

# 5G-PICTURE: A Programmable Multi-tenant 5G Compute-RAN-Transport Infrastructure

Daniel Camps-Mur<sup>1</sup>, Kostas Katsalis<sup>2</sup>, Igor Freire<sup>3</sup>, Jesus Gutierrez<sup>4</sup>, Nikos Makris<sup>5</sup>, Salvatore Pontarelli<sup>6</sup>, and Robert Schmidt<sup>7</sup>

**Abstract**—Flexibility is a key capability to allow future 5G networks to support varying service offerings over a common infrastructure. 5G-PICTURE investigates the design of programmable compute and transport network infrastructures, able to instantiate third-party 5G connectivity services on demand. This paper introduces the 5G-PICTURE vision on an integrated compute, RAN and transport architecture, and describes a set of innovative functions in the RAN, Transport and Synchronization domains that 5G-PICTURE has developed to fulfill its vision. Initial evaluation results are presented for the aforementioned functions.

## I. INTRODUCTION

A definitive characteristic of future 5G networks is the ability to accommodate over the same physical substrate concurrent connectivity services on behalf of multiple mobile and vertical service providers. To accomplish this goal, it is essential to design network infrastructures that can be dynamically programmed to embed the network functions required to support integrated communication services.

The 5G-PICTURE project [1] focuses on the design and implementation of programmable network infrastructures able to provide multi-tenant 5G connectivity services, while building on two main design paradigms. First, the *Disaggregated RAN (DA-RAN)* paradigm, whereby a logical base station is disaggregated into various functional elements that can be instantiated in different parts of the network to mix and match available resources [2]. Second, software defined networking to enable *network programmability*, where the physical infrastructure is composed of programmable platforms, including specialized packet processors able to embed stateful functions at line rate.

The main contributions of this paper are the following: i) we describe the 5G-PICTURE unified compute, RAN, and Transport infrastructure, ii) we describe a set of novel RAN and Transport functions designed to provide integrated 5G connectivity services, and iii) we describe the problem of multi-technology end-to-end synchronization, while introducing the novel concept of a Synchronization Harmonizer.

This paper is organized as follows. Section II introduces the 5G-PICTURE integrated compute and network infrastructure. Sections III, IV, and V describe respectively

the selected set of RAN, Transport, and Synchronization functions. Finally, Section VI concludes the paper.

## II. 5G-PICTURE INTEGRATED COMPUTE-RAN-TRANSPORT ARCHITECTURE

5G-PICTURE builds on the 5G-XHaul transport architecture [5], and expands it by considering the integration of RAN functions and compute resources. Figure 1 illustrates the designed architecture that builds on the following design principles: i) configurable *radiating elements*, including Small Cells and Remote Units, ii) *distributed compute facilities*, able to instantiate virtualized RAN functions, and iii) a *heterogeneous transport network* connecting compute facilities and the core network. Telecom operators can exploit the 5G-PICTURE solution to instantiate 5G mobile connectivity services on behalf of different tenants, which could be traditional mobile network operators or vertical services.

### A. Integrated Compute and Network Infrastructure

5G-PICTURE adopts the 3GPP RAN architecture [3], where an eNB is decomposed into Remote Units (RUs), Distributed Units (DUs), and Centralized Units (CUs). Several functional decompositions are possible between RUs, DUs, and CUs, which we describe in Section III. While the RUs are physical elements composed of antennas and RF front ends, the DUs and CUs can be virtualized and instantiated on an NFV Infrastructure (NFVI) on behalf of each tenant.

In the RAN domain, 5G-PICTURE considers macro-cells, typically deployed at rooftop level, and Small Cells, typically deployed at street level. For macro-cells, a C-RAN architecture is adopted to favor spectral efficiency gains through collocated DUs. For Small Cells, when a high quality transport network is not available, the RUs and DUs can be collocated [4]. Finally, a RAN Control Function (RCF), described in Section III, is considered to manage the DU/CU resources according to the tenants' Service Level Agreement (SLA).

In the transport domain 5G-PICTURE considers four differentiated segments. First, at the very edge of the network, a wireless domain (*Area 1* in Figure 1) connects street-level Small Cells to the wired network. Second, passive WDM technologies connect Small Cells and macro-cell RUs to an aggregation site or Central Office (CO). Subsequently, a transport network that is able to jointly transport backhaul (BH), fronthaul (FH) and timing services is considered (*Area 2* in Figure 1) in order to connect the Optical Line Terminal (OLT) with the compute facilities where virtual DUs (vDUs)

<sup>1</sup>Daniel Camps-Mur is with i2CAT Foundation, Spain ([daniel.camps@i2cat.net](mailto:daniel.camps@i2cat.net)). <sup>2</sup>Kostas Katsalis is Huawei, Germany ([kostas.katsalis@huawei.com](mailto:kostas.katsalis@huawei.com)). <sup>3</sup>Igor Freire is with Blu Wireless, UK ([igor.freire@bluwirelesstechnology.com](mailto:igor.freire@bluwirelesstechnology.com)). <sup>4</sup>Jesus Gutierrez is with IHP - Leibniz-Institut für innovative Mikroelektronik, Germany ([teran@ihp-microelectronics.com](mailto:teran@ihp-microelectronics.com)). <sup>5</sup>Nikos Makris is with University of Thessaly, Greece ([nimakris@uth.gr](mailto:nimakris@uth.gr)). <sup>6</sup>Salvatore Pontarelli is with CNIT, Italy ([salvatore.pontarelli@unroma2.it](mailto:salvatore.pontarelli@unroma2.it)). <sup>7</sup>Robert Schmidt is with Eurecom, France ([robert.schmidt@eurecom.fr](mailto:robert.schmidt@eurecom.fr))

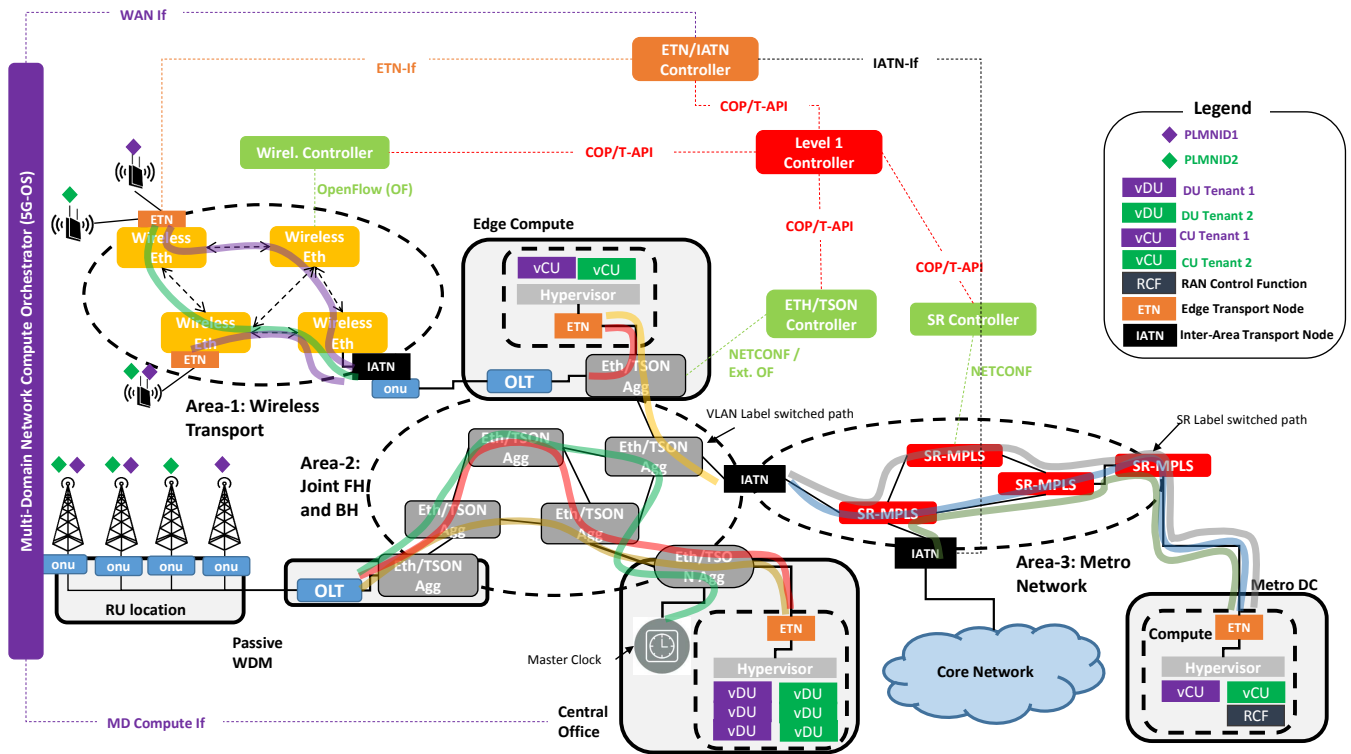


Fig. 1: 5G-PICTURE integrated RAN, Compute, and Transport infrastructure

are instantiated. In Section IV we describe enhancements to Ethernet and Time Shared Optical Networks (TSON) that were designed to instantiate this network segment. To connect DUs and CUs, strict timing services are not required, thus L3 technologies like Segment Routing are considered (*Area 3* in Figure 1). In order to connect different technology domains, a translator function referred to as *Inter-Area Transport Node (IATN)* is adopted and implemented using programmable stateful packet processors that are described in Section IV-D. Finally, a virtual transport function referred to as *Edge Transport Node (ETN)* interfaces the virtual compute domain with the transport network.

Regarding the compute domain, 5G-PICTURE features distributed compute facilities, spanning from the edge to the metro levels, where each facility acts as an independent MANO domain. Service chains across compute facilities can be instantiated using multi-domain orchestration as described in [6]. Compute facilities instantiate virtual DUs and CUs on behalf of the 5G-PICTURE tenants. Moreover, these facilities may contain one or more packet master clock [20] providing timing services for the network.

### B. Control and Management Plane

The integration of multi-domain compute and network is achieved in 5G-PICTURE through the 5G-OS architecture [6]. In this paper, we focus on the hierarchical SDN control plane part of the 5G-OS that provides end-to-end connectivity services between distributed compute facilities.

Each transport area implements forwarding using pre-provisioned label switched paths (LSPs) between the ETNs

and IATNs in that area (c.f. Fig 1). VLAN tags are used as LSP identifiers in the wireless and Ethernet/Optical areas, whereas MPLS labels serve the same purpose in Segment Routing areas. The IATN function binds LSPs in adjacent areas, and the ETNs bind traffic coming from the tenant functions (i.e. DUs and CUs), to the corresponding LSPs.

Each transport area features technology-specific SDN controllers (green boxes in Fig. 1) to set up LSPs, using OpenFlow or NETCONF to control the network elements. To provide end-to-end connectivity, a *Level 1 controller* aggregates the (abstracted) topology of the different areas, and decides how to establish a connection across multiple areas. The Level 1 controller is triggered by an *ETN/IATN controller*, which interfaces with the 5G-OS providing a unified WAN interface. Upon receiving a connection request from the 5G-OS, the ETN/IATN controller triggers a connection request in the Level 1 controller, which returns the LSP identifiers of the affected areas. Then, the ETN/IATN controller programs the necessary bindings in the ETN and IATN functions. The Control Orchestration Protocol (COP) [7] or the Transport API [8] can be used to establish communication between the aforementioned controllers.

## III. DISAGGREGATED RAN FUNCTIONS

### A. Virtual RAN functions

5G-PICTURE has developed various RAN functional splits based on the OpenAirInterface (OAI) platform, using IP interfaces between the base station entities. OAI currently supports 4 3GPP functional splits [9], namely: i) *Option 2* that splits between the PDCP and RLC layers, ii) *Option*

6 splitting between MAC and PHY layers 3) *Option 7.1*, in which some PHY functions are kept at the RU, while the rest are shifted to the DU, and iv) *Option 8* that separates the whole PHY layer from the RU providing full centralization.

Among the considered splits, Option 2 enables the integration of legacy or non-3GPP technologies (e.g., WiFi), whereby a single CU can control WiFi, 4G and 5G DUs. A good example of this split is the work in [10], where LTE and WiFi are controlled using the same CU, and a policy selection mechanism decides on the access technology

To reduce the required FH bandwidth of the low PHY-layer functional splits (e.g. Option 8), 5G-PICTURE investigates radio sample (de-)compression schemes. An A-law compression for these functional splits has been explored in [11], achieving up to 50% reduction for a constant bitrate FH throughput and round-trip time, and a negligible impact in terms of jitter and packet drop rate due to this lossy compression scheme. The proposed (de-)compression scheme has a negligible computational cost.

Finally, it is worth noting that the developed RAN functions can be deployed through MANO-compliant orchestrators included in the 5G-OS.

### B. Flexible Control of Heterogeneous RAN

The increasingly disaggregated and heterogeneous nature of the RAN challenges traditional resource management schemes. For example, in Option 2 DU and RU are both stateful entities that need to be synchronized for an effective resource management. To address this issue, 5G-PICTURE adopts a Radio Control Function (RCF) (c.f. Fig. 1) to manage RAN functions and expose them according to the tenant's SLA.

An example RCF implementation is the FlexVRAN platform [12], which flexibly composes a logical BS (IBS) from disaggregated RAN entities. The IBS abstraction is exposed to the tenant simplifying resource management, as shown in Fig. 2. FlexVRAN allows to reconfigure the underlying RAN functional splits without modifying the exposed IBS. This feature allows a 5G-PICTURE infrastructure operator to optimize its infrastructure without impacting its tenants. In addition, an IBS can be further divided into multiple virtualised base stations tailored to a given tenant or network slice.

The underlying heterogeneous physical RAN entities host a number of RAN PNFs/VNFs for Control Plane and User Plane (CP/UP) processing. These PNFs/VNFs are driven by a split-aware agent called *RAN runtime* [13]. This agent allows to configure RAN processing, and feeds related CP/UP information to the FlexVRAN controller, which unifies the configuration and statistics to be further consumed by an IBS. RUs do not possess a local RAN runtime agent, due to their limited processing power. Instead, RUs rely on in-band control to the DU, where the runtime agent processes information on behalf of the RU. Hence, it is also possible to modify the functional split between RU and DU at runtime by reconnecting to another RU featuring the appropriate

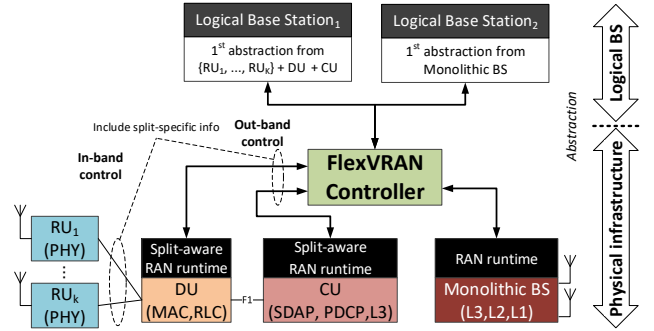


Fig. 2: The FlexVRAN controller and exposed IBSs from sample deployments.

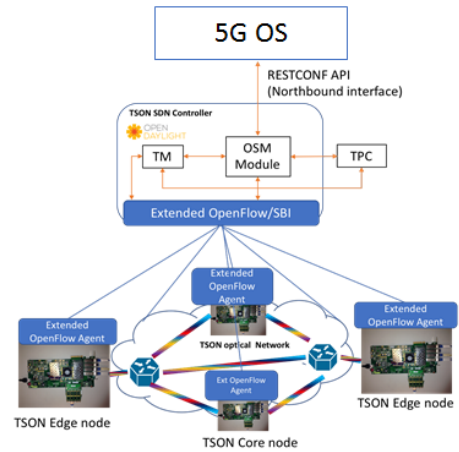


Fig. 3: Architecture of TSON control domain

functional split. Functional split modifications involving multiple RAN runtimes need to be coordinated by the 5G-OS.

## IV. HETEROGENEOUS TRANSPORT NETWORK

Under the umbrella of transport networking, BH and FH networks underpin the connectivity services required to enable the disaggregated RAN paradigm. In this section we identify key enabling transport technologies in the domains considered by 5G-PICTURE, namely optical, Ethernet/IP and wireless transport.

### A. Flexible Optical Transport

TSON [14] is proposed in 5G-PICTURE to provide the elasticity required in the optical domain to support joint FH/BH services (Area 2 in Fig. 1). TSON is currently implemented on FPGA and provides flexibility in the optical network by means of dynamic Time Division Multiplexing (TDM). The dynamic TDM is achieved by programming the size of the TSON frame, as well as the size and number of the component time slots. In addition, TSON supports native transport of both Ethernet and CPRI [5].

To fully benefit from the TSON technology, a control plane is designed on top of the TSON network as depicted in Fig. 3.

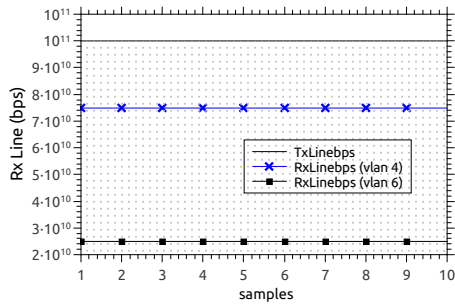


Fig. 4: Flex-E example with two flows (flow 1, vlan 4) and (flow 2, vlan 6) precisely utilizing a sliced 100G link.

The TSON control plane consists of an OpenDayLight (ODL) SDN controller, where OpenFlow is extended to handle the specific TSON parameters. LSPs in the TSON domain are defined using VLAN tags. The TSON Path Computation (TPC) application in the controller is in charge of allocating LSPs and configuring the TSON nodes (frame size, number of time slots and size of the time slot). The TPC application derives optimal paths and TSON frame configurations based on the network topology, and based on a developed empirical model that matches latency and bandwidth requirements to the TSON parameters.

### B. Packet Transport

Besides flexible optical networks, 5G-PICTURE also investigates how to provide joint FH/BH services over packet-based networks, using a combination of Flex-E [15], and X-Ethernet [16] technologies.

Flex-E is a physical layer technique introduced by the OIF, which consists of a thin layer (called Flex-Shim) between the Ethernet MAC and PCS able to support multiple MAC clients over multiple PHY layers. Flex-E allows the MAC layer speed of a client to be decoupled from the actual PHY layer speed. A comprehensive analysis of the technology can be found in [15]. Flex-E appears as a very promising solution for slicing the transport network, because it is able to exploit high multiplexing gains and increase network utilization efficiency, while at the same time guaranteeing isolation through exclusive use of timeslots (Fig. 4).

Furthermore, to enable fast switching for FH services, X-Ethernet [16] introduces Ethernet PCS switching based on the interface offered by Flex-E. The switch device redirects Flex-E Clients (64B/66B block streams) from the inbound port to the outbound port without waiting for the arrival of the whole Ethernet frame for checksum detection and lookup-based forwarding. Therefore, all the time-consuming procedures can be removed, e.g. encapsulation/decapsulation, queuing and table lookup. For packet streams of different packet lengths at different rates, X-Ethernet is able to exhibit an ultra-low latency forwarding capability at around 0.5  $\mu$ s. Compared to the classic router/switch delays (30  $\mu$ s to 200 ms), X-Ethernet is much better suited to carry latency sensitive services.

Although technologies like TSON and Flex-E are able to provide throughput guarantees for each slice of the transport network, they are not able to provide guarantees on the control plane operations, like for example delay guarantees or fast routing protocol convergence times. In 5G-PICTURE we exploit *Segment Routing* [17] as a technology that is able to provide service guarantees and support advanced functionality for the virtualized network in L3 (c.f. Area 3 in Fig. 1).

### C. Wireless Transport

5G-PICTURE considers a wireless transport segment to connect Small Cells with the wired network (c.f. Area 1 in Figure 1). Two types of technologies are considered in this segment, namely transport based on IEEE 802.11ad working at 60 GHz, and transport based on IEEE 802.11ac operating at 5 GHz. The combination of high throughput but Line of Sight (LoS) at 60GHz, with the lower throughput but non LoS operation at 5 GHz, is considered optimal to address Small Cell connectivity in cluttered urban environments.

Small Cell wireless transport devices are based on embedded ARM platforms running Linux, featuring a programmable software SDN agent. An SDN control plane is considered ideal to balance traffic between mmWave and Sub6 transport technologies. The interested reader is referred to [5] for an experimental evaluation of this architecture in a Smart City testbed.

An aspect of particular interest is joint access and backhaul, where the same interfaces are used to serve mobile terminals and provide wireless backhaul connectivity. In [18] a multi-tenant SDN based architecture for joint access and backhaul is proposed, which allows to instantiate virtual wireless access points serving different tenants (c.f. PLMNID in Figure 1), connect them to a wireless transport, and support end-user mobility while updating the bindings between user terminals and backhaul tunnels in less than 20 ms.

### D. Per-flow Programmable Dataplane

The integration of different transport segments and the need to provide efficient slicing functionality requires to deploy programmable platforms in the network (mainly at the borders between different transport domains, but also inside the same transport domain). In particular, a programmable dataplane able to provide functions such as: fast/programmable encapsulation/decapsulation, load balancing, traffic classification and QoS policy, etc.

5G-PICTURE features a flexible programmable dataplane named FlowBlaze [19], which is able to provide all the above-mentioned functionalities. FlowBlaze is an open abstraction for building stateful packet processing functions in hardware (FPGA and multicore processor architectures). The abstraction is based on Extended Finite State Machines (EFSM) and introduces the explicit definition of flow state. FlowBlaze is expressive, supporting a wide range of complex network functions; and easy to use, hiding low-level hardware implementation issues from the programmer.

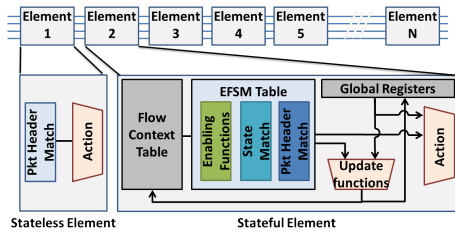


Fig. 5: FlowBlaze architecture

As shown in Fig. 5, FlowBlaze extends the OpenFlow Match Action Table (MAT) pipeline. As in OpenFlow, packet headers (including packet metadata) are processed through the pipeline’s elements to define the forwarding actions and packet operations. Each element can be either stateless or stateful. A stateless element is a MAT, similar to those of OpenFlow. Stateful elements implement an EFSM definition. As a result, a pipeline can combine both stateless and stateful elements. The architecture of a stateful element has the following elements: i) *Flow Context Table*, linking incoming packets to a given context (i.e. the set of per-flow variables), ii) *EFSM Table*, which, in addition to supporting matching on the packet header fields, it can also match on the state label and evaluate enabling functions, iii) *Update Functions*, which may execute instructions ranging from simple integer sums, for instance to update the value of a register representing a packet or byte counter, to more complex ones, e.g. multiplications, and iv) *Action*, which applies actions on the packet header.

As shown in [19], FlowBlaze is able to realize a wide range of network applications, and achieves (in the FPGA prototype) a throughput of 40 Gb/s, holding per-flow state for hundreds of thousands of flows.

## V. SYNCHRONIZATION AS A SERVICE

In the 5G-PICTURE architecture, reference signals or packets of time and frequency synchronization protocols are optionally provided as a service to tenants. For example, a tenant function that supports time synchronization via the IEEE 1588 Precision Time Protocol (PTP) can be instantiated and, provided that the appropriate timing service is requested for this particular function, it will start receiving the PTP packets that carry the time reference provided by a master clock (c.f. Figure 1). This is meant to address miscellaneous time synchronization needs, from RAN use cases such as coordinated multipoint (CoMP) to applications such as accurate timestamping exploited by a given vertical service.

Alternatively, a tenant may also request the transport of its own time and (or) frequency reference signals through the 5G-PICTURE network. For instance, a tenant that owns and wants to rely on its own primary reference time clock (PRTC) and telecom grandmaster (T-GM) clock [20] in order to supply the timing for its end applications may connect these and request the specific timing-aware transport that it needs. A tenant can request for example the transport of its PTP messages via telecom boundary clock (T-BC) nodes that

support the profile specified in ITU-T G8275.1 [21].

### A. Synchronization Harmonizer

5G-PICTURE envisions a control function called Synchronization Harmonizer (SyncH), which communicates with local (domain-level) controllers or directly with the individual nodes of a transport area (c.f. Fig. 1). The SyncH collects timing information, and configures network elements.

Some uses of the SyncH are the following. The SyncH can send a PTP management message [22] to a node in the network in order to request its PTP *clock description* and discover the clock type that the node implements (boundary or transparent). Based on collected information, the SyncH can serve and optimize synchronization paths and services. This concept has also been explored in [23]. Another use of the SyncH is to periodically collect the PTP *currentDS* dataset [22] from a slave node in order to observe the slave’s offset relative to its clock master. By observing eventual degradation on these figures, the SyncH is able to provide an alternative network path for timing messages, such that the slave’s Best Master Clock Algorithm (BMCA) can see a new better master and recover from the degrading time offset.

### B. Synchronization through heterogeneous transport

A distinctive feature of the 5G-PICTURE infrastructure is that it relies on heterogeneous domains, including wired and wireless networks, over which timing signals (physical or messages) are conveyed. This brings challenges in terms of performance, especially given each domain is constrained in its own way, e.g. with different packet delay properties and timestamping granularities.

In the wired domain, 5G-PICTURE brings forward a Guaranteed Time Service (GTS) for Ethernet interfaces, which minimizes Packet Delay Variation (PDV) of PTP packets. GTS aggregates a set of client 10 Gbps Ethernet interfaces into a 100 Gbps trunk interface, and minimizes PDV in the following way. In the client interfaces a snapshot is created of the high priority traffic (PTP packets), and the experienced inter-arrival time between these packets is replicated in the output trunk interface after adding a fixed offset delay. To maximize aggregation performance, the empty gaps between high priority packets are filled up with the low priority traffic received in the client interfaces. The interested reader is referred to [24] for a detailed description of the GTS service.

In the wireless domain, 5G-PICTURE favors IEEE 802.11ad mmWave mesh nodes, which provide multi-gigabit wireless transport while also behaving as PTP-aware transport nodes. In this domain, IEEE 1588 messages are embedded within IEEE 802.11 data frames and marked using the higher layer synchronization (HL-SYNC) approach from [26]. These data frames are readily identified at the IEEE 802.11ad transmit and receive interfaces and a corresponding nanosecond-accurate timestamp is taken in hardware upon transmission or arrival. Ultimately, the IEEE 802.11ad node can provide the PTP-aware transport with accuracy under the figures required for most RAN and vertical use cases. For instance, as a Class B telecom transparent

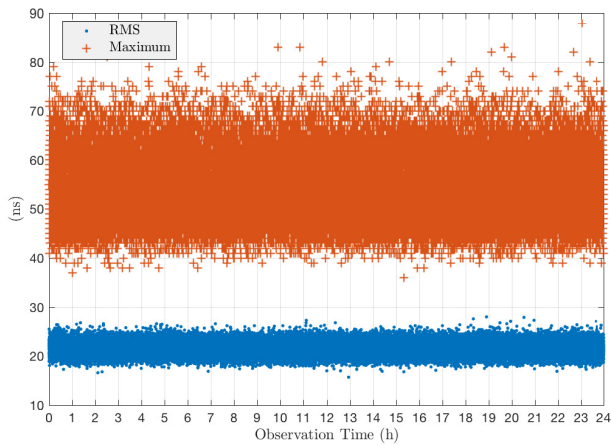


Fig. 6: IEEE 802.11ad PTP slave time offset performance measured over 24h in a master-TC-slave topology.

clock (T-TC) [27], namely a T-TC with maximum absolute time error contribution less than or equal to 70 ns. Fig. 6 presents an example measurement corresponding to the time offset of a wireless PTP slave relative to a wireless master port that is reachable after crossing one such IEEE 802.11ad TC. The reader is referred to [25] for further details.

## VI. CONCLUSIONS

In this work we presented the integrated Compute-RAN-Transport architecture proposed in 5G-PICTURE to provide multi-tenant 5G services. Along with the architecture we describe a set of enabling technologies in the RAN, Transport, and Synchronization domains. In the RAN domain, we present the implementation of software based disaggregated RAN functions for User and Control plane processing based on the OAI platform. In the transport domain we describe technologies to provide advanced FH and BH services over optical, packet, and wireless transport. Finally, we describe enhancements to transport IEEE 1588 over Ethernet and IEEE 802.11ad networks, while introducing the concept of a Synchronisation Harmonizer, which can be used to fine-tune PTP configuration over multi-domain, multi-technology networks.

Our future plans include end-to-end integration of the presented functions horizontally in a multi-technology setup, and vertically with the 5G-OS to control the entire life-cycle of integrated communication services.

## VII. ACKNOWLEDGEMENTS

This work is supported by the European Commission in the frame of the Horizon 2020 project 5G-PICTURE (grant #762057).

## REFERENCES

[1] H2020 5G-PICTURE. Available: <https://www.5g-picture-project.eu/>  
 [2] N. Gkatzios, M. Anastasopoulos, A. Tzanakaki and D. Simeonidou, "Compute Resource Disaggregation: An Enabler for Efficient 5G RAN Softwarisation", European Conference on Networks and Communications (EuCNC 2018)  
 [3] 3GPP TS 38.401-V15.2.0, "5G NG-RAN: Architecture description", July 2018

[4] Demirkol, I., Camps-Mur, D., Bartelt, J., and Zou, J. (2017, June). 5G transport network blueprint and dimensioning for a dense urban scenario. In *Networks and Communications (EuCNC)*, 2017 European Conference on (pp. 1-6). IEEE.  
 [5] D. Camps-Mur, et.al., "5G-XHaul: A novel wireless-optical SDN transport network to support joint 5G backhaul and fronthaul services", under submission to *IEEE Communications Magazine*.  
 [6] S. Dräxler, H. Karl, H. Razzaghi, A. Machwe, C.D. Young, K. Katsalis and K. Samdanis, "5G OS: Control and Orchestration of Services on Multi-Domain Heterogeneous 5G Infrastructures", *European Conference on Networks and Communications (EuCNC 2018)*.  
 [7] R. Muñoz, A. Mayoral, R. Vilalta, R. Casellas, R. Martinez, and V. Lopez, The need for a transport API in 5G networks: The control orchestration protocol, in *Optical Fiber Communications Conference and Exhibition (OFC)*, 2016. IEEE, 2016, pp. 13.  
 [8] C. Janz, L. Ong, K. Sethuraman, and V. Shukla, Emerging transport sdn architecture and use cases, *IEEE Communications Magazine*, vol. 54, no. 10, pp. 116121, 2016.  
 [9] 3GPP TR 38.801, "Study on New Radio Access Technology; Radio Access Architecture and Interfaces", V.1.0.0 (Dec. 2016).  
 [10] N. Makris, C. Zarafetas, P. Basaras, T. Korakis, and L. Tassioulas, "Cloud-based Convergence of Heterogeneous RANs in 5G Disaggregated Architectures", in *IEEE International Conference on Communications (ICC 2018)*, pp. 1-6.  
 [11] C.-Y. Chang et al., "FlexCRAN: A Flexible Functional Split Framework over Ethernet Fronthaul in Cloud-RAN", *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1-7.  
 [12] R. Schmidt, C.-Y. Chang and N. Nikaein, "FlexVRAN: A Flexible Controller for Virtualized RAN over Heterogeneous Deployments", *2019 IEEE International Conference on Communications (ICC)*, 2019.  
 [13] C. Chang and N. Nikaein, "RAN Runtime Slicing System for Flexible and Dynamic Service Execution Environment," in *IEEE Access*, vol. 6, 2018, pp. 34018-34042.  
 [14] A. F. Beldachi et. al, Experimental Demonstration of 5G Fronthaul and Backhaul Convergence based on FPGA-based Active Optical Transport, *ECOC 2018*.  
 [15] K. Katsalis, L. Gatzikis and K. Samdanis, "Towards Slicing for Transport Networks: The Case of Flex-Ethernet in 5G," *IEEE CSCN*, Paris, 2018, pp. 1-7.  
 [16] R. Li et al., "X-Ethernet: Enabling integrated fronthaul/backhaul architecture in 5G networks," *2017 IEEE CSCN*, 2017, pp. 121-125.  
 [17] Filsfils, Clarence, et al. "The segment routing architecture." *Global Communications Conference (GLOBECOM)*, 2015 IEEE. IEEE, 2015.  
 [18] M. Grandi, D. Camps-Mur, A. Betzler, J. J. Aleixendri and M. Catalan-Cid, "SWAM: SDN-Based Wi-Fi Small Cells with Joint Access-Backhaul and Multi-Tenant Capabilities," *2018 IEEE/ACM 26th International Symposium on Quality of Service (IWQoS)*, Banff, AB, Canada, 2018, pp. 1-2.  
 [19] S. Pontarelli et al. "Flowblaze: Stateful packet processing in hardware", In *16th USENIX Symposium on Networked Systems Design and Implementation (NSDI 19)*. USENIX Association, 2019.  
 [20] ITU-T Recommendation G.8271, "Time and phase synchronization aspects of telecommunication networks", 2017.  
 [21] ITU-T Recommendation G.8275.1, Precision time protocol telecom profile for phase/time synchronization with full timing support from the network, 2016.  
 [22] IEEE Std 1588-2008, IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, 2008.  
 [23] S. Ruffini et al., "A Novel SDN-Based Architecture to Provide Synchronization as a Service in 5G Scenarios," in *IEEE Communications Magazine*, vol. 55, no. 3, pp. 210-216, March 2017.  
 [24] S. Bjornstad, D. Chen, and R. Veisllari, "Handling delay in 5G ethernet mobile fronthaul networks", in *2018 European Conference on Networks and Communications (EuCNC)* (pp. 1-9). IEEE.  
 [25] 5G-PICTURE D4.2, Complete design and initial evaluation of developed functions, 2018. Available: <https://www.5g-picture-project.eu/>.  
 [26] IEEE Computer Society LAN/MAN Standards Committee. (2016). Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. IEEE Standard 802.11-2016.  
 [27] ITU-T Recommendation G.8273.3, Timing characteristics of telecom transparent clocks, 2017.