

Traffic-Aware Dynamic Functional Split for 5G Cloud Radio Access Networks

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Abstract—The recent adaption of virtualization technologies in the next generation mobile network enables 5G base station to be segregated into a Radio Unit (RU), a Distributed Unit (DU), and a Central Unit (CU) to support Cloud based Radio Access Networks (C-RAN). RU and DU are connected through a fronthaul link. In contrast, CU and DU are connected through a midhaul link. Although virtualization of CU gives benefits of centralization to the operators, there are other issues to be solved such as optimization of midhaul bandwidth and computing resources at edge cloud and central cloud where the DUs and CUs are deployed, respectively. In this paper, we propose a dynamic functional split selection for the DUs in 5G C-RAN by adopting to traffic heterogeneity where the midhaul bandwidth is limited. We propose an optimization problem that maximizes the centralization of the C-RAN system by operating more number of DUs on split Option-7 by changing the channel bandwidth of the DUs. The dynamic selection of split options among each CU-DU pair gives 90% centralization over the static functional split for a given midhaul bandwidth.

Index Terms— 5G, dynamic functional split, fronthaul, midhaul, virtualisation.

I. INTRODUCTION

The recent exponential growth of network users and enormous capacity requirements of mobile applications such as high definition video streaming and AR/VR videos imposes high requirements on future networks. In anticipation of such high need, Mobile Network Operators (MNOs) and researchers have investigated various solutions such as Massive multiple-input multiple-out (MIMO), Millimeter-wave (mmWave) communications, or deploying small cells to offload the load of macrocells. Each of these solutions has its limitations. Some challenges related to channel estimation, user scheduling, energy efficiency, and deployment cost have been discussed by authors in [1]. Therefore, Cloud Radio Access Network (C-RAN) has emerged as a prominent solution that can support up to hundreds of gigabit data rates cost-effectively without degrading the performance [2]. In recent times, industries are adopting C-RAN architecture for the 5G network [3] due to less CAPEX and OPEX in deployment and better scalability. C-RAN is considered as an architectural solution that can reduce the CAPEX & OPEX in dense 5G cellular networks while allowing better network performance.

In 5G C-RAN, the Base Station (BS) (also known as gNB) protocol stack is divided (*i.e.*, it is functionally split) into the following network components [4]: (i) the Central Unit (CU) which consists of the upper layers of the protocol stack such as Packet Data Convergence Protocol (PDCP) and Radio Resource Control (RRC); (ii) the Distributed Unit

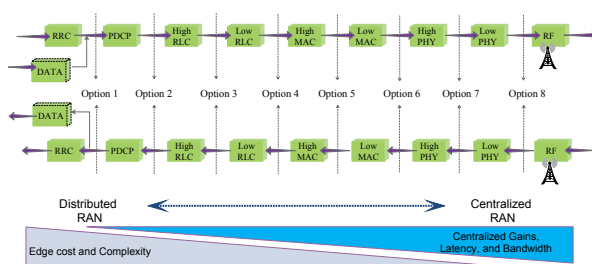


Fig. 1: Split options as defined in the 3GPP TR 38.801.

(DU) which consists of the lower layers of the protocol stack such as Radio Link Control (RLC), Medium Access Control (MAC), and Upper Physical (U-PHY) layer; (iii) the Radio Unit (RU) which consists of the Lower Physical (L-PHY) layer functionalities. The RU and DU communicate over a fronthaul interface (also called as fronthaul I) while DU and CU communicate over a midhaul interface (also called as fronthaul II). The fronthaul requirement depends on the functional split selected and network bandwidth used. As shown in Fig.1, the 3GPP has proposed various functional splits [5], and the choice of optimal functional split by MNOs depends on several factors related to radio network deployment scenarios, traffic constraints, and intended supported services. Moreover, computationally costly operations like Fast Fourier Transformation (FFT), Inverse Fast Fourier Transformation (IFFT), Rate Matching, and Turbo encoding/decoding are shifted to the CU side as we move towards Option-8 from Option-1. MNOs intend to use Option-7 or Option-8 to gain maximum centralization and other benefits at the cost of more network bandwidth for the midhaul interface. Authors in [6] proposed a flexible functional split solution in which authors choose the different split options for each CU-DU pair based on the resource available. Due to limited resources, only a few CU-DU pairs can operate on Option-7 or Option-8. We accentuate that, the requirement of high network bandwidth for Option-7 or Option-8 primarily depends upon transferring IQ (Inphase and Quadrature) samples and other signaling information from DU to CU and vice-versa. Furthermore, the number of IQ samples generated is based on channel bandwidth used by BS. Dynamically tuning the channel bandwidth is a viable option that supports the above proposition in the 5G C-RAN architecture. Based on available computing resources, most of the existing literature optimize the delay experienced in fronthaul or midhaul link [7]. To the best of our knowledge, none of the recent works take into account the channel

bandwidth in C-RAN. Hence, to mitigate challenges incurred due to high channel bandwidth in 5G C-RAN, we propose a Traffic-Aware Dynamic Functional Split that inculcates the channel bandwidth as one of the key parameters. The major contributions are summarized as follows:

- A dynamic functional split for 5G C-RAN is proposed to leverage midhaul bandwidth, and resulting maximum centralization by efficiently tuning channel bandwidth considering spatio-temporal traffic heterogeneity.
- An optimization problem is proposed to optimally select functional split for a given traffic load at a given time.

II. TRAFFIC AWARE DYNAMIC FUNCTIONAL SPLIT SELECTION

The bandwidth and latency budget required to run a fully centralized 5G C-RAN is very high, *e.g.*, Option-8 of the 5G C-RAN with 100 MHz channel bandwidth and 32 antennae requires a midhaul bandwidth of 157.3 Gbps [8]. Such a high bandwidth is neither cost-efficient nor energy-efficient for MNOs. Moreover, deploying isolated gNBs is also not an adequate solution to meet the data rate requirement of the 5G network [9]. According to the 3GPP, 5G RAN can support a downlink peak data rate of up to 4 Gbps using a channel bandwidth of 100 MHz [10]. Due to diurnal human activity pattern, the spatio-temporal traffic heterogeneity (tidal traffic) results in non-uniform utilization of available channel resources at the BS [11]. The BS suffers from resource shortage during peak hours, and resources remain idle during non-peak hours. Hence, a dynamic scheme to efficiently utilize channel bandwidth coping with varying traffic load is of utmost importance.

Table I shows the peak downlink traffic and midhaul bandwidth requirement for different functional split options for difference channel bandwidths [10]. From the table, we want to accentuate that Option-7 and Option-8 are traffic independent functional splits, *i.e.*, midhaul bandwidth requirements for these options do not change based on the BS load. On the other hand, the bandwidth requirement for Option-2 and Option-6 changes with BS load *i.e.*, the midhaul bandwidth requirement is the User Traffic (UT) from the BS with an added fixed overhead based on the split option used. These key features

Split Option	Channel BW MHz	Midhaul BW Gbps	Max DL Traffic Gbps
Option-2	100	$UT + 0.016$	4
Option-6	100	$UT + 0.133$	4
Option-7	100	9.4	4
	80	7.52	3.2
	60	5.64	2.4
	40	3.76	1.6
	20	1.88	0.8
Option-8	100	157.28	4
	80	125.8	3.2
	60	94.37	2.4
	40	62.9	1.6
	20	31.45	0.8

TABLE I: Maximum downlink traffic and midhaul bandwidth requirement for different channel bandwidths of 5G RAN

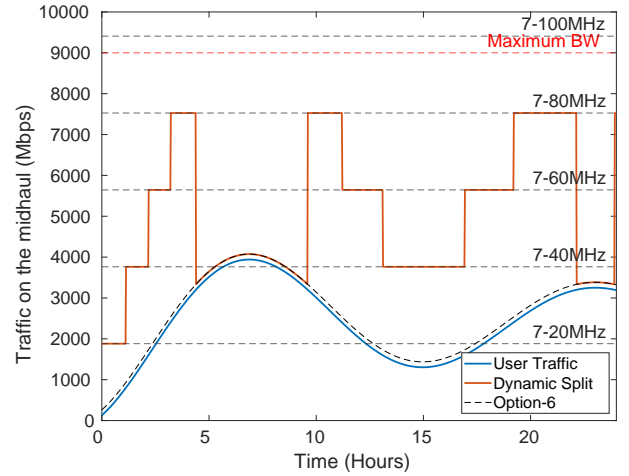


Fig. 2: Midhaul traffic generated by 5G C-RAN implementing a traffic aware dynamic functional split.

enable us to perform dynamic functional split in 5G C-RAN to achieve maximum centralization for a given midhaul bandwidth. Fig. 2 shows an example scenario to demonstrate the benefits of using dynamic functional split based on channel bandwidth. The maximum available midhaul bandwidth is assumed to be 9 Gbps in the figure. When the traffic changes, the dynamic split technique can switch from Option-7 20 MHz to Option-7 80 MHz to support the traffic load beyond which the midhaul bandwidth becomes the bottleneck. At this point, the BS can switch to Option-6 100 MHz. Here, we do not consider Option-8, because for a minimum channel bandwidth (*i.e.*, 20 MHz), it requires 31.45 Gbps midhaul bandwidth for a one CU-DU pair. We are assuming that the operator does not have enough resources to provide such a high bandwidth to each CU-DU pair. Moreover, our model scrutinizes either Option-2 or Option-6 due to similar midhaul bandwidth requirement for these options. We can observe that, the dynamic functional split technique can give more centralization which in turn can benefit from Coordinated Multi-Point (CoMP), Inter-Cell Interference Coordination (ICIC) [12], and energy efficiency by adapting to change in the BS load. In this paper, we propose an optimization model that can result best possible functional split for BSs of 5G C-RAN with an objective of maximizing the centralization for a given midhaul bandwidth.

III. OPTIMAL FUNCTIONAL SPLIT AS AN OPTIMIZATION MODEL

Let \mathcal{B} be an array of different channel bandwidths in descending order which represents the breakpoints for Option-7 functional split (*i.e.*, 100 MHz, 80 MHz, 60 MHz, etc.). The operator is assumed to use aforementioned set of bandwidths for the BSs. In our model, we assume that this set is same across all the BSs in the network. But the model can be extended for different set of bandwidths for each of the BSs as well. A glossary of mathematical notations used in optimization model are highlighted in Table II. For each split option i , we can calculate the midhaul bandwidth cutoff $W(i)$ using Eqn.(1). Here, $i = 1$ means Option-6, while $i > 1$ means Option-7 with different channel bandwidth given in set \mathcal{B} .

Notation	Definition
UT_i	User traffic at DU_i in Mbps
n_{DU}	Number of DUs
BW_i	Midhaul bandwidth of i_{th} DU
BW_{max}	Maximum midhaul bandwidth available
x_i	A binary variable which indicates if DU i uses Option-7 (0) or Option-6 (1)
W	A set of bandwidth cut off for each of the available split options
w_i	Index of the elements in list W

TABLE II: Variables used in the Optimization Model

$$W(i) = \begin{cases} 133 \text{ Mbps,} & \text{if } i = 1 \\ 9.408 \times \mathcal{B}(i-1) \text{ Mbps,} & \text{if } i > 1 \end{cases} \quad (1)$$

The midhaul bandwidth required for each DU i , $W(i)$ for a given split option x_i can be calculated by Eqn.(2).

$$BW_i = x_i \times UT_i + W(w_i) \quad (2)$$

where

$$w_i = x_i + k(1 - x_i)$$

and

$$k = 1 + \text{index in } \mathcal{B} \text{ to support } UT_i$$

The objective function of our optimization problem that finds the optimal selection of split option for each DU is given below in Eqn.(3) and constraint in Eqn.(4). The value of $W(w_i)$ and BW_i are given in Eqn.(1) and Eqn.(2), respectively.

$$\max_{x_i, w_i} : \left(\underbrace{\sum_{i=1}^{n_{DU}} x_i \times UT_i}_{(A)} + \underbrace{W(w_i) \times (1 + UT_i)}_{(B)} \right) \quad (3)$$

$$\sum_{i=1}^{n_{DU}} BW_i \leq BW_{max}; \quad (4)$$

- 1) Term A in the objective function maximizes the midhaul bandwidth utilization by considering maximum centralization for the given set of BSs.
- 2) Term B in the objective function ensures that the DUs with higher number of users are considered over DUs with less number of users in order to achieve more centralization.

The constraint given in Eqn.(4) ensures that the sum of midhaul bandwidths utilized for each CU-DU pair does not exceed the available midhaul bandwidth in the RAN network. This optimization model is flexible enough to consider any set of channel bandwidths that the BS can operate. Apart from deciding the split option for the DUs, the optimization also provides the channel bandwidth to be used when Option-6 is considered for the DUs.

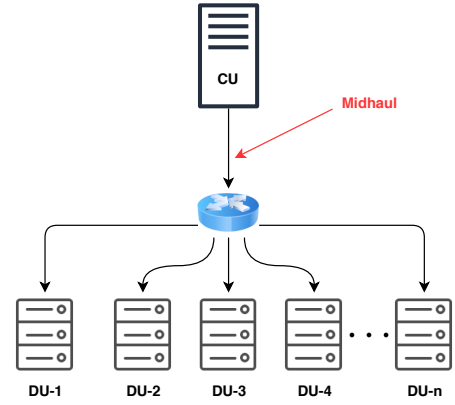


Fig. 3: Setting up CU-DU using a shared midhaul network.

IV. PERFORMANCE EVALUATION

A. Experimental Setup

To evaluate the benefits of the proposed dynamic functional split mechanism, we consider a RAN architecture based on the reference architecture of the 3GPP [13]. Fig. 3 shows the considered RAN topology which consists of a CU that connects with the DUs through an optical network connected switch. In our model, we assume that the optical network has a fixed allocated bandwidth between the CU and the DUs which is very much essential for the C-RAN requiring guaranteed bandwidth and delay budget. Moreover, the CU is assumed to possess sufficient computing resource for the split option selected for all the DUs given by the algorithm (*i.e.*, CU computing resource is not a bottleneck here). For a realistic traffic pattern for the load on the DUs, we consider the data collected from a real network available at [14]. The data is collected in an LTE network for approximately 1 year in 57 cells at every 1 hour interval. As the data is collected in an LTE network, we have scaled the data using Eqn.(5) to make it suitable for 5G network. As given in Table I, the maximum data rate of a 5G BS having a 100 MHz channel is considered to be 4 Gbps.

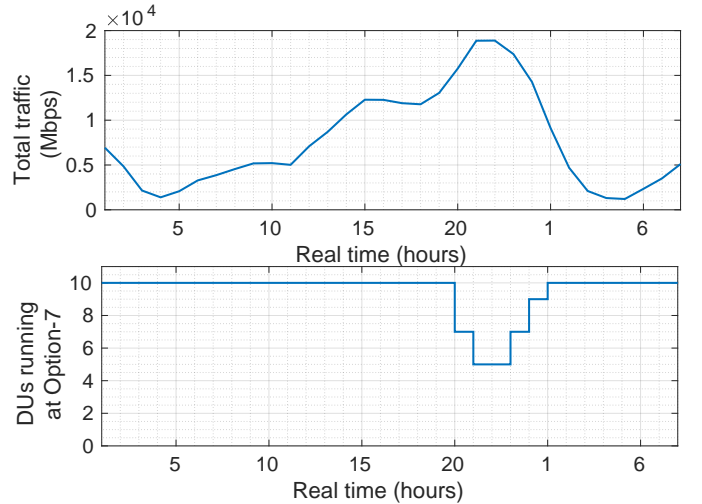


Fig. 4: Number of DUs centralized (lower part of figure) w.r.t. variation in total traffic load of DUs (upper part of figure).

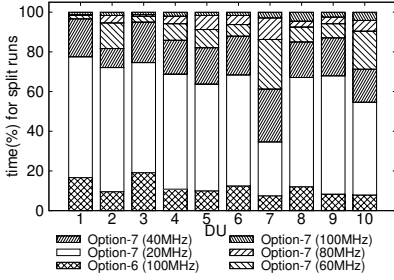


Fig. 5: Percentage of the time each DU operates on different functional split options.

$$DU_i = \frac{4Gbps}{\max\{UserTraffic_{DU_i}\}} \quad \forall DU \in \text{Dataset} \quad (5)$$

In the scaled dataset, we have chosen 10 DUs among the 57 DUs, that are placed at a different geographical locations following distinct traffic patterns. A subset of DUs are placed near the commercial area while remaining DUs are located in residential colonies. We used the data for these 10 DUs for 10 consecutive days to observe the effect of both weekday and weekend traffic patterns. We considered only 5 channel bandwidths given in Table I and a RAN network similar to Fig. 3 where all the 10 DUs are connected to a single CU sharing the midhaul bandwidth. A midhaul bandwidth of 41 Gbps is considered which is sufficient to run all the 10 DUs in Option-6 with 100 MHz. Hence, we do not scrutinize Option-2 with 100 MHz in our experiment. The main benefit of the dynamic function split is to use the tidal traffic pattern of the BSs and optimally use the available midhaul bandwidth. For the simulation, we solve the optimization problem for every time epoch of traffic data, to find the optimal functional split for each of the 10 DUs. We present the results obtained over 30 simulation [15] trials.

B. Centralization benefits of dynamic functional split

Fig. 4 shows the number of DUs centralized with varying traffic load (sum of downlink traffic of 10 DUs) for a period of 32 hours. We observe that, all the DUs are able to achieve maximum centralization (using Option-7) in low and moderate traffic conditions. During high traffic load, 6 DUs are running on Option-7 with different channel bandwidth while other DUs are running Option-6 with 100 MHz channel bandwidth. If the operator chooses Option-7 100 MHz statically for 10 DUs, it costs operator 90 Gbps midhaul bandwidth, which is only needed during the high traffic load. Consequently, the operator underutilizes the network resources during low and moderate traffic loads.

C. Percentage of time each DU operates on different functional split options

Fig. 5 shows the percentage of time each DU operates on different split options over a 10 days period for given midhaul bandwidth. Note that, about 60% of the time, each DU is able to operate on Option-7 with 20 MHz channel bandwidth, i.e., each DU is achieving the maximum centralization without compromising on meeting the required BS capacity for a

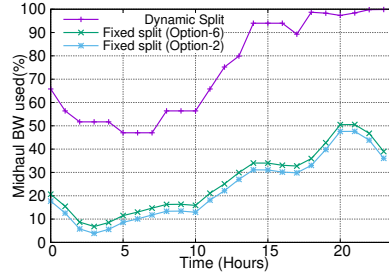


Fig. 6: Percentage of midhaul bandwidth used by different functional split options.

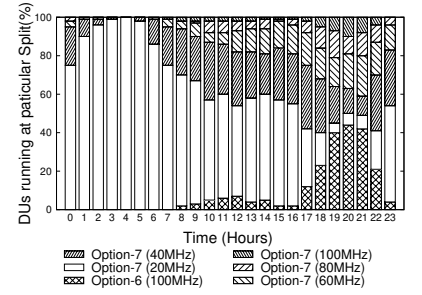


Fig. 7: Percentage of DUs operate on different functional split at different time of the day.

given midhaul bandwidth. We could not achieve this maximum centralization for 60% of the time if we have considered the Option-7 with a fixed channel bandwidth of 100 MHz.

D. Percentage of midhaul bandwidth used by different functional split options.

Fig. 6 compares and contrasts among dynamic functional split, fixed functional split (Option-6), and fixed functional split (Option-2) with respect to percentage of midhaul bandwidth used at different time of a given day. We observe that, dynamic split uses available bandwidth optimally while Option-6 and Option-2 use maximum 50% of the midhaul bandwidth only during the peak traffic hours. We haven't shown the fixed functional split (Option-7), because the available midhaul bandwidth is not sufficient to handle all the DUs.

E. Percentage of DUs operate on different functional split options at different time of the day

Fig. 7 depicts the percentage of DUs among the 10 DUs in our experiment operating on each of the functional split options at every hour of the day. We can observe that, during the early hours (12 AM - 9 AM), most of the DUs operate on Option-7 20 MHz channel bandwidth as the traffic loads on the DUs are very low during this period. During medium traffic load (10 AM - 4 PM), most of the DUs operate on both Option-7 40 MHz and Option-7 20 MHz to meet the traffic requirement at each of the BSs. During the peak load (6 PM - 10 PM), only half of the DUs operate on Option-7 40 MHz and Option-7 60 MHz variations while remaining DUs operate on Option-6 to meet the traffic demand and with the limited midhaul bandwidth.

F. Percentage of time each functional split options were used for a 10 days period

Fig. 8 shows average percentage of the time different functional split options are used by 10 DUs over 10 days period. Option-7 with 20 MHz channel bandwidth is used for more than 50% of the time as we can observe from the traffic pattern in the dataset that peak traffic load for the BSs occur only for a small duration in a given day. We can see that, 90% of the time, the proposed dynamic functional split mechanism is able to maximize the centralization by operating them on Option-7 with one of the available channel bandwidths 20 MHz, 40 MHz, 60 MHz, and 100 MHz.

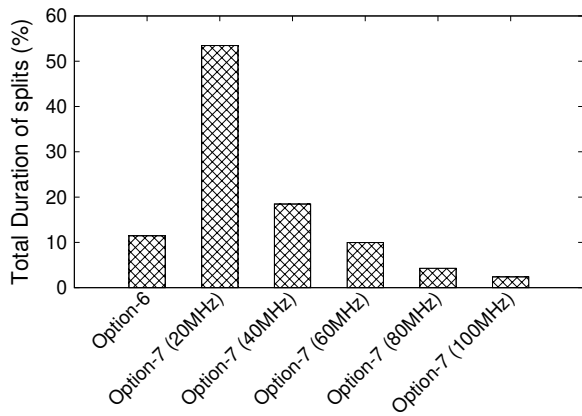


Fig. 8: Percentage of time each functional split options were used over 10 days period.

V. RELATED WORK

In the literature, trade-off between different functional splits are explored thoroughly. In [4], the author did the experimental evaluation of the impact of virtualizing eNB functions on the fronthaul latency and jitter budget when different virtualisation methods are utilized. Their results showed that lighter virtualization methods (e.g., Docker) are impacting the fronthaul latency budget for Option 7-1 (*i.e.*, intra-PHY) split less than heavier virtualization methods (e.g., VirtualBox). However, in all the cases, the fronthaul latency budget reduction depends on the considered signal bandwidth. The higher the bandwidth the higher the computations required and the higher the fronthaul latency budget reduction. The authors of [16] provide a comprehensive literature overview of the functional split options proposed by the 3GPP. Each functional split has been discussed in a detailed description of the location and abilities. This gives insight on what is being transmitted on the fronthaul link but also which functions are located in the DU and the CU, respectively. This also gives the impact of the chosen functional split on the fronthaul network connecting the DU to the CU-pool both in terms of fronthaul bitrates and latency. The authors in [17], proposed Flex5G which selects the appropriate functional split for different small cells utilizing midhaul bandwidth and minimizing the inter cell interference. The authors in [18] proposed a flexible function split between CU and DUs for delay critical applications and showed the impact of delay constraints on the required midhaul bandwidth and the power consumption. Their simulation results demonstrate that delay constraint has a significant impact on the required fronthaul bandwidth and power consumption.

In [4], the authors studied the effect on the latency budget available for the midhaul caused by the choice of functional split option and virtualization technology used in a virtualized C-RAN. All these works assume that either functional split between the CU and DU is fixed at the time of network deployment because the functional split for a given CU DU pair is based on the available midhaul bandwidth and the delay budget requirement of the specific functional split used. The authors of [19] presented an adaptive 5G RAN implementation that supports migrations between functional splits at run-time.

They described the challenges related to service disruption due to split migration at run time. Then a proposal to switch from MAC-PHY to PDCP-RLC without service interruption is given.

VI. CONCLUSIONS

In this paper, we proposed a dynamic functional split mechanism for 5G C-RAN to effectively use the midhaul bandwidth and achieve maximum centralization gains by tuning the channel bandwidth optimally. Optimal functional split selection for a given traffic load for the DUs is obtained using the proposed optimization model. We achieve 90% of centralization using our proposed mechanism, encompassing the channel bandwidth. This mechanism opens up a lot of other problems to be solved in the future such as how to switch between functional splits for a given cell site in real-time and cost-benefit analysis of different split options.

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