Traffic Management in Cell-Free-Based 6G Networks

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***Abstract*—6G networks are envisioned as the key enabler for the intelligent information society of the next decade, targeting to achieve improved performance and satisfy demanding services and applications. This transition from the fifth generation requires novel and efficient approaches in the network design and network management domains that are able to achieve vital key performance indicators related to network densification, network throughput, positioning accuracy, energy efficiency. Cell-free networking is considered as a promising candidate for 6G, as it combines the advantages of distributed systems and massive number of antennas, thus being able to significantly improve the wireless transmission efficiency and provide better coverage. In this paper, we present a simulation study of a cell-free based 6G network that jointly considers the utilization of the communication resources at the radio edge and at the fronthaul. The proposed study considers various techniques for the allocation of the resources at the two network segments, targeting to reduce the case where bandwidth compression (due to unavailability of resources) occur. The evaluation of the proposed solutions reveals that the application of a threshold policy may be beneficial for the end-users in terms of lower bandwidth compression rate.**

Keywords—6G, cell-free, fronthaul, traffic management, bandwidth compression.

I. INTRODUCTION

As 5G networks are becoming widely available and the standardisation process is evolving, through the 3GPP Rel. 17 and Rel. 18 [1], researchers are focusing in the future 6G network by discussing novel network architectures that are able to meet the future service requirements [2]. The development of the 6G vision is expected to address vital limitations of the 5G networks that are related to reliability, availability, network latency, and ultra-dense user density ([3]), by integrating terrestrial and aerial communications into a robust network [4].

In this new environment, the main focus of the research community is oriented on the definition of the specifications of the new network architecture [5], as well as on the determination of the key technologies that are required in order to meet the strict 6G network requirements [6]. One of the promising approaches for the radio-edge domain is the cell-free paradigm, where all end-users are served by a significant number of distributed Radio Units (RUs) connected to a CPU and managed by a centralized processing pool in the backhaul network. This approach is able to minimize the cell-edge user problem and provide high-quality connectivity to all end-users, as well as to enhance the network's energy efficiency and support of quality of service [7]. Consequently, this novel networking solution is a promising approach for 6G networks, mainly due to its unique advantages related high macro-diversity and increased expected coverage. However, such a radio-edge approach requires a solid X-haul infrastructure support, in order to provide reliable and continuous connectivity to a large number of RUs.

In parallel to the definition of the network architecture, the research community also focuses on optimizing the network resource allocation, targeting to utilize this fundamental mechanism in order to ensure efficient network performance. From the traffic management point of view, such approaches can utilize the knowledge of corresponding analyses for converged optical-wireless 5G networks ([8], [9], [10]). However, a traffic management methodology for 6G networks should incorporate the allocation of network resources at both the radio-edge and X-haul domains, while also targeting to define specific performance metrics that can be considered as practical criteria for the evaluation of such network configurations.

In this paper, we present a traffic management study of a cell-free-based 6G network, by focusing on the allocation of the network's communication resources to the User Equipments (UEs). The network architecture under study consists of an evolved radio access network that is extended with emerging cell-free technologies where each UE can be simultaneously serviced by multiple RUs, as well as of an innovative optical transport domain that deploys a distributed edge infrastructure with Data Centers (DCs) structured in 2 tiers, featuring Regional Edge and Radio Edge nodes. This network architecture is based on a converged optical-wireless configuration based on the cell-free networking solution, targeting to flexibly interconnect a massive number of RUs. Considering the unique features of this network architecture, we have developed a simulation framework that simulates specific procedures: firstly, the creation of the RU cluster that provides service to each UE, based on the channel state information of the RU-UE links; secondly, the simulator considers the available communication resources both at the radio-edge and frontaul domains, in order to provide service to the UE; thirdly, in case where the available communication resources are less than the requested amount from the UEs, the bandwidth requests are compressed in order to avoid the case where the UE service-request is blocked.

To this end, we propose three different methodologies for the bandwidth compression procedure in the fronthaul domain: i) under the first method, the controller assigns the same amount of bandwidth to each RU based on the fronthaul capacity; ii) under the second method, the bandwidth allocated to each RU is related to the number of connected UEs; iii) under the third method, half of the RUs that are connected with the same Distribution Unit (DU) are assigned the maximum amount of bandwidth that can be assigned to an RU while the other RUs allocate equally the rest of the bandwidth. In addition, a bandwidth threshold policy is also applied at the radio-edge part as a percentage of the radio capacity, in order to reduce the effect of the bandwidth compression procedure. We evaluate the proposed solutions through extensive simulations, which reveal that the application of a threshold policy may be beneficial for the end-users in terms of lower bandwidth compression rate.

The remainder of this paper is organised as follows. Section II provides the description of the system model, focusing on the description of the network architecture, and on the bandwidth allocation procedures at the radio-edge and fronthaul domains of the network. Section III is the evaluation section, where simulation results are presented and the proposed bandwidth compression methods are evaluated. Finally, we conclude our paper in Section IV.

II. System Model

We consider the cell-free-based network of Fig. 1 that consists of L RUs that provide connectivity to K UEs. All RUs are identical and equipped with MIMO antennas that comprise of N antenna-elements. A set of RUs that is embedded to a radio-stripe is connected to a DU, as illustrated in Fig 1. This novel network configuration extends the classical cell-free approach by disaggregating the Central Processing Unit (CPU) into multiple DUs, thus triggering distributed computation and coordination between RUs and between DUs. The multiple DUs are interconnected by considering a converged optical-wireless configuration, which interconnects the DU by incorporating a 10-Gigabit-Symmetrical (XGS)- Passive Optical Network (PON); the latter consideration is applied in order to ensure the reliable support of dense RU deployment ([11]). In this configuration, the DUs are connected to the PON via Optical Network Units (ONUs), which perform the required optical to electrical and electrical to optical conversions. In addition, the proposed network configuration considers the splitting of the Next-Generation-NodeB (gNB) protocol stack into Centralized Unit Control Plane (CU-CP), CU-User Plane (CU-UP), and DU nodes, while a Near-Real-Time RAN Intelligent Controller (Near-RT RIC) is considered at the regional edge that implements the radio resource management functions. It should be noted that the regional edge comprises of multiple Data Centers (DCs), which are interconnected by considering a ring topology through Reconfigurable Optical Add Drop Multiplexers (ROADMs) that are acting as all-optical switches [12] .

We consider that the network configuration under study comprises of M DUs located at the radio edge, which are connected to the regional edge through T PON configurations, while a set of DUs is connected to their corresponding Optical Line Terminal (OLT) through a wavelength-specific fronthaul link. Each UE k ($k = 1, \dots K$) has a specific bandwidth requirement of b_k bandwidth units (b.u.) that should be satisfied by both the radio edge and the fronthaul.

Following the cell-free notion, a cluster of available RUs is formed in order to serve the requirement of each user. Specifically, when a UE arrives at the system, the channel conditions between the UE and the RUs in the area proximate to the UE are estimated by the Near-RT RIC located at the regional edge. The channel conditions that are examined for the RU assignment refer to the channel gain over the noise considering factors such as pathloss and shadow fading. The RU that achieved the best channel conditions with the UE is appointed as the master RU to this specific UE. This procedure is performed in order to ensure that all UEs will be served by at least one RU [13]. Consequently, the cluster that is formed by the master RU and the RUs with channel conditions that satisfy a predefined threshold, provide service to this specific UE, constituting a user-centric cluster. When clusters are formed for all UEs that request service, the available bandwidth for the radio edge part is distributed to the UEs as described in Section 2.1. In accordance, when the fronthaul bandwidth allocation is completed, the corresponding resources in the RUs (i.e. the Resource Blocks (RBs)) are also allocated. This process is explicitly presented in Section 2.2.

A. Fronthaul bandwidth allocation procedure

The bandwidth of each fronthaul link is distributed to the underlying RUs, which is performed by the Near-RT RIC. This procedure can be realised by following one of the following proposed bandwidth allocation schemes:

i Under the first scheme, all RUs are treated fairly by the Near-RT-RIC; thus the controller assigns the same amount of bandwidth to each RU, which equals to capacity of the fronthaul link divided by the number of the RUs that communicate with the underlying DU.

ii The bandwidth allocated to each RU is related to the number of UEs that they connected (e.g. the RU that serves the majority of UEs allocates the highest portion of the available bandwidth). In further detail, the number of UEs per RU is enumerated and then the fronthaul's bandwidth is divided and distributed to the RUs according to the number of UEs that they serve.

iii In the final case, half of the RUs that are connected with the same DU are assigned the maximum number of b.u. that can be assigned to an RU while the other RUs allocate equally the rest of the bandwidth. At greater length, the RUs per DU are divided into sets of two RUs per set according to their position. Following this, the bandwidth is equally distributed to these sets. Among two RUs belonging to the same set, the maximum number of b.u. is assigned to the one RU and the rest of the b.u. to the other. This solution constitutes a simple load balancing mechanism for serving UEs that are uniformly distributed in the area.

The selection of the appropriate bandwidth allocation scheme depends on the network parameters, as well as of the bandwidth allocation in the radio edge, as it is shown in the evaluation section.

B. Radio-edge bandwidth allocation procedure

The controller is also responsible for the allocation of the RU bandwidth to the UEs. This decision is assigned

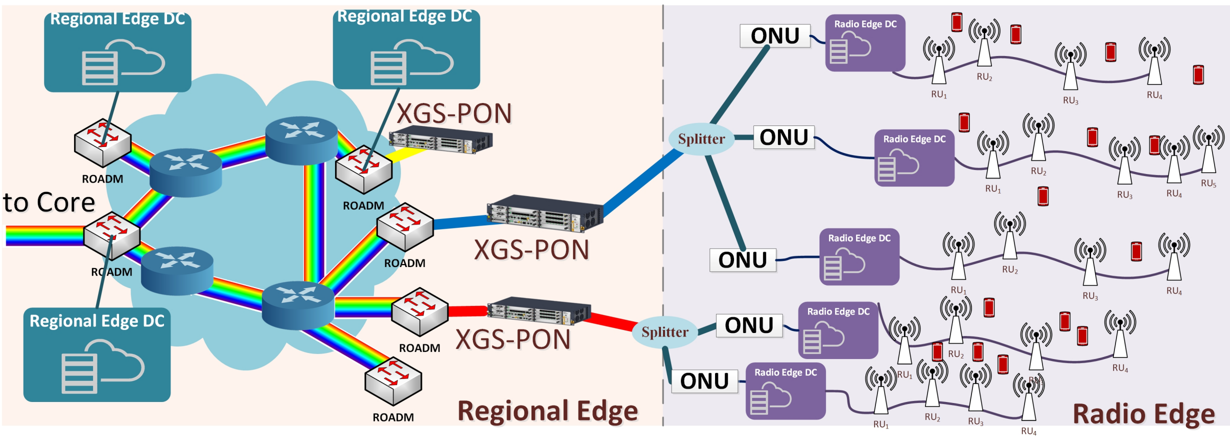

Fig. 1. The proposed cell-free based converged optical-wireless network.

to the Near-RT RIC since RU clusters are formed by RUs that may belong to different DUs. We assume that all RUs treat their UEs equally and there is no priority among the UEs; thus, the available bandwidth is assigned fairly to the UEs according to their bandwidth requirements. In more detail, each RU initially divides its available resources equally according to the number of UEs that it serves. In case that the portion of resources accounted for a UE is greater than the required resources, only the required resources are allocated, while the surplus portion is allocated to the UEs that could not satisfy their needs. However, the available number of bandwidth resources, $b_{assigned,k}$ b.u., may not suffice to serve the bandwidth need b_k of the UE (where $b_{assigned,k} < b_k$); in this case, the UE's bandwidth requirement should be compressed in order to be served by the network. The bandwidth requirement compression of a UE k can be expressed via the following compression ratio equation:

$$CR_k = \frac{b_k - b_{assigned,k}}{b_k} \quad (1)$$

As mentioned above, a UE is served if and only if both the UE's required b.u. in the fronthaul and the RBs at the RU are allocated, in order to ensure that a UE will satisfy its bandwidth demand. Each RU has a specific number of RBs that is denoted as C, which is the same for all RUs. In our analysis, we assume that each b.u. at the fronthaul domain corresponds to a specific number of RBs at the radio-edge domain. It is worth mentioning that, in a situation of fronthaul bandwidth requirement compression, the RBs demand is based on the b.u. that were eventually assigned to a UE, i.e. the compressed bandwidth requirement and not on the initially required resources.

For the allocation of RBs to the UEs, two methods are considered in our approach: a) RB allocation without thresholds, and, b) RB allocation with thresholds.

a) *RB allocation without threshold*: When a UE requests service from the network, a procedure takes place at the RU (and controlled by the Near-RT RIC) in order to allocate the necessary RBs to the UE, and to process the UE's request. If the required number of RBs is available at the RU, then the controller allocated these RBs to the UE. However, in case that the RU also serves other UEs, or the UE's need is high, the number of available RBs may not be sufficient. In such cases, the UE's bandwidth requirement should be compressed, in order to ensure that its request will be served; the portion of this compression at the radio-edge level can also be described by (1).

b) *RB allocation with threshold*: In contrast to the previous method, in a *threshold* approach, the UE's bandwidth requirement compression is activated when the total number of occupied RBs at the RU exceeds predefined thresholds. Specifically, when a connection request arrives at the controller, the latter checks the number of available RB in the master RU after the acceptance of the connection request; if this number of occupied RBs exceeds a predefined threshold of the total number of the RBs, then the bandwidth requirement is compressed. In this case, the bandwidth requirements of the UE are compressed, even though the required RBs are available in the RU. The amount of this compression is predefined and denoted as p_r percent of the initial bandwidth requirement, and is constant for all UEs regardless of their initial bandwidth demands. However, there exist cases where the UE's RB requirement is higher than the available RBs in the RU, even after the compression that is expressed by the parameter p_r. To deal with this situation, it is proposed that all the available RBs of the RU are allocated for this UE and the compression ratio is expressed via (1).

III. Evaluation and Discussion

In this section, we evaluate the performance of the proposed cell-free based system model. To this end, we have developed a simulator that considers the physical layer functions of a cell-free network that are described in [1] that have been extended in order to simulate the network architecture of Fig. 1, i.e. to incorporate the features of the optical fronthaul domain. We assume that the underlying system consists of $M = 6$ DUs, $T = 2$ OLTs and $L = 24$ RUs, each one equipped with $N = 4$ antennas. The evaluation of the proposed system is realised for a various number of supported UEs, with a number ranging from $K = 11$ UEs, up to $K = 20$ UEs. Each OLT is interconnected with 3 DUs and each DU communicates with 4 RUs. The fronthaul capacity is assumed to be equal to 100 b.u. for all radio-stripes, while

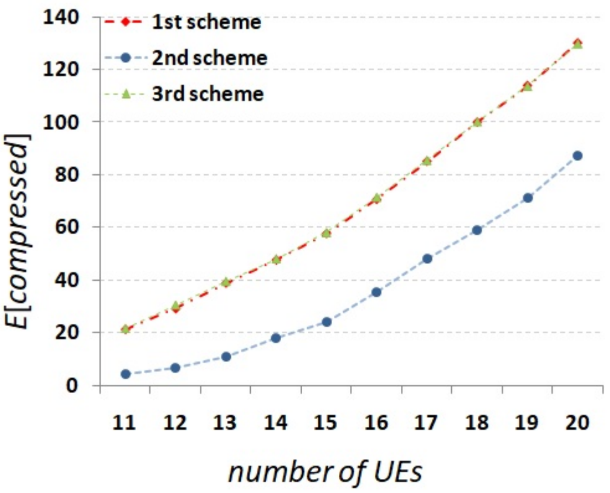

Fig. 2. Mean bandwidth compression ratio of the fronthaul resources versus the number of UEs.

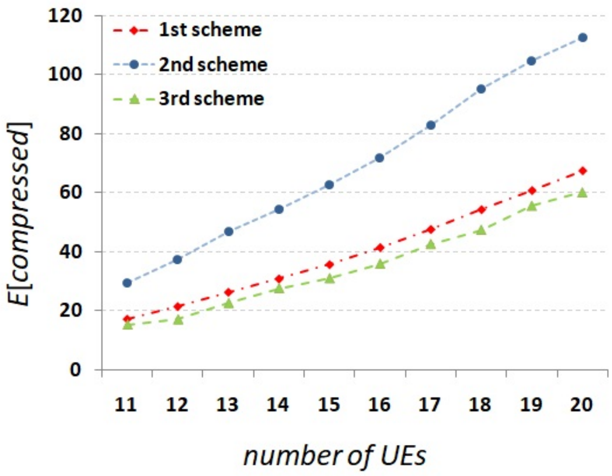

Fig. 3. Mean bandwidth compression ratio of the fronthaul and RU resources versus the number of UEs, without threshold consideration in the RU resources.

the capacity of each RU is assumed to be equal to $C = 36$ RBs. In order to proceed with the allocation of the b.u. in the fronthaul link and the RBs in the RU to a UE, we assume the analogy 1 b.u. at the fronthaul per 2 RBs at the RU.

When the RB allocation method with bandwidth threshold is applied, the compression percentage is $p_r = 0.4$, while the threshold J is determined so that $j_0 = 0.7$. We also assume that each UE has different bandwidth requirements; the bandwidth requirement of the k-th UE is assumed to be equal to $b_k = 4 * k$, where $k = 1, .., K$. It should be noted that all simulation results presented in this section are mean values of 70 simulation runs. In addition, in order to present the simulation results on Fig. 2, 3 and 4 we utilized the equation of the mean value of discrete variables as follows:

$$E[compressed] = \sum_{k=1}^{K} k \cdot CR_k \tag{2}$$

in order to provide the mean compressed bandwidth that is achieved in the network as a function of the number UEs and their compression ratios.

Fig. 2 presents the simulation results of the mean compressed bandwidth versus the number of UEs in the network, for the three schemes presented in Section 2.1; thus, the bandwidth compression procedure is applied only in the fronthaul link without considering the threshold procedure. By considering the proposed bandwidth allocation of the fronthaul capacity, it can be easily observed that the second scheme provides remarkably better results, as depicted in Fig 2, because the mean bandwdith compression experienced by the UEs is lower compared to the other two schemes which has almost the same performance. This outcome is due to the fact that in the second proposed scheme the bandwidth is distributed by considering the specific UE needs, while in the other two cases the bandwidth is assigned based on a specific distribution, irrespective of the UEs' requirements.

The situation described in Section 2.2 when both the b.u. on the fronthaul capacity and the RBs allocation are considered in Fig. 3 and Fig. 4, where the mean compressed bandwidth versus the number of UEs, for the case without a threshold, respectively, are illustrated. In contrast to the previous case, where the compression is applied only in the fronthaul link, in this case the bandwidth compression procedure presented in Section 2.2 for the radio-edge is applied. The comparison of Fig. 2 with Fig. 3 and Fig. 4 reveals that the second proposed scheme performs significantly worse, while the third scheme provides slightly better results than those provided by the first scheme, in the case of Fig. 3 and Fig. 4. This can be easily explained if we consider the number of b.u. reserved for the UEs in each scheme. In particular, after the fronthaul resources allocation, the UEs in the first and the third scenario suffer from higher demand compression, and thus, the number of allocated b.u. is lower compared to that in the second case. In accordance, the number of required RBs is also smaller in the first and the third scenario causing lower requirement compression.

As far as the threshold utilization during the RBs allocation is concerned, we can see on Fig. 3 and Fig. 4 that, in a macroscopic point of view, the mean compression values are almost the same in the two cases with minor differences. However, observing the results considering from each UE perspective, (i.e. without averaging their contribution as in (2)), it can be observed that an individual UE may suffer from higher bandwidth compression when no threshold is applied. In particular, when the threshold policy is applied, the average bandwidth compression that a UE experiences is anticipated to be near to p_r. On the other hand, in the no-threshold case, the bandwidth compression depends exclusively on the number of the requested resources which are different for each UE. As a consequence, a great variance in the range of the bandwidth compression values is remarked, which results in a barely predictable mechanism for Quality of Service (QoS) estimation. For instance, in the no-threshold case a great range of bandwidth compression values was noticed starting from 10% up to 80%, whilst when threshold was applied e.g. when $j = 0.7$ and $p_r = 0.4$ it was observed that the majority of bandwidth compression ratio values were

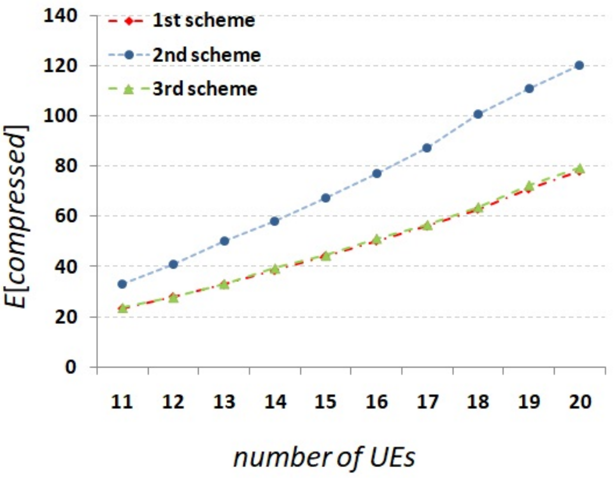

Fig. 4. Mean bandwidth compression ratio of the fronthaul and RU resources versus the number of UEs, with threshold consideration in the RU resources.

in a narrower range, such as between 40% and 60%.

In order to evaluate our system at a greater extent, we also examine the effect of the value of the parameter p_r to the compression ratio. To this end, we consider the aforementioned simulation scenario, while we consider 3 different values for the parameter p_r: i) $p_r = 0.2$, ii) $p_r = 0.3$, and, iii) $p_r = 0.4$. The compression ratio results for the 3 cases are similar with the results on Fig. 4, with a very small increase of the compression ratio with the increase of p_r value. However, from each UE perspective, the bandwidth compression experienced by a single UE was strongly affected by the value of p_r. In more detail, the values of bandwdith compression generally range from pr up to 50% i.e. for the 1st set from 20%-50%. As a consequence, choosing the third set of parameters provides more predictable results and by extension a better QoS. Moreover, as it was anticipated, it was interestingly observed that the number of UEs that finally could not be served even with compressed bandwidth requirements is significantly higher when the no-threshold method was applied compared to those of the other method which utilizes thresholds. In particular, the majority of UEs that could not be served even with compressed demands in the no-threshold approach was served without any conflict when thresholds were utilized, but with a higher bandwidth compression compared to the other UEs. On the other hand, it should be mentioned that the number of UEs whose requirement is compressed is higher when the threshold is utilized.

As a general conclusion, the number of UEs that cannot be served is significantly decreased when the threshold mechanism is applied but at the expense of the other UEs who suffer from higher compression. In addition, by utilizing the threshold mechanism and choosing the suitable set of parameters, a system with a more foreseeable behavior and a better QoS can be provided.

IV. Conclusion

This paper provides a simulation study for the evaluation of diverse traffic management approaches in a cell-free based 6G network. The developed solutions consider the allocation of communication resources to the UEs both at the radio-edge and the fronthaul domains of the network. The proposed solutions target to reduce the probability of bandwidth compression of the UEs due to the unavailability of communication resources at both network segments. An extensive simulation-based of the proposed solutions is provided, targeting to illustrate the effect of various network parameters, such as the number of UEs, or the bandwdith threshold levels. The evaluation of the proposed solutions reveals that the application of a threshold policy may be beneficial for the end-users in terms of lower bandwidth compression rate. In our future work, we plan to extend our solution to consider UEs that are able to simultaneously connect to multiple RUs, a dynamic allocation method for the allocation of the resoures to the UE, as well as the allocation of the computational resources of the network to the UE connections, for the execution of the corresponding network functions.

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References

[1] R. Imadur, et al. "5G evolution toward 5G Advanced: An overview of 3GPP releases 17 and 18", *Ericsson Technology Review*, Oct. 2021.

[2] H. Tataria, et. al., "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities", *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166-1199, Jul. 2021.

[3] J. S. Vardakas et al., "Towards Machine-Learning-Based 5G and Beyond Intelligent Networks: The MARSAL Project Vision", *in Proc. IEEE MeditCom*, pp. 488-493, Athens, Greece, 7-10 Sept. 2021.

[4] M. W. Akhtar, et al., "The shift to 6G communications: vision and requirements", *Human-centric Computing and Information Sciences*, vol. 10, no. 1 pp. 1-27, Dec. 2020.

[5] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The Road Towards 6G: A Comprehensive Survey", *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334-366, Febr. 2021.

[6] C. D. Alwis et al., "Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research"*IEEE Open Journal of the Communications Society*, vol. 2, pp. 836-886, Febr. 2021.

[7] H. A. Ammar, et al., "User-Centric Cell-Free Massive MIMO Networks: A Survey of Opportunities, Challenges and Solutions", *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, First quarter 2022.

[8] K. Ramantas, et al., "A C-RAN Based 5G Platform with a Fully Virtualized, SDN Controlled Optical/Wireless Fronthaul", *in Proc. ICTON*, Bucarest, Romania, 1-5 July 2018.

[9] L. Wu, J. Cui, J. Zhang and Y. Ji, "Demonstration of Slice Fault Monitoring and Handling for Converged Optical-Wireless Access Networks", *in Proc. OFC*, Washington, DC, USA, 6–11 June 2021.

[10] M. Maule, J. Vardakas and C. Verikoukis, "5G RAN Slicing: Dynamic Single Tenant Radio Resource Orchestration for eMBB Traffic within a Multi-Slice Scenario", *IEEE Communications Magazine*, vol. 59, no. 3, pp. 110-116, March 2021.

[11] E. Datsika et al., "SDN-Enabled Resource Management for Converged Fi-Wi 5G Fronthaul, "*IEEE Journal on Selected Areas in Communications*, vol. 39, no. 9, pp. 2772-2788, Sept. 2021.

[12] M. Mosahebfard, J. S. Vardakas and C. Verikoukis, "Modelling the Admission Ratio in NFV-Based Converged Optical-Wireless 5G Networks", *IEEE Trans. Vehic. Techn.*, vol. 70, no. 11, Nov. 2021.

[13] E. Björnson, L. Sanguinetti, "Scalable Cell-Free Massive MIMO Systems", *IEEE Trans. Commun.*, vol. 68, pp. 4247-4261, Jul. 2020.