# Adaptive Function Chaining for Efficient Design of 5G Xhaul

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**Abstract.** Next generation fronthaul interface has been recently proposed to support different functional splits in 5G access networks. Each split option is characterized by different requirements in terms of latency and bandwidth. The mapping of different functional splits on the nodes of 5G access network introduces several degrees of freedom in relation to the variation of the traffic during the day. This paper proposes a novel function location algorithm, which adopts dynamic function chaining in relation to the evolution of the traffic estimate. The obtained results show remarkable improvement in terms of bandwidth saving and multiplexing gain with respect to conventional C-RAN fronthaul and suggest design criteria for the emerging 5G access network.

**Keywords:** 5G · Xhaul · NGFI · C-RAN · Function chain · Location algorithm · Multiplexing gain

## 1 Introduction

Today's networks continue to face rapidly growing traffic demands while supporting an increasingly wide range of services and applications. Future 5G is expected to provide end users with unbeatable user experience in terms of data rate, ultra-low latency, and unlimited access. In addition to enhanced Mobile Broadband (eMBB) service, 5G will exceed 4G systems with better support of two other kinds of applications: ultra Reliable Low Latency Communications (uRLLC) and massive Machine Type Communication (mMTC). These types of applications highly rely on optical networks. 4G radio access network with baseband processing at every access points may not scale well for the high capacity and a large number of demands which are expected in 5G networks [1].

Cloud/Centralized Radio Access Networks (C-RAN) have been proposed as a scalable solution by separating the radio components, namely Remote Radio Unit (RRU) from the BaseBand Unit (BBU), in order to gain the efficiency and flexibility of centralization and cloud computing for radio networks. C-RAN has demonstrated its advantages on network deployment speed-up, cost saving

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and power efficiency. Introduction of shared processing resources and commodity hardware used in the C-RAN architecture provide various benefits, such as low energy consumption, statistical multiplexing gain, and Coordinated Multi-Point (CoMP) transmission/reception.

In the 5G era, C-RAN is evolving by itself with additional features such as Software-Defined Networks (SDN), Network Function Virtualization (NFV) and new fronthaul solutions. In particular, NFV coupled with SDN control and management capabilities add extreme flexibility in service configuration and allow full exploitation of new methodologies that make service provisioning to shift from static hardware to dynamically reconfigurable virtual machines [2].

Despite C-RAN appealing design aspects, one key obstacle in its adoption is the excessive capacity requirements on the fronthaul links to provide BBU and RRU connections. Shifting all baseband processing to the remote BBU hotel implies the adoption of a high number of optical channels with strict latency constraints. To relax the excessive fronthaul requirements, the concept of C-RAN is being revisited, and more flexible distribution of baseband functionalities between the RRU and BBU hotel is considered. Rather than offloading all baseband processing to a single entity like the BBU hotel, it is possible to divide it into several blocks throughout the network which leads to significant reduction of the bandwidth needed on the transport links [3]. This concept is known as "functional split" and was firstly introduced in the new architecture design for the 5G access network named "xhaul" or "crosshaul" [4]. Next Generation Fronthaul Interface (NGFI) is defined as the fronthaul interface between BBU and RRU for the next generation of radio network infrastructure. NGFI redefines the baseband processing split through the positioning of baseband processing stack components between BBU and RRU. The basic idea of NGFI is to design a fronthaul interface with traffic-dependent and antenna-independent data rate. Traffic-dependent feature means that the data rate is dynamically changing with the real network traffic, i.e., as the traffic increases, the fronthaul data rate increases too and vice versa. In this way, the fronthaul transport capacity can be efficiently shared by actual traffic. The antenna-independent feature decouples the number of antennas and dedicated interfaces from the actual fronthaul traffic, by applying statistical multiplexing. In other words, the impact of the number of antennas is reduced and multiple antenna systems can be efficiently supported by fronthaul transport networks. Design methodologies to apply functional split in the 5G network in order to exploit this potential still need investigation. In particular, the bandwidth available on the fronthaul links should be efficiently used and dynamically allocated to service slices [5].

In this work, a methodology is proposed to implement an adaptive function chain, based on the dynamic 24-hour behavior of the antennas connected to a 5G access area. The aim is to achieve efficiently use of the bandwidth of the involved fronthaul segments. The effectiveness of the approach is shown in comparison with conventional C-RAN by evaluating the bandwidth multiplexing gain and taking into account the effect of different constraints, namely distance and processing units.

The paper is organized as follows. In Sect. 2 previous and related works are introduced. Section 3 describes the architecture and the methodology used in this work. The numerical results are reported in Sect. 4 and finally Sect. 5 draws the conclusions.

## 2 Related Work

One of the motivations of xhaul network is its ability to split different functions and executes them in separate entities. Functional splits determine the number of functions which stay locally and the number of baseband functions which are centralized in the relatively well-connected locations in the network. There is a vast number of works already done in the literature which study different functional splits.

The concept of NGFI (xhaul) was proposed for the first time in 2014 to meet the ambitious targets of 5G demands [4]. They specifically introduced a two-level NGFI architecture and defined in details the effect of different functional splits in their proposal. Main reasons to introduce NGFI for 5G deployment are the greatly reduced data rate, the independence of the number of antennas, the possibility to apply statistical multiplexing on fronthaul links. In [6], the authors proposed a dynamic PHY split strategy as well as using the edge data centers in order to distribute processing throughout the network so, as a result, optical transport requirements are reduced about 45 %. The heuristic algorithm considers only the split for PHY level and drops requests not finding a suitable connection to the data center. In a similar line of research, authors of [7] designed an adaptive strategy for placement of processing units in WDM-based aggregation network in case of dynamic traffic. Their results show striking a balance between processing unit consolidation and traffic blocking probability. Eliminating the blocking probability in such a system with sensitive requirements is one of our main goals in this paper.

The concept of "soft failure" has been investigated in [8]. The authors consider a soft failure as the degradation resulting in bit error rate over acceptable thresholds. In their performance evaluations, they investigated only two options, conventional C-RAN and split in PHY layer (options 8 and 7a respectively according to 3GPP terminology [9]). They run the system by option 7a and in case of distortion, the splits automatically scale up to option 8. Their proposal supported by the experimental evaluation clearly shows the ability of fast recovery of optical layer even when rerouting is not possible.

Transition from C-RAN to the new proposed architecture is a major issue which has to be addressed carefully. In [10] the authors proposed a framework for current C-RAN that can support both a flexible functional split and fronthaul transport protocol over Ethernet. Their results are obtained by OpenAirInterface (OAI), a software implementation of LTE/LTE-A systems, under two functional splits and different deployment scenarios.

The authors of [11] proposed similar architecture under the name "Flexible RAN" in which baseband processing distributed within the access network.

They investigated the trade-off between radio performance maximization and transport capacity minimization. They introduced two methods of distributions (fully and partially) and applied them on a ring and tree-like topology. Based on their results the full distribution of processing units can achieve better performance in terms of utilization of transport resources.

## 3 Architecture and Methodology

The methodology presented here is referred to the 5G network architecture as defined by 3GPP [9]. This architecture consists of two parts: radio access network and core network. The radio access network is expected to be based on concepts like xhaul which differs from current implementation in many ways. First, it extends between the user and the base station, which is called “gNodeB” (gNB). The gNB consists of three logical entities: Central Unit (CU), Distributed Unit (DU) and Remote Unit (RU). One gNB could contain one CU and multiple DUs and several RUs. In this sense, a gNB is a kind of mini-C-RAN. Each split option comes with different requirements such as latency, bandwidth, and usage of Processing Units (PU).

Figure 1 shows a 5G logical network architecture as divided into 3 parts. Fronthaul is the network segment from RU till the corresponding DU. The distance of these two entities can not be more than 20 km due to the delay sensitive functionalities which will be executed in DU. Normally the bandwidth in this segment is the highest because of the low layers splits. The network segment between DU and responsible CU, where upper layer BBU functionalities are performed, is called midhaul. Several DUs can reside in this part of the network which are connected to the same CU. The distance in this segment is more relaxed (80–100 km), compared to the fronthaul, due to more relaxed delay requirements of upper layers splits. The third part is the backhaul which is extended between gNB and the core network.

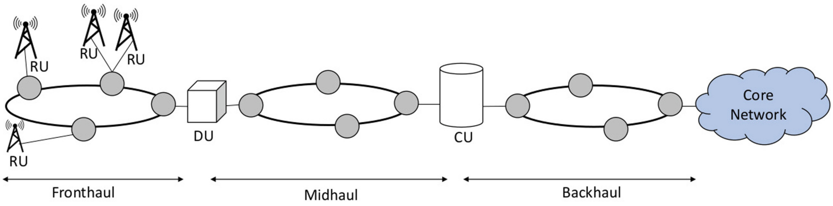

**Fig. 1.** Scheme of the xhaul network.

As far as the latency we assumed that the reference access network has a diameter less than 20 km, which ensures the latency constraint for the most demanding option 8, that is 250 microseconds. In addition, we need to assign the PUs to each functionality allocated in a node. The baseband functions can be executed on the General Purpose Processor (GPP) x86 architecture [12]. Based on [12] one Intel x86 CPU core with the 2.07 GHz frequency is considered suitable to meet the processing delay requirements. There are several splits options with specific requirements can be applied and investigated. Table 1 shows the three different functional splits chosen in this work and their requirements. Based on [13], each functional split is assigned a fraction of the total processing unit needed for whole functionality.

**Table 1.** Functional splits requirements

| Layers | Split option | Bandwidth [Gbps] | PU units |
|---|---|---|---|
| L1 | Opt.8 | 2.4 | 0.5 PU |
| L2 | Opt.6 | 0.152 | 0.3 PU |
| L3 | Opt.2 | 0.151 | 0.2 PU |

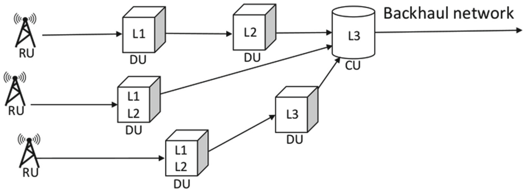

**Fig. 2.** Sample xhaul function chain configurations considered in the algorithm.

In relation to the adoption of different functional split options, in this paper, the classic residential-industrial traffic over 24 h has been considered but the approach presented here can be adapted to any other variation of the traffic. The possibility to dynamically assigning different functions to different entities

**Table 2.** Notation used in the algorithm

| | |
|---|---|
| $N$ | Set of nodes in the network $\|N\| = n$ |
| $d_i$ | Nodal degree of node $i \in N$ |
| $S_{DU,i}$ | Set of active DUs under the hop and processing units constraint for node $i \in N$ |
| $S_A$ | Set of active nodes in the network |
| $DU_i$ | DU in the location of node $i \in N$ |
| $P_i$ | Total processing units of the DU in node $i \in N$ |
| $P_{i,1}$ | Number of PUs for $L1$ in node $i \in N$ |
| $P_{i,2}$ | Number of PUs for $L2$ in node $i \in N$ |
| $P_{i,3}$ | Number of PUs for $L3$ in node $i \in N$ |
| $A_i$ | Number of active antennas at node $i \in N$ |
| $Path_{ij}$ | The shortest path between nodes $i$ and $j \in N$ |

and nodes in the access network is studied according to the traffic profile. As it can be seen in Fig. 2 this approach assumes that function splits are not statically assigned but instead, depending on the traffic demand and availability of the PUs, dynamic chaining of the function is configured based on the xhaul to efficiently allocate network resources. In order to make this function chaining feasible there are a few constraints that need to be taken into consideration:

- Latency: Among all the options for splitting, PHY and MAC layers are the most delay sensitive. The main reason is due to the Hybrid Automatic Repeat Request (HARQ) which is controlled by lower layer MAC and executed in the PHY layer. Splitting the PHY and MAC layers lead to stricter requirements over latency. In this work, we evaluated the latency parameters as a function of distance in terms of hops.
- Bandwidth: As we mentioned several times one of the major benefits of functional splits in the xhaul network, is the bandwidth usage reduction. Since NGFI is traffic dependent, in case of low traffic extra bandwidth can be used for other purposes. By implementing the functional chain, there is the possibility for executing the bandwidth hungry functions in the local or the closest DU. As a result, the outgoing low bandwidth signal can be routed throughout the network to be executed on another DU or in the CU.
- Processing units (PU): in the previous generation of the access network, all functionalities were executed in either data center or BBU hotels with high amount of resources. Xhaul, on the other hand, is introducing the possibility to perform some processing in DUs with a limited amount of processing resources (namely the number of PUs). In CUs, instead of unlimited processing resources are still considered, as in previous configurations. As a consequence, the proper dimensioning of the PUs in DUs is an important aspect of optimization.

The heuristic algorithm presented here aims at locating baseband functionalities in the access network as a reconfigurable function chain, by efficiently adapting to traffic generated by active antennas, in relation to distance (hop) and PU constraints. The problem to solve is formally defined as follows (Table 2):

- **Given** the physical network with interconnected nodes supporting antennas, the number and placement of CUs, the number of PUs in DUs and the daily traffic profile.
- **Find** the minimum number of active DUs according to delay (hops) and PU constraints in order to adapt to the daily traffic profile while dynamically reconfiguring the xhaul function chain.

**Algorithm 1.** Function chain

```
1  Initialization: $S_{DU,i}, S_A \leftarrow \emptyset$
2  while $(N \neq \emptyset)$ do
3      find node $i \in N$ s.t. $d_i$ is maximum
4      create $S_{DU,i}$
5      if $(S_{DU,i} \leftarrow \emptyset)$ then
6          $S_A \leftarrow DU_i$
7          $P_i = P_i - A_i * \sum_{x=1}^{3} P_{i,x}$
8      else
9          for each node $j \in S_{DU,i}$ do
10             if $(P_j \geq A_i * \sum_{x=1}^{3} P_{i,x})$ then
11                 $P_j = P_j - A_i * \sum_{x=1}^{3} P_{i,x}$
12                 update bandwidth in $Path_{ij}$
13             else if $(P_j \geq A_i * \sum_{x=1}^{2} P_{i,x})$ then
14                 $P_j = P_j - A_i * \sum_{x=1}^{2} P_{i,x}$
15                 update bandwidth in $Path_{ij}$
16                 if $(\exists\ z \in [S_{DU,i} - j]\ s.t.\ P_z \geq [P_{i,3}] * Ai)$ then
17                     $P_z = P_z - [P_{i,3}] * A_i$
18                     update bandwidth in $Path_{jz}$
19                 else
20                     find closest $CU$
21                     $P_{CU} = P_{CU} - P_{i,3} * A_i$
22                     update bandwidth in $Path_{jCU}$
23             else if $(P_j \geq P_{i,1} * A_i)$ then
24                 $P_j = P_j - P_{i,1} * A_i$
25                 update bandwidth in $Path_{ij}$
26                 if $(\exists z \in [S_{DU,i} - j]\ s.t.\ P_z \geq A_i * \sum_{x=2}^{3} P_{i,x})$ then
27                     $P_z = P_z - A_i * \sum_{x=2}^{3} P_{i,x}$
28                     update bandwidth in $Path_{jz}$
29                 else
30                     find closest $CU$
31                     $P_{CU} = P_{CU} - A_i * \sum_{x=2}^{3} P_{i,x}$
32                     update bandwidth in $Path_{jCU}$
33             else
34                 $S_A \leftarrow DU_i$
35                 $P_i = P_i - A_i * \sum_{x=1}^{3} P_{i,x}$
36         remove node $i$ from $N$
```

The algorithm is executed sequentially in all the nodes of the network. Each node has the possibility to execute the baseband functionalities but they are all assumed to be de-activated before starting the algorithm. The algorithm stops after the last node in the network executes the algorithm (the condition in line 2). It is also assumed that the dimensioning of the PUs has been precomputed and all DUs have a certain amount of available PUs.

The algorithm starts in line 3 in the node $i \in N$ with the highest nodal degree. The effect of the starting point in the assignment algorithm has been already studied [14]. Depending on different constraints (maximum distance and available PUs) the set $S_{DU,i}$ is created in line 4. This set is composed of all the possible DU candidates under the requirement constraints. If node $i$ is the first node that executes the algorithm or, the constraints are so tight that there is no possible DU candidate, then the set $S_{DU,i}$ turns out empty. Lines 5 to 7 investigate this situation. If node $i$ cannot find any DU, then it activates the DU in its own location and the active $DU_i$ will be added to the set $S_A$ in line 6. This set contains all active DUs in the network. In line 7 node $i$ uses the available PUs in $DU_i$. Since $DU_i$ is just opened, it has enough PUs to executes all the layers (line 7). On the other hand, if there are some possible DU candidates exist, a decision has to be made regarding the assignment (line 8). The decision making logic is based on finding the DU with the highest available PUs in order to execute all the layers and prevent routing and assigning the bandwidth throughput of the network. In line 9 each DU in the set $S_{DU,i}$ namely $DU$ in node $j$ is checked for the availability of the PUs. If DU in node $j$ has enough PUs that can execute all the layers (line 10) then node $i$ will be connected to the DU in node $j$ and related PUs will be assigned to it (line 11). For assigning the bandwidth, the algorithm finds the shortest path between nodes $i$ and $j$ which has been precomputed and allocates the required bandwidth to all the links associated to the $Path_{ij}$ (line 12). Lines 13 to 23 consider the situation when the chosen DU has only enough PUs to executes layer 1 and 2 (line 13). In that case, node $i$ will be connected to DU in node $j$ and uses the available PUs for layer 1 and 2 (lines 13–14). Upon the connection to DU in the node $j$, all the links in the $Path_{ij}$ also get the required bandwidth (line 15). For the execution of layer 3, the algorithm first searches for all the possible DUs namely $z \in S_{DU,i}$ under the required constraints (line 16). If such DU exists then node $i$ uses its PUs for executing layer 3 functions (line 17). The required bandwidth also will be assigned to all the links in the shortest path between nodes $j$ and $z$ (line 18). Otherwise, the shortest path towards all predefined CUs will be computed and the closest one will be identified (line 20) so that the rest of the functions will be routed and executed in that CU (lines 21–22). In line 23 the last possible scenario will be tested. If the available DU only has enough PUs for the execution of layer 1, then node $i$ will be connected to DU in node $j$ and executes layer 1 functions (line 24). The bandwidth in the shortest path between nodes $i$ and $j$ also will be updated in line 25. For the rest of the functions again the algorithm looks for all the possible DUs in the set $S_{DU,i}$ (line 26). If such DU exists, in line 27, the assignment for layer 2 and 3 is presented and the related bandwidth will be updated accordingly (line 28). Otherwise, the algorithm connects node $j$ to the closest CU (based on the shortest path) and uses the available PUs for executing layer 2 and 3 (lines 30–31). The related bandwidth will be updated accordingly in line 32. If none of the above conditions hold, then node $i$ activates the DU in its location and the new DU will be added to the set $S_A$ in line 34. Upon the assignment, all the layers will be executed in the newly opened DU in line 35. In line 36, node $i$ will be removed from the set $N$ and the algorithm passes the control to the next highest nodal degree node in the network. The worst case complexity of the algorithm is $\mathcal{O}(N^3)$. It is calculated by considering the maximum number of iterations for all the loops in the algorithm.

## 4 Numerical Results

To show the effectiveness of the algorithm, a set of results is here presented organized into two parts. Firstly, the algorithm is applied with no limitation on PUs to evaluate the effect of distance constraints, expressed in hops. In the second part, the effect of the combination of the two constraints, namely the maximum distance and the PUs available in the nodes is outlined. In all the cases considered the benchmark is the conventional C-RAN, designed based on the location algorithms previously developed [15].

Figure 3 shows the reference network for evaluations, consisting of 38 nodes and 48 high capacity transport links. Three CUs are considered to serve the network where data centers are located. The figure also is shown two simple examples of the decision logic of the algorithm. The connection between RUs and CUs for service purposes can happen through a chain of intermediate DUs. All the nodes in the network including the one hosting CUs can produce traffic and need to be assigned to proper entities for processing.

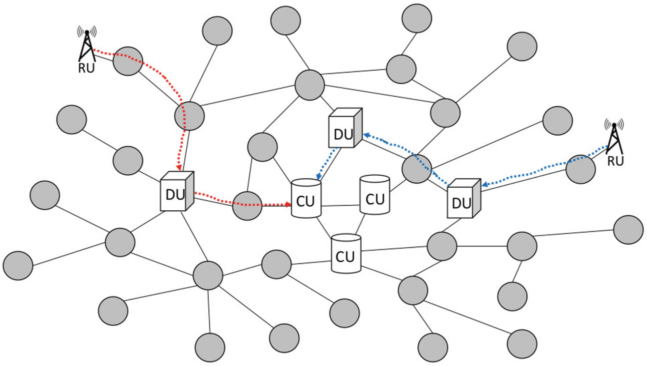

**Fig. 3.** Reference access network for evaluations.

The main motivation of the algorithm is to adopt the proper amount of network resources to the traffic pattern evolution, assumed in Fig. 4 as the number of active antennas per node over 24 h of the day [1]. The pattern presents low traffic in the early hours of the day, a peak in the middle and then decreases while reaching the end of the day. In this paper, we assumed the same amount of traffic at each hour for all the nodes in the network. This value is the highest amount of traffic predicted on each specific hour of a day.

The total number of the PUs is calculated based on the average of this pattern, in relation to the requirements of each functional layers and then averaged on the number of nodes in the network. The aim of the algorithm is to find suitable chaining of the functions throughout the network while using the available resources and avoiding any blocking of requests.

Figure 5 shows the comparison of C-RAN and xhaul in terms of activated nodes, namely BBU hotels, DUs and CUs respectively, varying the distance constraints. It is assumed the latency constraint is not violated for both architectures due to the diameter of 20 km of the use case in terms of hops. For this comparison, the xhaul network does not have any limitation over the available PUs in DUs which is the same situation in the C-RAN architecture. As a consequence, the variation of the traffic during the day does not affect the number

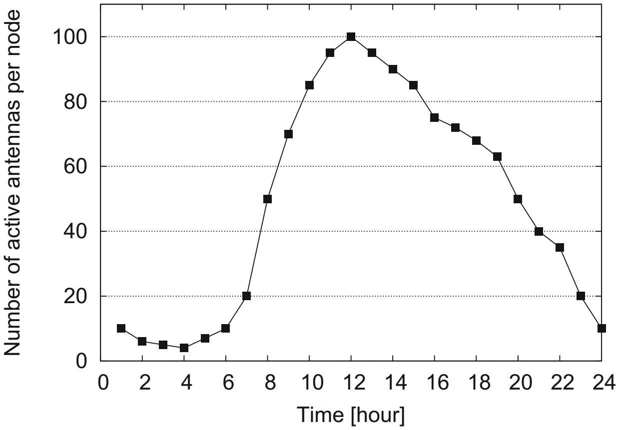

**Fig. 4.** Evolution of the number of active antennas per node during the 24 h.

of active DUs in the network. In all distance constraints, the two approaches achieve close results. In C-RAN the number of active BBU hotels decreases as the constraint on distant relaxes. This is also true for the xhaul except in the cases that algorithm due to the physical network topology cannot find a better solution even by relaxing the distance (hops 3 and 4). In the xhaul, the trend also shows the contribution of DUs and CUs. When distance constraint is strict (1 hop) the algorithm relies also on CUs for execution of functions. In the very relax distance constraints (5 and 6 hops) the dependencies on CUs is completely eliminated due to the fact that the algorithm prioritizes using DUs over CUs. In the 6 hops constraint, C-RAN and xhaul have the same requirement of activating only 1 node that corresponds to full centralization.

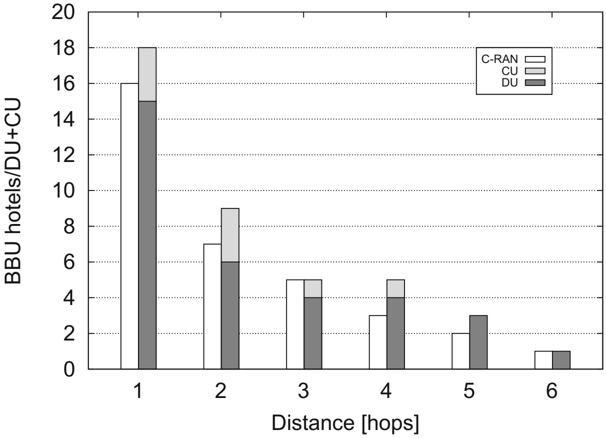

**Fig. 5.** Comparison of the total number of active nodes (BBU hotels, DUs and CUs) as a function of the distance constraint for C-RAN and xhaul with no limitation on the PU.

Figure 6 reports the evaluation of the required bandwidth in the same conditions of Fig. 5, showing the real advantage of the xhaul architecture. This figure compares the total assigned bandwidth in the network as a function of the distance constraint, again for C-RAN and xhaul, with no limitation on the PUs. By relaxing the distance constraint, the total bandwidth usage increases in all scenarios, which represents the well-known cost of centralization. Even though the PUs are assumed to be infinite, the variation of the traffic during the day sensibly affects the bandwidth in xhaul. Instead, being C-RAN at a constant bit rate, the variation of the traffic does not affect the assigned bandwidth. In particular, xhaul adapts to the traffic variations and in both the low (6 a.m.) and the peak (12 p.m.) traffic situations there are effective bandwidth savings in adopting the xhaul approach.

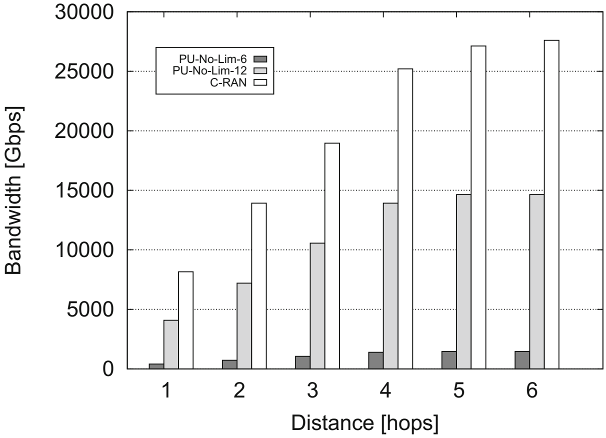

**Fig. 6.** Comparison of the total bandwidth as a function of the distance constraint for C-RAN and xhaul with no limitation on the PU in two different traffic situations (i.e. at 6 a.m. and 12 p.m. from Fig. 4).

This is also shown in Fig. 7 by plotting the multiplexing gain in terms of bandwidth indicated by $G$ in Eq. 1. It is defined as the difference between the total amount of used bandwidth in C-RAN ($BW_c$) and xhaul ($BW_x$) scenarios divided by the value for the C-RAN. This value shows the statistical saving in the usage of bandwidth in xhaul compares to the C-RAN. The multiplexing gain results almost independent of the distance constraint and much higher for xhaul then for C-RAN. This means that with xhaul the access network is able to allocate more services with respect to C-RAN, given a set of transport resources.

$$G = \frac{BW_c - BW_x}{BW_c} \tag{1}$$

Figures 8 and 9 show the results for the xhaul architecture when both limitations over distance and available PUs have been applied, in the low (6 a.m.)

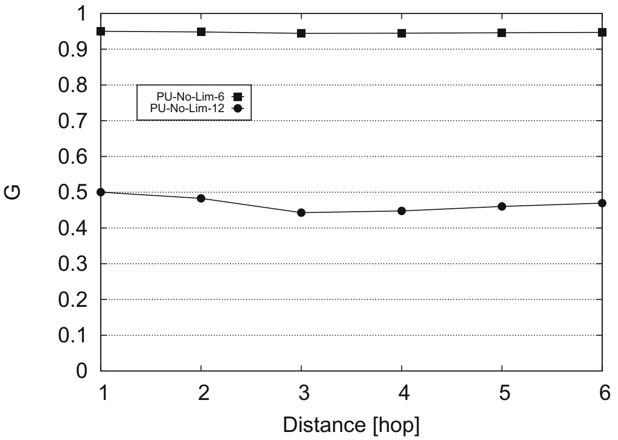

**Fig. 7.** Comparison of the xhaul multiplexing gain with respect to the C-RAN with no limitation on the processing units in low (6 a.m.) and peak (12 p.m.) traffic hours.

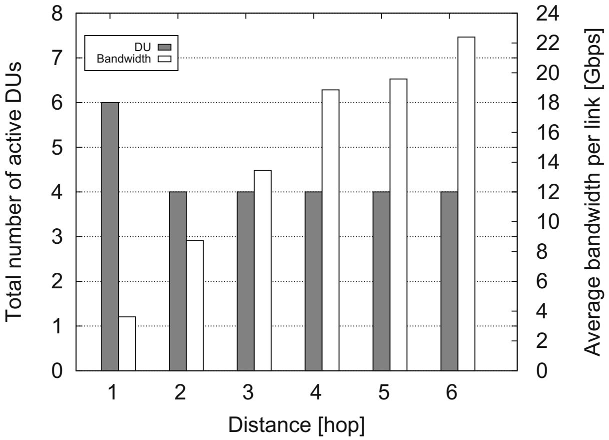

**Fig. 8.** Comparison of the average bandwidth per link and total active DUs as a function of the distance constraints for xhaul with the limitation on both processing units and hops in the low traffic (6 a.m.).

and the peak (12 p.m.) traffic situations, respectively. The figures are showing the comparison of the total number of active DUs and bandwidth per link as a function of different distance constraints. The dimensioning of the PUs in the nodes is based on the average traffic and on the processing required for each layer. As the distance constraint is relaxed, the constraint on PUs leads to a higher number of active nodes with respect to the ideal case. As far as the bandwidth, even with the same number of active DUs, having longer path means also more bandwidth needed. These figures both suggest designing the network to

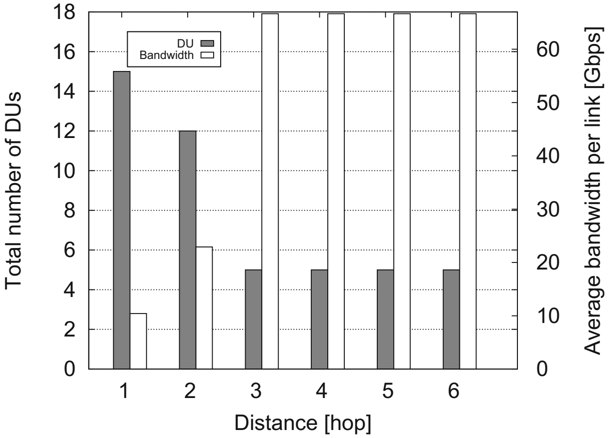

**Fig. 9.** Comparison of the average bandwidth per link and total active DUs as a function of the distance constraints for xhaul with the limitation on both processing units and hops in the high traffic (12 p.m.).

have a distance around 2 or 3 hops so that both aspects, number of nodes and bandwidth, can be optimized.

## 5 Conclusions

This paper has described a novel approach to location algorithm in 5G access network, based on function chaining as defined by the xhaul architecture. The algorithm is able to assign L1, L2 and L3 functionalities to nodes according to distance and processing constraints, while adapting to aggregate traffic variation during the day. Results have been obtained in terms of nodes to be activated, bandwidth and multiplexing gain on transport links, showing the benefits of the xhaul approach with respect to conventional C-RAN fronthaul, especially in terms of bandwidth saving. The multiplexing gain with respect to dedicated channels as in C-RAN shows the margin for dynamic bandwidth allocation to other service slices. The effectiveness of this design can be also shown in terms of centralization gain and can be further extended to support reliability in relation to specific use cases.

## References

1. Larsen, L.M.P., et al.: A survey of the functional splits proposed for 5G mobile crosshaul networks. IEEE Commun. Surv. Tutor. **21**, 146–172 (2018)
2. Askari, L., et al.: Virtual-network-function placement for dynamic service chaining in metro-area networks. In: Proceedings of IEEE ONDM, pp. 136–141 (2018)
3. Small Cell Virtualization: Functional Splits and Use Cases, Small Cell Forum release 7.0 (2016)

4. Chih-Lin, I., et al.: RAN revolution with NGFI (xHaul) for 5G. IEEE/OSA JLT **36**(2), 541–550 (2018)
5. Raza, M.R., et al.: Dynamic slising approach for multi-tenant 5G transport networks. IEEE/OSA JOCN **10**(1), A77–A90 (2018)
6. Yu, J., et al.: Midhaul transmission using edge data centers with split PHY processing and wavelength reassignment for 5G wireless networks. In: Proceedings of IEEE ONDM (2018)
7. Musumeci, F., et al.: Dynamic placement of baseband processing in 5G WDM-based aggregation networks. In: Proceedings of OSA OFC, p. M2G-4 (2017)
8. Kondepu, K., et al.: Orchestrating lightpath adaptation and flexible functional split to recover virtualized RAN connectivity. In: Proceedings of OSA OFC (2018)
9. 3GPP: Study on new radio access technology; radio access architecture and interfaces, 3GPP TR 38.801, vol. 2.0.0 (2017)
10. Chang, C.Y., et al.: FlexCRAN: a flexible functional split framework over ethernet fronthaul in Cloud-RAN. In: Proceedings of IEEE ICC (2017)
11. Li, Y., et al.: Flexible RAN: a radio access network concept with flexible functional splits and a programmable optical transport. In: Proceedings of IEEE ECOC (2017)
12. Nikaein, N.: Processing radio access network functions in the cloud: critical issues and modeling. In: Proceedings of ACM (2015)
13. Harutyunyan, D., et al.: Flex5G: flexible functional split in 5G networks. IEEE Trans. Netw. Serv. Manage. **15**(3), 961–975 (2018)
14. Khorsandi, B.M., et al.: BBU location algorithms for survivable 5G C-RAN over WDM. Comput. Netw. **144**, 53–63 (2018)
15. Khorsandi, B.M., et al.: Centralized vs. distributed algorithms for resilient 5G access networks. Photon. Netw. Commun. (2019). https://doi.org/10.1007/s11107-018-00819-7