Optimized Resource Allocation and RRH Attachment in Experimental SDN based Cloud-RAN

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***Abstract*—In this paper, we design and implement an SDN-based architecture `Pgm−RAN` which provides an effective representation of the radio network state at different network levels. Thanks to its programmability, `Pgm−RAN` enables the implementation of real-time RAN control algorithms in a modular fashion within a Cloud-RAN environment. To demonstrate the effectiveness of `Pgm−RAN` and assess its applicability, we design and implement a control plane application that ensures an enhanced joint Remote Radio Head assignment and physical radio resource allocation denoted by `enhanced−DPS`. To do so, we formulate the problem as Integer Linear Program while taking into consideration the mobile users requirements and the radio environment conditions. The problem is then resolved in a polynomial time leveraging linear relaxations and Branch & Cut algorithm. Both experimental and simulation results are provided to prove the effectiveness of our framework and to gauge the performance of `enhanced−DPS`. It is worth noting that our experimental platform relies on two main building blocks: i) Open Air Interface platform and ii) extended version of FlexRAN SDN controller.**

Keywords: Cloud-RAN, SDN, Radio resource allocation, Open Air Interface, FlexRAN, Optimization.

I. Introduction

The impressive proliferation of smart devices has led to the explosion of traffic demand. Billions of connected users are expected to deploy a myriad of services with stringent requirements in terms of throughput and latency. To deal with such an explosion, mobile operators and vendors make every effort to grow and consolidate network infrastructures. The objective is to design an innovative new generation of cellular network (i.e., 5G) supporting the demanding requirements in terms of QoS and SLAs of end-users. In this respect, Cloud-RAN and Software Defined Networks (SDN) are the pillars of 5G physical and software infrastructures. Relying on virtualization, the long-awaited programmability and agility finally become possible to guarantee ultra-low latency, high throughput, scalable and real-time access to 5G services.

Cloud-RAN is the cornerstone of 5G architecture [1]. It enables the deployment of centralized BaseBand Units (BBUs) hosting all baseband operations within a cloud environment. These BBU are hosted in a Remote Cloud Center (RCC), while keeping the Radio Frequency (RF) functionalities at the cellular site within Remote Radio Heads (RRHs). Besides, SDN [2] is one of the key blocks of 5G architecture enabling an efficient management of operators' virtualized infrastructures. Thanks to the separation of the forwarding and the control planes, the routing complexity is considerably reduced while providing tremendous computational power compared to legacy devices. Indeed, SDN controllers offer the opportunity to implement more efficient (reactive and/or proactive) algorithms thanks to real-time and centralized control leveraging an accurate view of the physical and virtual network topologies.

In this paper, we address the design and implementation of an SDN-based architecture for Orthogonal Frequency-Division Multiple Access (OFDMA) resource management in the context of Cloud-RAN. In order to support real-time RAN applications for novel 5G services, our main objective is to deal with the challenge of separating the control and data planes within the RAN while considering both theoretical and experimental aspects: i) deployment of experimental platform based on Universal Software Radio Peripheral (USRP) equipment [3] and Open Air Interface platform [4], ii) optimization problem formulation and resolution, and iii) performance evaluation in both experimental and simulation environments.

The contribution of our work is twofold. Firstly, we design and implement an SDN-based framework, called `Pgm−RAN`, on which RAN control algorithms can be efficiently executed within a Cloud-RAN environment. Secondly, exploiting the modularity of the designed and implemented `Pgm−RAN`, we propose an optimized joint RRH assignment and radio resource allocation approach relying on Coordinated Multi-Point (CoMP) transmission technology [5].

`Pgm−RAN` provides precise and effective representation of the network state in terms of topology, attached Users Equipment (UE), current data flows, available and allocated OFDMA resource blocks, etc. Besides, `Pgm−RAN` supports a custom-tailored southbound protocol to ensure efficient communication between the controller and its managed RRHs. To do so, a set of functions building the southbound API have been defined to allow the interaction between the control plane and the data plane such as: i) acquisition and setting of configuration parameters, ii) collection of statistics for example uplink/downlink Signal-to-Interference-plus-Noise Ratio (SINR) measurements, iii) installation of control decision, etc. It is straightforward to see that such a flexible framework enables the deployment of radio resource allocation strategies over the controller while considering real-time requirements. The software and hardware of our prototype relies on i) USRP cards [3], ii) Open Air Interface platform [4], iii) extended version of FlexRAN SDN controller [6], and iv) LTE network simulator.
Moreover, we propose an Enhanced Dynamic Point Selection scheme denoted by `Enhanced−DPS` in order to jointly optimize the radio resource allocation for UEs while mitigating inter-cell interferences. Our proposed softwarized `Enhanced−DPS` exploits the gathered network UE statistics at multiple base stations (i.e., eNodeBs) in order to jointly optimize i) the transmission point selection (i.e., choice of serving RRHs) that will operate the data transmission, and ii) the allocation of Physical Resource Block (PRB) carrying UE data. The main idea behind our proposal is to take profit from the global view of the SDN controller to implement an SDN-based Cloud CoMP solution. The latter makes use of the Cloud-RAN infrastructure to enable low latency coordination between co-located virtualized BBUs. We formulate the dynamic point selection problem as Integer Linear Programming (ILP). The latter is resolved with i) linear relaxations to exploit the underlying structure of the problem and ii) Branch and Cut algorithm to efficiently reach the optimal solution. The performance of `Enhanced−DPS` is validated by robust experimentations within our `Pgm−RAN` platform and a custom network simulation environment. First, we evaluate `Pgm−RAN` in terms i) fronthaul performances, ii) UE's throughput and iii) CPU consumption in the Cloud-RAN environment. Then, we compare our proposal with the conventional Open Air Interface scheduler. The results obtained are very satisfying.

The remainder of this paper is organized as follows. Section II will describe, `Pgm−RAN`, our SDN-based Cloud-RAN platform. Section III will formulate the OFDMA RB allocation and RRH attachment problem. Then, our proposal `Enhanced−DPS` will be described in Section IV. Performance evaluation based on experimentations will be detailed in Section V. In Section VI, we will summarize the related work dealing with SDN based solutions for Cloud-RAN and addressing CoMP problematic. Finally, Section VII will conclude the paper.

II. `Pgm−RAN`: SDN-based Cloud-RAN

In this section, we put forward our SDN-based framework designed for an efficient Cloud-RAN environment.

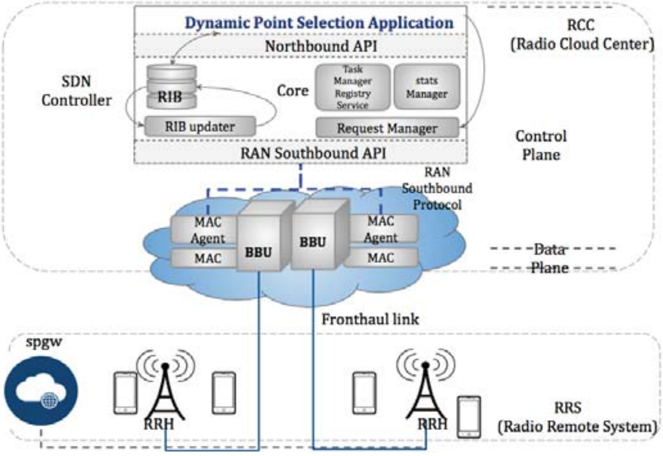


Fig. 1. `Pgm-RAN` architecture

This platform, called `Programmable-RAN` and denoted by `Pgm-RAN`, controls and manages the hardware (i.e., RRHs, UEs) and Software (i.e., BBU) components. To do so, we design and implement an SDN-based multi-cell processing solution in Cloud-RAN to enhance the UEs's QoS through a centralized multi-cell cooperation. In addition, we propose an optimized Dynamic Point Selection approach of Coordinated Multi-Point interference management. Hereafter, we will describe in depth `Pgm-RAN`.

A. Architecture Overview

The overall framework of the proposed architecture is illustrated in Fig. 1. Our SDN controller is deployed in the Remote Central Cloud (RCC) pool and communicates directly with the MAC agents hosted in the BBUs. Indeed, the SDN controller makes use of a custom-tailored southbound protocol to ensure a real time exchange with remote MAC agents. The placement of these agents depends on the adopted split [7]. Consequently, agents could be deployed whether in the BBU (i.e., RCC) or in the Remote Radio System (RRS). These agents continually send/receive MAC configuration and control data to/from the controller. The collected MAC-related measurements are stored in the local data base denoted by Radio Information Base (RIB). `Enhanced-DPS` makes use of this stored data to jointly select the best transmitting RRHs and PRBs resources for each UE. Once the decision made, the latter is communicated to the MAC agents in order to be executed by the data plane. In accordance with SDN principles, our architecture relies on three main layers: i) Southbound, ii) Core and iii) Northbound API.

1) Southbound Layer: The southbound protocol ensures the communication between the SDN controller and the eNodeB agent. It is implemented using an extended version of Google protocol buffer API provided by FlexRAN [6]. Note that the message exchange is asynchronously carried out and hence guaranteeing high flexibility. For example, some messages could be asynchronously sent by the controller in order to request the configuration of an UE. However, other message may need to be independently transmitted such as: control commands of the applications, periodic statistics request, etc. In this context, two main classes of messages are defined: i) request configuration/statistics and ii) control command messages. The first type is carried out to get and share both eNodeB and UE configuration information, and user statistics reports. Concerning the control data, the latter is used to communicate with the eNodeB agents the decisions taken by the SDN controller applications. To implement our `Enhanced-DPS` application, we propose two main southbound messages: i) **dl-mac-config** and ii) **ue-config**.

- **dl-mac-config** is a control command message which is sent by the SDN controller to the agent of the serving eNodeB to transport the MAC decisions and Downlink Control Information (DCI). It is worth noting that the dl-dci is encapsulated in the dl-data message which is transported over the dl-mac-config message. This configuration message transports the entire eNodeB user's dl-dci of the current subframe which will be converted to the LTE DCI. For each user, the SDN scheduler application, corresponding to `Enhanced-DPS` application, generates the user dl-data identified by its RNTI (Radio Network Temporary Identifier).
  To ensure CoMP operations, three flags have been defined in the dl-dci message. The CoMP-DCI flag permits to recognize the CoMP DCI and to launch the appropriate operations. The Transmit-Data flag indicates whether to transmit data at the indicated PRBs on the DCI or mute it. Finally, the Transmit-DCI flag defines the rule related to the transmission of the DCI on the eNodeB PDCCH. It means that, the DCI will be transmitted only to the User Serving RRH. Consequently, none of the coordinating RRHs will receive the DCI.
- **ue-config** is a configuration information message that is requested by the RIB Updater using a ue-config-request message and get by ue-config-reply message from the agent. This message contains user MAC configuration such as i) cqi-config which gets the the CQI (Channel Quality Indicator) configuration modes and periodicity, ii) the user transmission mode, and iii) the configuration of the neighboring cells.

2) Core layer: As depicted in Fig. 1, the SDN controller core layer relies on the RIB Updater. The latter requests the RAN information by interrogating the agent and then updates the user configuration and the statistics to make these data available to the northbound applications. This data base, named Radio Information Base (RIB), contains a list of enb-rib-info entries. They are created when the agent is registered the first time at the SDN controller. The update is performed when the following information is received: i) new eNodeB configuration (i.e., enb-config), ii) user configuration (i.e., ue-config), or iii) logical channel configurations (i.e., lc-config). In addition to the MAC information of the eNodeB cell and users (i.e., cell-mac-info, ue-mac-info), the latter contains the cells statistics and the user statistics reported by the agent. These reports are crucial for the northbound applications.

Concerning CoMP operations, one field is defined at the enb-rib-info entry to identify the list of neighboring eNodeBs of each eNodeB. Such a list will be used by our `Enhanced-DPS` application to select the best serving RRH for a given UE. Note that, within a coordinating area, a global RNTI is allocated for each user in order to assume a central control plane for coordinating eNodeBs.

The real time controller is the responsible for the Core creation, including the RIB, the RIB updater, task manager and the requests manager. In addition, it registers the northbound applications that are planned to be executed under the controller. The requests manager allows the northbound applications to send the southbound messages to the concerned agent via the network asynchronous interface.

3) Northbound layer: In order to show the benefits of the SDN-based Cloud-RAN architecture, we design and implement an optimized Dynamic Point Selection approach (DPS) of Coordinated Multi-Point Interference management. This use-case proves that the virtualization and the centralization of RAN entities allow a low latency coordination and consequently ensures a better response delay and an efficient use of resources. To do so, we implemented a central control plane responsible for a set of eNodeBs. This control plane manages and controls, in a centralized manner, the MAC layers of a coordinating eNodeBs set.

We recall that DPS is a Coordinated Multi-Point transmission mechanism. It enables the switching of the transmitting RRH that will deliver the user data with dynamicity's switching of T subframes. The implemented application refers

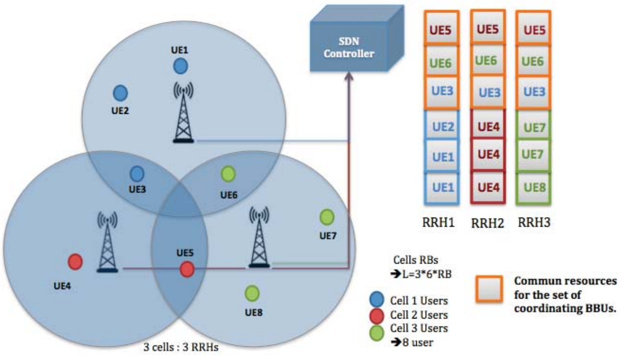


Fig. 2. Example: LTE Cloud-RAN network

to the scenario of Intra-frequency CoMP. It means that the coordinating cells use the same central frequency to send and receive physical channels.

Note that our `Enhanced-DPS` application has access to the RAN information (users' configuration and statistics) of the set of the coordinating eNodeBs. This global information is available for the central control plane at the RIB thanks to centralization offered by the SDN architecture. Indeed, `Enhanced-DPS` application manages the MAC scheduling of the coordinating RRHs set and the best transmitting RRH selection among the latter set. The centralized control plane of the coordinating RRHs will send the generated UE scheduling information to its agents responsible for i) serving RRH and ii) coordinating RRHs including the best transmitting RRH. The decision is executed within the serving RRH to send the downlink shared channel (dlsch) buffered user data on the PDSCH of the selected transmitting RRH. In addition, the decision is executed at the rest of the coordinating cells in order to blank dlsch and to do not transmit data on it.

III. Problem Formulation

In this section, we will formulate our Dynamic Point Selection problem of the Coordinated Multi-Point Transmission within an SDN based Cloud-RAN infrastructure. To this aim, we will first detail LTE Cloud-RAN network model. Then, we will formulate the centralized RRH assignment and OFDMA resource allocation of cell edge UEs problem.

A. LTE Cloud-RAN network model

We consider, as illustrated in Fig. 2, a set of K coordinating RRHs denoted by $\mathcal{K} = \{k \mid 1 \leq k \leq K\}$. The latter are operating in Frequency Division Duplexing (FDD) mode. We denote by $\mathcal{N} = \{i \mid 1 \leq i \leq N\}$, the set of N UEs attached to the RRHs. Orthogonal Frequency Division Multiple Access (OFDMA) is considered with frequency reuse equals to 1. Note that all RRHs deal with the same set of L available Physical Resource Blocks (PRBs) in which the assignment decision is performed by the SDN controller. This set is denoted by $\mathcal{J} = \{j \mid 1 \leq j \leq L\}$. Besides, we consider that cell edge UEs (e.g., UE3), belonging to $\mathcal{N}_1 \subset \mathcal{N}$, are scheduled based on a frequency reuse equals to 1/3. It means that these UEs share the same subset of PRBs $\mathcal{J}_1 \subset \mathcal{J}$ of the coordinating set's cell edges in an independent manner of the UEs localized in the cell center.

B. Enhanced Dynamic Point Selection Problem

In this paper, we deal with the downlink resource allocation problem of **cell edge mobile users** supporting CoMP technology. Each UE is connected at Radio Resource Control (RRC) level to one serving RRH but may receive data from other RRHs belonging to the coordinating set. Each user requests an amount of bandwidth which can be expressed as a number of requested PRBs.

Let B_i^k be the UE$_i$'s throughput ensured by the RRH$_k$. The objective function can be formulated as follows:

$$\underset{i,k}{\text{maximize}} \sum_{i=1}^{N_1} \sum_{k=1}^{K} x_i^k B_i^k \tag{III.1}$$

where x_i^k is a binary variable such as:

$$x_i^k = \begin{cases} 1 & \text{if RRH}_k \text{ is selected to serve UE}_i \\ 0 & \text{otherwise} \end{cases}$$

We define R_i as the number of allocated PRBs for UE$_i$. Formally,

$$R_i = \sum_{j=1}^{L_1} y_i^j \tag{III.2}$$

where L_1 corresponds to the size of $\mathcal{J}_1$ and y_i^j is a binary variable defined as follows:

$$y_i^j = \begin{cases} 1 & \text{if PRB}_j \text{ is allocated to UE}_i \\ 0 & \text{otherwise} \end{cases}$$

The relation between UE$_i$'s throughput B_i^k offered by RRH$_k$ and the respective demand for PRBs D^i is defined by [8] as:

$$B_i^k = \frac{\text{TBS}\left(\text{MCS}^k, D^i\right)}{C} [\text{mbps}] \tag{III.3}$$

where TBS is the MAC transport block size function in bits as defined in [8] considering a baseline *Modulation and Coding Scheme* (MCS). C is a constant equal to 1000.

Consequently, B_i^k can be formulated as follows:

$$B_i^k = \beta_i^k \sum_{j=1}^{L_1} y_i^j \tag{III.4}$$

where β_i^k defines approximately the relation between the allocated PRBs and the Transport Block Size (TBS).

Our main objective is to maximize the overall throughput of edge users while considering their requirements. To do so, we jointly optimize the transmitting RRH assignment and the PRB allocation of cell edge UEs in each Transmission Time Interval (TTI). Such a problem could be formulated as an extension of the Dynamic Point Selection approach in Coordinated Multi-Point (CoMP) transmission. In fact, we aim to calculate both the best downlink transmitting RRHs and allocated PRBs, by selecting the best RRH in term of Channel Quality Indicator (CQI) and the convenient number of PRBs guaranteeing higher throughput. The calculation of the RRH assignment and PRB allocation is ensured by our centralized SDN controller in `Pgm-RAN`. We recall that the latter makes use of RAN information which is collected from the radio environment and then stored in the RAN Information Base (RIB). We denote our problem by `Enhanced-DPS`.

The Signal-to-Interference-plus-Noise Ratio (SINR) of UE$_i$, which is served by RRH$_k$ is defined as follows:

$$\gamma_{i,k} = \frac{p_{i,k}}{\sum_{t \in \mathcal{T}} p_{i,t} + \Psi_\sigma} \tag{III.5}$$

where $p_{i,k}$ corresponds to the received power at UE$_i$, from RRH$_k$, Ψ_σ represents the spectral density of the thermal noise. $\sum_t p_{i,t}$ corresponds to the interference caused by interfering RRHs. $p_{i,t}$ is the received power at UE$_i$ from interfering RRH$_t$. This power is estimated based on the distance between the UE$_i$

and the interfering RRHs denoted by $\mathcal{T} = \{t \neq k \mid 1 \leq t \leq K-1\}$.

UE can only be served by at most one RRH, which can be formulated as:

$$\sum_{k=1}^{K} x_i^k \leq 1 \ \ \forall i \in \{1, ..., N_1\} \tag{III.6}$$

One PRB can be allocated to only one UE. Consequently, it will be exclusively used by one transmitting RRH and muted by other coordinating RRHs. Formally,

$$\sum_{i=1}^{N_1} y_i^j \leq 1 \ \ \forall j \in \{1, ..., L_1\} \tag{III.7}$$

The total number of the allocated PRBs to an UE_i cannot exceed its requested volume. Formally,

$$\sum_{j=1}^{L} y_i^j \leq D^i \ \ \forall i \in \{1, ..., N_1\} \tag{III.8}$$

It is worth noting that a further step is needed to linearize the objective function containing product terms by a standard technique. To do so, we introduce for each term $x \cdot y$ an additional auxiliary binary variable λ_{xy} add three more linear constraints as follows:

$$\lambda_{xy} \leq x \,(a),\ \lambda_{xy} \leq y \,(b),\ \lambda_{xy} \geq x + y - 1 \,(c) \tag{III.9}$$

It is straightforward to see that the proposed model is an instance of Integer-Linear Programming (ILP) that compromises the joint RRH assignment and downlink OFDMA resource allocation of cell edge UEs. To solve this model, we put forward a two-stage algorithm presented in the following section.

IV. Proposal: Enhanced Dynamic Point Selection algorithm

In this section, we present our optimized joint RRH assignment and PRB allocation algorithm to solve the aforementioned problem. Our proposal takes profit from linear relaxations to deal with the underlying structure of the problem. Our scheme makes use of of Branch and Cut algorithm. The main idea consists in combining two powerful schemes: i) Gomory Cutting Planes and ii) Branch-and-Bound to ensure an efficient research and hence achieve faster the optimal solution.
Our algorithm `Enhanced-DPS` proceeds as follow. First, the binary variables are relaxed into continuous values varying between 0 and 1. Afterwards, the relaxed problem is solved using *simplex* algorithm. Once the optimal relaxed solution is calculated, we check wether fractional values for variables exist or not. If the optimal solution includes at least a fractional value for a variable, then a *branch* is executed on that variable. Indeed, the main idea is to add new linear constraints that eliminate fractional solutions to the LP without eliminating any integer solution. In this context, a branch corresponds to two subproblem nodes which are scheduled to be recursively solved while adding new inequality constraints.
Each cut bounds the variable in subproblems by 0 or 1. The procedure is repeated until a set of feasible integral solutions including the optimal one is found. Note that, a subproblem node is *pruned* if its objective-function value in the relaxed solution is worse than the best integral solution reached so far. By doing so, the search for the optimal integral solution becomes considerably faster. Algorithm 1 illustrates the pseudo-code of our proposal `Enhanced-DPS`.

Algorithm 1: Pseudo-code of `Enhanced-DPS`

1 Inputs: LP Model p^0
2 Output: V^* as $[\boldsymbol{x^*}, \boldsymbol{y^*}]$
3 Let $\mathcal{L} = \{p^0\}$ be the set of active problem nodes
4 $f^* \leftarrow -\infty$
5 **repeat**
6   Select and delete a problem p^l from $\mathcal{L}$
7   Resolve $\tilde{p}^l$, relaxed version of p^l, with continuous V^*
8   **if** *$\tilde{p}^l$ is infeasible* **then**
9   Go back to step 6
10   **else**
11         $\tilde{V}$ is the optimal solution with an objective function value $\tilde{f}$
12   **if** $\ f \leq f^*$ **then**
13   Go back to step 6 // cut the branch
14   **if** $\ \tilde{V}$ *are all integer* **then**
15             $f^* \leftarrow \tilde{f}$
16             $V^* \leftarrow \tilde{V}$
17   Go back to step 6
18   Search for cutting planes $\mathcal{C}$
19   **if** $\ \mathcal{C} \neq \emptyset$ **then**
20   **for** $c \in \mathcal{C}$ **do**
21             $p^l = p^l \cup \{c\}$
22   Go back to step 7
23   **else**
24   Branch to partition the problem into new problems with restricted feasible regions
25   Add these problems to $\mathcal{L}$
26   Go back to step 6
27   return V^*
28 **until** $\mathcal{L} = \emptyset$;

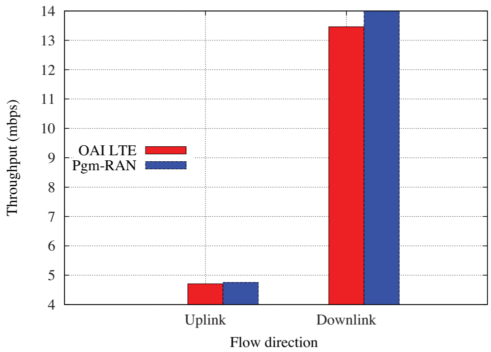
V. Performance evaluation

In this section, we will assess the fesability of our `Pgm-RAN` framework and evaluate the performance of our SDN-based solution `Enhanced-DPS` in realistic conditions. To do so, experimental testbed and simulation environment have been designed and implemented. Firstly, we made use of the testbed to evaluate the fronthaul performance in terms of latency, the UE's throughput and the CPU consumption in the Cloud-RAN environment. Then, we measure its impact on UE 's QoS. Secondly, in order to evaluate our `Enhanced-DPS` application performances, we have designed and implemented a discrete event Java based simulator. Finally, we compare our solution to the conventional Round Robin scheduler implemented in Open Air Interface in terms of i) offered throughput, ii) resource block usage and iii) interference mitigation.

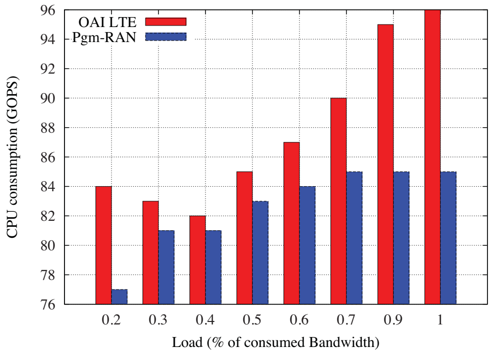
A. Experimental platform

We make use of OAI platform. The Latter offers a full stack layer eNodeB which can operate thanks to an USRP Card emulating the eNodeB antenna and also an emulated EPC (i.e., Evolved Packet Core) including MME (i.e., Mobility Management Entity), HSS (i.e., Home Subscriber Server) and SPGW (i.e., Serving-PDN Gateway).
Our prototype, relies on `Pgm-RAN` framework. It is in accordance with the NGFI Cloud-RAN architecture, wherein the baseband processing functions are carried out at the Radio Cloud Center node, which in turns sends I/Q samples to the Radio Remote Unit via a fronthaul interface. Note that the prototype relies on an Ethernet-based fronthaul to interconnect RCC and RRU. The Cloud-RAN architecture adopts the IF4p5 splitting provided by OAI. It is worth noting that IF4p5 refers to the split-point at the input (TX) and output (RX) of the OFDM symbol generator. More details about the Cloud-RAN splitting solutions, made available by OAI, are provided here[1].
In our prototype, the RRHs consist of Ettus USRP B210 card [3] which are connected to servers via USB 3:0 interface. Each server has a processor power (CPU) Intel Core i7-3770 8-core (@3GHz), and a Random Access Memory (RAM) of 16 GB performances. It is running with a Ubuntu 14:04 operating system characterized by a Linux kernel release 3:19:0-61-lowlatency SMP PREEMPT and has 1 Gigabit Ethernet port. The RRHs are connected to the RCC through Ethernet cable. The RCC, which implements the remaining levels of the

[1]www.openairinterface.org



(a) CPU consumption vs Traffic load



(b) Downlink and Uplink throughput comparison

Fig. 3. `Pgm-RAN` vs OAI LTE

LTE protocol stack in accordance with IF4p5, consists in a server, characterized by i7 - 6500U 4-core (@2.50GHz) CPU and RAM of 16 GB. The latter is running with the same operating system as the RRH. Upon the aforementioned operating system, we run a VMware Ubuntu 14:04 Virtual Machine where all the functionalities of the Core Network are implemented by the OAI software. We recall that the RCC runs an SDN controller, which is based on our implemented DPS framework.
We used physical cell phones (Samsung Galaxy 4, Nexus 4 and Sony ExperiaM4). The OAI software allows creating an emulated LTE network operator which does not permit cooperation with security rules of the newest android operating systems. This is due to the connection with an unknown operator. For this reason, we used only LTE cell phones with an operating system of android version 5.0 Lollipop. Our cell phones operate using configurable Sim card, programmed with the Sim Card writer according to [3]. Further details about our demonstrator could be found on this link[2].

B. Experimental results

We compare the vanilla LTE OAI solution (i.e., non splitted eNodeB) to `Pgm-RAN` in terms of CPU consumption and Round Trip Time (RTT) delay's fronthaul performance. Besides, we evaluated UE's throughput with both solutions to investigate the impact of our solution on the QoS.

In Fig. 3(a), we evaluated the CPU consumption while varying the frontahul traffic load between 10% and 100% of the total bandwidth. To do so, `Pgm-RAN` dynamically sets the amount of allocated resource blocks to achieve the required load. It is straightforward to see that OAI LTE (4G) consumes more CPU than `Pgm-RAN`, especially for high load. This can be explained by the fact that the RRU and RCC containers deployed in the data center are less consuming than the physical eNodeB software.
In Fig. 3(b), downlink and uplink throughput are evaluated for both `Pgm-RAN` and OAI LTE solutions. We notice that, with `Pgm-RAN`, the UE is experiencing the same throughput as with OAI LTE. It is worth noting that this is valid for both directions. Such a result shows that the deployment of our splitted SDN based RAN is fully transparent for UEs and the fronthaul has not impact on their QoS.
Finally, we measured the average RTT delay on the fronthaul with `Pgm-RAN` using ping tool. It is equals to 0.1 ± 0.03 ms which is significantly lower than 1 ms which corresponding to the time budget allocated for propagation and processing.

[2]https://youtu.be/uWqLUOavfI0

C. Network simulation environment and setup

We designed and implemented a discrete event simulator written in Java to evaluate the performances of our proposal in larger scale. The latter integrates both i) `Enhanced-DPS` approach and ii) conventional OAI scheduler. We simulated a wireless LTE environment consisting of a RRHs's coordinated set, each one at the center of a hexagonal cell. The distance between two nearest RRHs is 1 Km. The bandwidth is set to 5 MHz which corresponds to 25 PRBs. The transmit power, the transmit Power Gain and the thermal Noise are fixed to 5 watt, 3 dBi and -174 dBm/Hz respectively. Path loss model is expressed as follows: $148.1 + 37.6 \times log_{10}$. We used IBM's linear solver CPLEX [9] to implement our model. We assume that UEs are randomly distributed and their number varies between 4 and 10 users. The results are obtained over 30 simulation instances with a confidence interval of 95%. Note that tiny confidence intervals are not shown in the following figures.

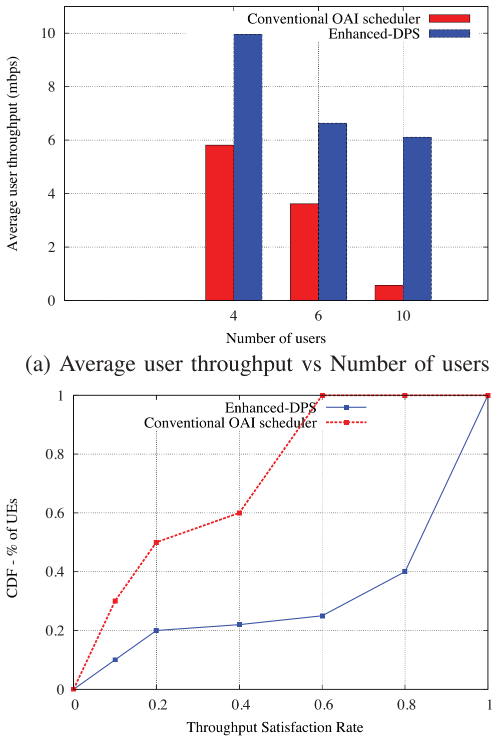
D. Simulation results

Fig. 4(a) depicts the average throughput while varying the number of served UEs. It is straightforward to see that when the number of users increases, the average throughput decreases which is due the PRBs consumption. Thanks to the interference elimination, `Enhanced-DPS` achieves high throughput compared with the conventional scheduler which operates without coordination and consequently is considerably affected by the inter-cell interference. We recall that, when relying on the conventional scheduler, the users are always served by their serving RRH. That is why we evaluated a scenario of overlapped RRH's cells, where a user can still in the serving RRH coverage area while entering the neighbouring RRH's coverage area which could offer a better quality of channel. Thanks to `Enhanced-DPS`, the users could be served by a new transmitting RRH when the latter is able to provide better QoS. In doing so, we can load balance between coordinated RRHs.
Besides, we evaluated the throughput satisfaction rate (i.e., TSR) of UEs. Note that TSR corresponds to the satisfaction degree of an UE with respect to its initial demand. Hence, it can be expressed as the ratio of the number of its allocated PRBs on its initial demand D. Fig. 4(b) shows the Cumulative Distributed Function (CDF) of the TSR. We can observe, by comparing the `Enhanced-DPS` and the conventional OAI scheduler CDF, that for the former, more than 50% of UEs have their TSR greater than 90%. The TSR is lessened to 30% with the conventional scheduler. The obtained results corroborate the previous ones confirm that our proposal is capable of enhancing UEs QoS.

VI. Related Work

The emergence of SDN has offered new opportunities to mobile networks. Thanks to the separation between the control and data planes, the network management is considerably optimized. Most of SDN research [10] [11] deals with the core part of mobile networks. In this context, SDN offers the opportunity to efficiently manage both traffic and mobility while ensuring a better scalability and higher performances.

The adoption of SDN in radio access networks infrastructures is still not well investigated. Though, such an innovative technology is envisioned as a key enabling approach for radio resource management in radio access networks infrastructures. Indeed, thanks to the centralization of baseband processing,



(a) Average user throughput vs Number of users

(b) CDF vs Throughput Satisfaction Rate

Fig. 4. `Enhanced-DPS` vs Conventional OAI scheduler

SDN provides the appropriate tools to deploy more powerful resource management algorithms leveraging the real-time centralized control and the accurate view of the network. In spite the aforementioned advantages, only few papers deal with RAN issues using SDN in a practical manner. In [12], authors put forward a centralized control plane for radio access network called SoftRAN. The main idea is abstracts all base stations in a local geographical area as a virtual big-base station comprised of a central controller and radio element to enable dynamic management of radio resources. FlexRAN [6] is a programmable SDN controller providing a control plane to deploy real-time RAN control applications. Thanks to its flexibility, it offers the capability to modify the degree of coordination among base stations in order to realize both distributed and centralized control operations control over time.

Inter-cell interference mitigation techniques, specifically Coordinated Multi-Point transmission, have been extensively studied. Many works advocate various approaches to increase UEs data rate while enhancing the overall coverage [13] [14] [15] [16]. CoMP encompasses a set of enhanced techniques that allows an efficient deployment of future heterogeneous networks, while improving the user throughput at cell edge. With the advent of Cloud-RAN, some papers have proposed novel solutions to take profit from the centralization of BBUs to facilitate inter-cell interference mitigation and thus, reduce the complexity of coordination and communication between distributed eNodeBs. In [13], authors put forward the capability of C-RAN to enhance Inter-cell interferences and to enhance the signal quality. Indeed, thanks to the centralization and the coordination of baseband processing among eNodeBs, CoMP techniques can be easily implemented. Authors, in [14], explore Cloud-RAN architecture as an enabler for CoMP. Their main idea is to split the physical layer processing between Remote Radio Units and the central processing unit for a subset of users to enable uplink Joint reception CoMP scheme, while maintaining an affordable fronthaul transport infrastructure.

The main contribution of our paper is to design and implement an SDN solution enhancing radio resource management in Cloud-RAN environment. Unlike [13] [14], our framework deals with the issue of decoupling the control and data planes in the RAN in concrete and practical manner. We extended FlexRan solution proposed in [6] to support enhanced CoMP technology. By doing so, we improve the UEs's QoS through thanks centralized multi-cell cooperation while mitigating inter-cell interferences.

VII. Conclusion

In this paper, we tackle the radio resource management in Cloud-RAN. To do so, we design and implement, first, an SDN-based architecture to enhance the radio resources allocation and hence improve the UE's throughput. To do so, our solution relies on OAI tool and an extended version of FlexRAN. Second, we put forward a novel scheme named `Enhanced-DPS` which optimizes jointly OFDMA resource allocation and RRH assignment of edge cell UEs. We evaluate through both experimental and simulation environments the performance of our proposed solution compared with the conventional OAI scheduler. As an extension of this work, we are considering a network slicing northbound application in order to show the efficiency of our framework. In this context, new challenges must be addressed in order to isolate radio resources and enhance their scheduling between operators.

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