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# Optical networking: An important enabler for 5G

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**Abstract** *This paper focuses on converged optical-wireless 5G infrastructures and proposes the novel architecture of "Dis-Aggregated RAN" adopting "disaggregation" of hardware and software components across wireless, optical and compute/storage domains. The proposed approach is evaluated through a purposely developed modelling framework.*

## Introduction

5G wireless access solutions will exploit a variety of technologies including Sub-6 GHz, mmWave, advanced beam-tracking and MIMO techniques together with legacy solutions. To enhance spectral efficiency and throughput, small cells will be deployed either adopting traditional Distributed Radio Access Networks (D-RANs), where Base Band Units (BBUs) and radio units (RUs) are co-located or the Cloud Radio Access Network (C-RAN). In C-RAN remote units (RUs), are connected to the Central Unit (CU) where the BBU pool is located through high bandwidth transport links known as fronthaul (FH) [1], offering pooling and coordination gains. However, C-RAN may require tremendous transport bandwidth and suffer strict latency and synchronization constraints. In this context, optical network solutions can play a key role offering advanced transport capabilities [1].

To address the limitations of the D-RAN and C-RAN approaches, we propose the adoption of flexible functional splits. These splits allow dividing processing functions between the CU and the BBUs collocated with the RUs. Flexible "optimal split" allocation can offer significant resource and energy efficiency benefits [2]. The required flexibility can be provided by programmable digital hardware (HW), able to support flexible reconfiguration of hardware-accelerated (HWA) and software-realized baseband functions. This enables a shared "pool of resources" that alleviates the need of owning HW. Towards this direction, the recently proposed concept of "disaggregation of resources" is expected to play a key role [4]. Disaggregation relies on decoupling components and mounting them on remote locations, instead of coupling all components on one integrated system. This facilitates independence across technologies and systems, offering increased granularity in the control and provisioning of resources.

This paper proposes a paradigm shift, from the D-RAN and C-RAN to the "Dis-Aggregated RAN" (DA-RAN) approach. DA-RAN is a novel concept adopting the notion of "disaggregation" of hardware and software (SW) components across the wireless, optical and compute/storage domains creating a common "pool of resources" that can be independently selected and allocated on demand to compose any infrastructure service. On demand selection and allocation of these resources (flexible mix-and-match) will enable provisioning of any service without having to own and install any specific HW or SW, adopting novel approaches such as service chaining (SC) and advanced features such as slicing and virtualisation [1].

To evaluate the proposed approach a multi-objective optimization framework considering jointly network and compute resources as well as service performance constraints (e.g. tight FH delay requirements) has been developed [1]. The performance of the proposed solution is examined showing significant benefits compared to the D-RAN and C-RAN solutions with real traffic statistics.

## Network Description and Problem Definition

We consider an elastic optical network interconnecting RUs with compute resources supporting both backhaul (BH) and FH services Fig. 1 (a). A key architectural decision is related with the placement of the BBU functions with respect to the RUs. In addition to this, to relax the stringent delay and synchronization requirements of existing FH protocol implementations, the concept of functional split processing is adopted [3]. As illustrated in Fig. 1 (b) the range of "split options", spans between the "traditional D-RAN" case where "all processing is performed locally at the RUs" to the "fully-centralized C-RAN" case where "all processing is allocated to a CU". All other options allow allocating some processing functions at the RU, while the remaining ones are performed remotely at the CU. The optimal "split", is decided based on a number of factors such as transport network, topology, and scale as well as type and volume of services.

We assume that the remote BBU processing resource pool comprises both general purpose and specific purpose processors (GPPs and SPPs) hosted at regional or mobile edge DCs supporting processing of the FH functions. Therefore, in addition to the optimal split selection, mapping of FH functions to suitable GPPs/SPPs within the DC is part of the optimization process.

For the optical metro network, we consider a frame-based optical network solution [1]

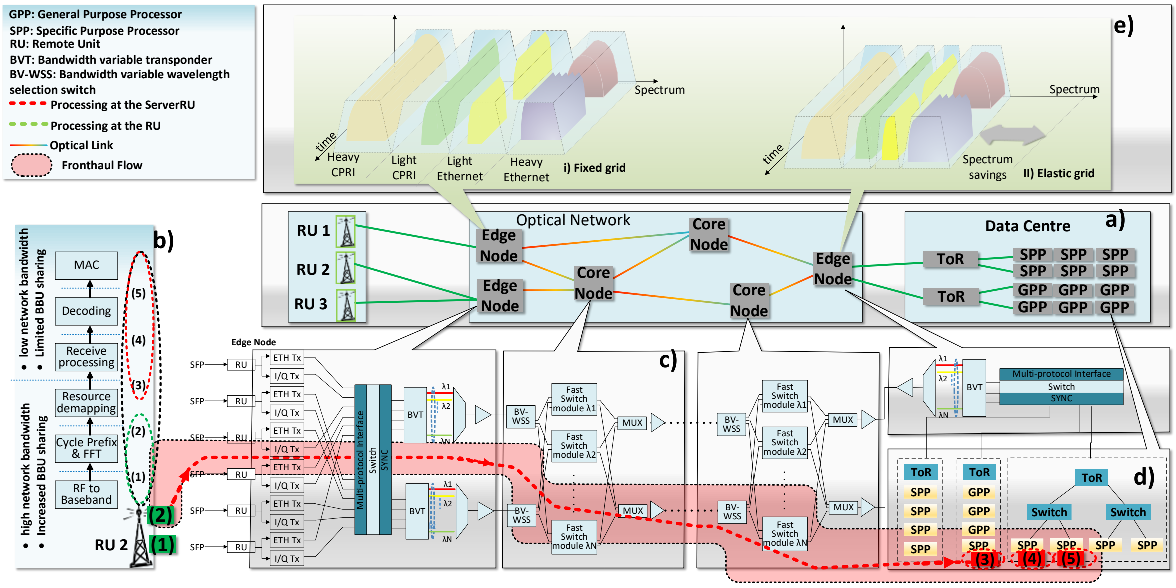

Fig. 1: 5G Network Infrastructure

interconnecting RUs and end-users with a set of GPPs and SPPs (Fig. 1(a)). GPPs enable the concept of virtual BBUs (vBBUs), facilitating efficient sharing of compute resources. The edge nodes can also handle both continues (CPRI data streams) and packetized flows. This functionality is implemented through the deployment of a hybrid circuit/packet switch. The circuit switch handles FH services with strict synchronization and bandwidth constraints - split options (1) and (2) - while the packet switch handles relaxed FH services, split options (3)-(5) (Fig. 1 b). The optical edge nodes are also equipped with Bandwidth Variable Transponders (BVTs) offering elastic bandwidth allocation, to allow efficiently matching the varying transport bandwidth requirements of different FH services (splits).

For the compute/storage (intra-DC) domain, we consider a standard switch-based topology interconnecting compute/storage resources, where switch layers form a hierarchical networking model. Switches are organized in a simple tree topology, although more sophisticated structures e.g. fat trees can be also adopted. A simple hierarchal network interconnecting GPPs and SPPs is shown in Fig. 1 (d). The SPP unit supporting FH function (3) (Fig. 1b), communicates through a set of high speed Ethernet switches with the SPP hosting function (4). The output of this SPP unit will be then sent to the next SPP (5). This way, an entire SC supporting the FH service is implemented.

## Problem formulation and Numerical Results

To maximise the converged 5G infrastructure energy efficiency, a two-stage optimisation for the wireless/optical and the intra-DC network domains is proposed. In the first stage, the optical transport network provisioning problem is formulated aiming at identifying the necessary optical network resources for the interconnection of the RUs with the DCs. Then, a second sub-problem linked to the allocation of the FH functions to the disaggregated pool of compute/storage resources is provided. To achieve this, once the FH data reach a DC hosting the candidate pool of resources, a path interconnecting the edge DC node with the GPP/SPP modules that will process the remaining FH functions is established. The order of FH functions processing is defined by the corresponding SC shown in Fig. 1b). The modelling details are shown in Table 1. In the first sub-problem, constraints related to flow (1.1), transport network capacity (1.2), split processing (1.3), RU demand (1.4) and BBU processing (1.5)-(1.8) are introduced. For the intra-DC network, constraints related to parallel processing of the BBU functions (2.1)-(2.2) and their associated communication requirements (2.3)-(2.4) are included.

The proposed optimization scheme is evaluated using the optical network shown in Fig. 2a) covering a 10x10 km$^2$ area with 50 uniformly distributed BSs. RUs demands are generated according to real datasets [5]. Based on the compute resource type and location the following cases are examined:

i) “Traditional-RAN (T-RAN)”: In this scheme, RUs and BBUs are co-located and FH service processing is carried out exclusively by SPPs. Sharing of BBUs between multiple RUs is not supported and BBUs sizing is performed based on worst case traffic statistics. The power consumption per RU ranges between 600 and 1200 Watts under idle and full load conditions, respectively.

ii) “C-RAN with fixed transport”: This scheme allows BBUs to be instantiated as virtual functions and run on GPPs enabling resource sharing and on-demand compute resource resizing to match the FH service requirements. This approach involves higher per giga operation processing cost (GOPS) at the GPPs compared to SPPs (i.e. 2W/GOPS vs

**Tab. 2:** A Problem Formulation

<table>
<tr><td colspan="4"><b>SP 1-Optical Transport Network: Objective:</b> $\min F_1 = \sum_{r\in \mathbf{R}} \mathcal{E}_r \left(\sum_{i\epsilon\Sigma} p_{ri}^{RU}\ \sigma_{ri}\right) + \sum_{e\in \mathbf{E}}\ \mathcal{E}_e\ C_e$</td></tr>
<tr><td>$\mathbf{R}, \mathbf{D}, \mathbf{E}, \mathbf{\Sigma}$</td><td>RUs, DCs, Optical Links Split Option Set</td><td>$P_d, P_r$</td><td>Total processing capacity of DC $d \epsilon \mathbf{D}$<b>,</b> RU $r \epsilon \mathbf{R}$</td></tr>
<tr><td>$\boldsymbol{p_{rd}}$</td><td>Paths interconnecting RU $r$ to DC $d \epsilon \mathbf{D}$</td><td>$h_r$</td><td>Transport network requirements of RU $r$</td></tr>
<tr><td>$H_{ri}, p_{ri},$</td><td>Network, processing requirement of RU $r$ under split option $i \epsilon \mathbf{\Sigma}$</td><td>$\delta_{erp}$</td><td>Binary coefficient taking value 1 if link $e\epsilon\mathbf{E}$ belongs to path $p$ realizing traffic generated at the RU $r$</td></tr>
<tr><td>$p_{ri}^{RU}, p_{ri}^{d}$<br>$\xi_e\ , C_e$</td><td>Local, remote (at DC $d \epsilon \mathbf{D}$<b>)</b> processing requirements of RU $r \epsilon \mathbf{R}$ under split option $i \epsilon \mathbf{\Sigma}$<b>.</b> Capacity, cost of link $e\epsilon\mathbf{E}$</td><td>$\sigma_{ri},$<br>$a_{rd}$</td><td>Binary variable equal to 1 if split option $i \epsilon \Sigma$ is adopted. Binary variable taking value equal to 1 if $d \epsilon \mathbf{D}$ hosts the BBU SC (or some of its parts) of $r \epsilon \mathbf{R}$</td></tr>
<tr><td>$u_{rp}$</td><td colspan="3">Binary variable forcing a single flow to be transferred from RU $r$ over a single path $p\epsilon\mathbf{P}_r$<b>,</b> $\mathbf{P}_r = \cup\ \boldsymbol{p}_{rd}$</td></tr>
<tr><td colspan="4"><b>Constraints:</b> (1.1). $\sum_{p\in\mathbf{P}_r} u_{rp} = 1,\ \ r\epsilon\ \mathbf{R},$ <b>(</b>1.2) $\sum_{r\in\mathbf{R}} h_r \sum_{p\in\mathbf{P}_r} \delta_{erp} u_{rp} \le C_e,\ \ e\epsilon\ \mathbf{E},$ (1.3<b>)</b> $\sum_{i\epsilon\Sigma} \sigma_{ri} = 1,\ \ r \in\ \mathbf{R}$ (1.4) $h_r =$ $\sum_{i\epsilon\Sigma} H_{ri}\sigma_{ri}\ ,\ \ r \in\ \mathbf{R},$ <b>(</b>1.5) $\sum_{i\epsilon\Sigma} p_{ri}^{RU}\sigma_{ri} \le P_r,\ \ r \in\ \mathbf{R},$ (1.6) $\sum_{r\in\mathbf{R}}\sum_{i\epsilon\Sigma} p_{ri}^{d}\ \sigma_{ri} \le P_d,\ \ d \epsilon\ \mathbf{D},$ <b>(</b>1.7) $\sum_{d\ \epsilon\ \mathbf{D}} a_{rd} \le 1,\ \ r \in\ \mathbf{R},$ 1.8) $p_{ri}^{RU} + \sum_{d\ \epsilon\ \mathbf{D}} a_{rd}\, p_{ri}^{d} = p_{ri},\ \ r \epsilon \mathbf{R}, i \epsilon \mathbf{\Sigma}$</td></tr>
<tr><td colspan="4"><b>SP 2-Optical Transport Network: Objective:</b> $\min F_2 = \sum_{k\in\mathbf{M}^d} \mathcal{E}_k \left(\sum_{r\in\mathbf{R}}\sum_{i\epsilon\Sigma}\sum_{\varphi\ \epsilon\ \mathbf{FH}_{ri}^{d}} p_\varphi\ a_{\varphi\kappa}\right) + \sum_{e\in\mathbf{E}^d} \mathcal{E}_e\ C_e$</td></tr>
<tr><td>$\mathbf{M}^{\boldsymbol{d}},$<br>$\mathbf{E}^{\boldsymbol{d}}$</td><td>Set of processing modules, inter-DC links of DC $d\epsilon\ \mathbf{D}$</td><td>$\zeta_{e\varphi p}$</td><td>Binary coefficient taking value 1 if link $e\epsilon\mathbf{E}^{\boldsymbol{d}}$ belongs to $p\epsilon\boldsymbol{p}_{\varphi km}^{\boldsymbol{d}}$ interconnecting modules $k$ and $m$</td></tr>
<tr><td>$\mathbf{FH}_{\boldsymbol{ri}}^{\boldsymbol{d}}$</td><td>Ordered set of remaining FH functions for RU $r \epsilon \mathbf{R}$ under split $i \epsilon \Sigma$</td><td>$\boldsymbol{p}_{\varphi km}^{\boldsymbol{d}}$</td><td>Set of paths interconnecting module $k\epsilon\ \mathbf{M}$ hosting function $\varphi \epsilon \{1,\ldots,FH_{\boldsymbol{ri}}^{\boldsymbol{d}} - 1\}$ to module $m \epsilon \mathbf{M}$ hosting function $\varphi + 1$ of the FH SC at DC $d \epsilon \mathbf{D}$</td></tr>
<tr><td colspan="4"><b>Constraints</b>:(2.1)$\sum_{\boldsymbol{k}\ \epsilon\mathbf{M}^d} \boldsymbol{a_{\varphi\kappa}} = \mathbf{1},\ \ \varphi \epsilon\ \mathbf{FH}_{\boldsymbol{ri}}^{\boldsymbol{d}},\ \ r \epsilon \mathbf{R}, \boldsymbol{\Sigma\ i\ \epsilon, d\epsilon}\ \mathbf{D},$ (2.2)$\sum_{r\in\mathbf{R}}\sum_{i\epsilon\Sigma}\sum_{\varphi\ \epsilon\ \mathbf{FH}_{ri}^{d}} \boldsymbol{p_\varphi\ a_{\varphi\kappa}} \le \boldsymbol{P_k},$ (2.3) $\sum_{\boldsymbol{p\in\mathbf{P}_{\varphi k}^{d}}} \boldsymbol{u_{kp}} =$ $\mathbf{1},\ \ \boldsymbol{\varphi\ \epsilon\ 1}, \ldots, \boldsymbol{FH_{ri}^{d}} - \mathbf{1}, k\epsilon\ \mathbf{M}^{\boldsymbol{d}}, d\epsilon\ \mathbf{D},$ (2.4) $H_{k\varphi} = H_{ri+1},\ \ \boldsymbol{k}\ \boldsymbol{\epsilon}\mathbf{M}^{\boldsymbol{d}}, \varphi \epsilon\ \mathbf{1}, \ldots, \boldsymbol{FH_{ri}^{d}} - \mathbf{1}, r\epsilon\ \mathbf{R}, i \epsilon 1, .., \mathbf{\Sigma} - \mathbf{1},$ (2.5) $\sum_{r\epsilon\ \mathbf{R}, i\ \epsilon\ \mathbf{\Sigma}, k\in\mathbf{M}^d} \sum_{\varphi\ \epsilon\ \mathbf{FH}_{ri}^{d}} H_{k\boldsymbol{\varphi}} \sum_{p\in\mathbf{P}_{\boldsymbol{\varphi k}}^{\boldsymbol{d}}} \zeta_{e\varphi p} u_{kp} \le C_e$</td></tr>
</table>

1.2W/GOPS)). Optical network resources are allocated with the granularity of the wavelength (fixed wavelength grid case) and the optical frame.

iii) "C-RAN with elastic transport". This scheme offers the flexibility to assign compute resources on demand exactly as in case (ii) "C-RAN with fixed transport", but enhanced with an elastic optical network solution allowing varying time (optical frames) and elastic spectral allocation capabilities.

iv) "Disaggregated-RAN (DA-RAN)": This novel scheme combines the benefits of D-RAN and C-RAN allowing FH functions to be processed either at SPPs or GPPs based on their specific characteristics. Through this approach, intensive FH functions can be performed at SPPs (ASICS) hosted at the DCs whereas the remaining functions are instantiated on shared GPPs. An elastic optical transport network solution is also proposed.

Fig 2 b illustrates the impact of traffic load on the optimal split option for the cases under consideration. As can be seen "elastic C-RAN" providing improved network efficiency performs optimally for lower split options (more remote processing) than "C-RAN". This trend is further emphasised in "DA-RAN" offering both improved network and compute resource efficiency through resource disaggregation. Fig.2c shows the total infrastructure power consumption with load for the schemes under consideration. The DA-RAN approach outperforms all alternative approaches. The benefits of the DA-RAN is attributed to its sharing gains both in space and time domains due to its flexible and on demand resource allocation capabilities. DA-RAN minimises overprovisioning requirements present in the alternative approaches leading to 10-50% power consumption savings..

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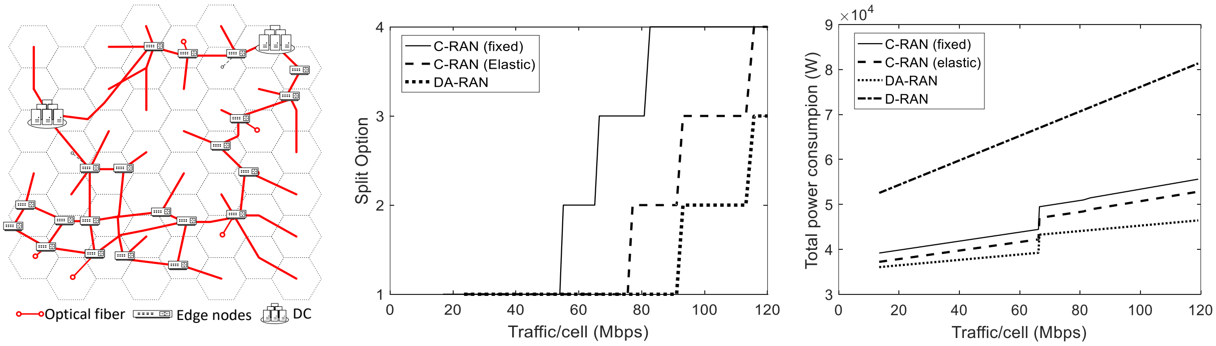

**Fig. 2:** a) The Bristol is Open city test bed, b) functional split vs network load, c) infrastructure power consumption