane able to support smart networking suitably configuring the network elements [14] according to the traffic need and finally h) a capacity greater than Ethernet to carry 5G new radio and beyond 5G.

V. CONCLUSIONS

If the pressure to reduce the user-perceived latency in 5G continues with the aim of supporting services such as URLLC (Ultra Reliable Low Latency Communications) the interest in producing cost-efficient optical circuit-based technologies may keep growing. In this paper we compared different circuit and

packet switching technologies and studied the opportunity of adopting SBVT (Sliceable Bandwidth Variable Transceivers) in the context of increasing data rates, low latency and jitter requirements as demanded by 5G. If proper adaptations of this type of devices to the metro-aggregation segment are performed SBVT may become a low latency low jitter cost-effective alternative to Ethernet.

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