Opportunistic Fog Computing for 5G Radio Access Networks: A Position Paper

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Abstract. Fog-based radio access networks (F-RAN) are posed to play a pivotal role in the much-anticipated 5th Generation (5G) cellular networks. The philosophy of F-RAN is to harness the distributed resources of collaborative edge devices to deliver localized RAN services to the end users. The current F-RAN is implemented mainly utilizing dedicated hardware and do not leverage on the available large number of distributed edge devices. This paper introduces the idea of opportunistic fog RAN (OF-RAN) which comprises of virtual fog access points (v-FAPs). The v-FAPs are formed opportunistically by one or more local edge devices also referred to as service nodes, such as WiFi access points, femtocell base stations and more resource rich end user devices under the coverage and management of the physical FAP, which can be dedicated fog server, fog-enabled remote radio heads (RRHs) or macrocell base stations. The proposed OF-RAN can be a low latency and high scalable solution for 5G cellular networks.

Keywords: Opportunistic fog computing · 5G radio access network
Virtual fog access points

1 Introduction

The future 5th Generation (5G) cellular networks will not only cater high-speed and reliable human communication services, but also support communications between a large number of smart objects or 'things' in the coming era of the Internet of Things (IoT) [1]. To sustain these objectives, centralized radio access networks (C-RAN) was developed where client data received by base stations (BSs) are transmitted over fiber links to a central unit for processing on specialized hardware [2]. Recently, the concept of Cloud-RAN was proposed to replace the specialized hardware in C-RAN with commodity cloud-computing platform to allow for more flexible splitting and allocation of RAN functionalities between radio access points (RAPs) and the cloud, depending on the available cloud resources. However, Cloud-RAN has the shortcomings of: (i) constrained backhaul capacity; (ii) load concentration on the centralized base band unit (BBU) pool; and (iii) difficulty in meeting the ultra low-latency requirements of 5G [3].

More recently, Fog-computing based Radio Access Network (F-RAN) is proposed as a promising candidate to tackle the aforementioned challenges. Fog computing is a

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paradigm that extends cloud computing by placing cloud-equivalent resources including processing and storage resources at the edge of the network [4]. In literature, fog computing is also considered as a more general concept of mobile edge computing (MEC). F-RAN harnesses the presence of such collaborative edge devices to deliver localized RAN services to end-users [5]. Its main philosophy is to make full use of local radio signal processing, cooperative radio resource management (CRRM) and distributed storage capabilities in edge devices [6]. Through ingestion and processing of end-user tasks close to their sources, F-RAN has potential to meet the stringent latency and bandwidth requirements of 5G services and applications.

However, the current proposed fog access points (FAPs) of F-RAN have been implemented mainly as dedicated fog servers, or fog-enabled remote radio heads (RRHs) or macrocell base stations [7]. It does not leverage on the presence of a large number of other distributed edge devices in the proximity of FAPs such as WiFi access points, femtocell base stations, and resource-rich end-user devices that can be incentivised to lease their resources and collaboratively serve as ‘service’ nodes to other end-users. This motivates us to propose the *opportunistic fog RAN (OF-RAN)* inspired by the concept of opportunistic resource utilisation network (oppnet) [8].

The oppnet is a type of specialised ad hoc network that features opportunistic expansion and opportunistic utilization of local resources gained by the expansion. It is a dynamic form of network comprising originally of a small set of ‘seed’ nodes, which can be expanded on-demand by recruiting ‘helper’ nodes in their local areas not employed initially but join the seed nodes in order to fulfill a given task. The FAPs in the current F-RAN and the local edge devices (also referred to as *service nodes* in our proposed OF-RAN) can be considered to resemble the seed nodes, and helper nodes, respectively, in oppnet [8].

Hence, this paper also proposes the concept of a *virtual FAPs (v-FAP)* formed by two or more local edge devices and monitored by physical FAPs for 5G radio signal processing. Intuitively, by being in close proximity to the user equipment (UE) that generate the processing tasks and harnessing the collective plethora of local computing resources, the proposed OF-RAN could emerge as a low-latency and high-scalability alternative to the current F-RAN and Cloud-RAN approaches.

The rest of the paper is organized as follows. Section 2 reviews the research literature on investigating various issues of Cloud-RAN and F-RAN. Section 3 presents the proposed OF-RAN architecture. The knowledge gaps are identified and corresponding research questions are discussed in Sect. 4. Finally, Sect. 5 concludes the paper.

2 Literature Review

This section performs a critical review of the relevant literature according to the type of research problems addressed. Four main research problems are identified, namely: (i) limited fronthaul capacity; (ii) flexibility and cost of deployment; (iii) user access mode selection; and (iv) service node selection.

2.1 Limited Fronthaul Capacity

In [11], the authors addressed the limited capacity of fronthaul links in Cloud-RAN by proposing an adaptive compression and joint detection scheme at baseband unit (BBU) pool, which exploits the correlation among the remote radio heads (RRHs) to minimize the fronthaul transmission rate while satisfying the quality of service (QoS) requirements. The RRHs are less sophisticated compared to classical base stations, thus they are considered as relaying nodes that forward IQ signals from the user equipment (UE) to the BBU pool. The block error rate (BLER) of the proposed scheme is analyzed in closed form by using pair wise error probability (PEP). Analytical result showed that a compression efficiency of 350% can be achieved by the proposed scheme. However, the authors have assumed that the BBU always have perfect knowledge of all channel information, which may not be practical and can incur significant overheads in their acquisition due to frequent large-scale message exchanges. When it comes to limited capacity of front haul, overhead reduction becomes more important in Cloud-RAN, which is intended to support a large number of users.

In [12], a joint power control and fronthaul rate allocation scheme for uplink communication in an OFDMA based cloud-RAN is proposed. The proposed scheme is designed for throughput maximization under fronthaul capacity constraint, which is found to have a significant impact on the optimal power control policy. The result showed that the joint design approach achieved better performance than an approach based on optimizing only power control or fronthaul rate allocation. However, the authors have assumed all fronthaul links to be of equal rates and perfectly lossless, and all mobile users are pre-allocated with the same number of sub-carriers, which made the analysis simple, but may not be realistic in real-world heterogeneous environment.

The authors in [13] studied the joint design of cloud and edge processing for the downlink in F-RAN. The BBU performed joint processing for its enhanced RRHs (eRRHs), which cache frequently requested contents of their users, in addition to being a conventional RRH. The objective was to maximize the minimum delivery rate of requested files under the constraints of limited fronthaul capacity and eRRH power. Two fronthauling modes: hard and soft transfer, with different baseline and pre-fetching strategies are considered. In hard transfer, non-cached files are delivered over the fronthaul links, whereas in soft transfer, fronthaul links conveyed quantized baseband signals as in a cloud-RAN. A simulation performance comparison between hard and soft transfer showed that the latter is more effective in using fronthaul resources except in very low signal-to-noise ratio (SNR) regime. However, the authors have largely adopted a heuristic approach to associating UEs to eRRHs, which may not achieve optimal performance as would be achieved under a more theoretically-grounded approach, e.g. by formulating a user association problem which finds the optimal set of eRRHs to associate with the UEs such that the minimum delivery rate is maximized under the constraints of limited fronthaul capacity and eRRH power. Furthermore, the non-associated eRRHs may be put into sleep mode in order to reduce the energy expenditure.

In [9, 10], the authors investigated the performance of a Cloud RAN under flexible centralization, which refers to the concept of suitably proportioning the BBU processing chain (or functional split) between the cloud and RRH, in order to alleviate the issue of limited fronthaul capacity. Various centralization options are analyzed with respect to their required fronthaul capacity, achievable latency and challenges for the signal processing. To enable different information types beyond raw I/Q samples to be transported over the fronthaul when a functional split is implemented between BBU and RRHs, a packet-based transport approach is proposed in [10]. However, this requires a careful design of the packetization method in order to minimize both header-related overhead and payload-filling latency. It is generally observed that existing Cloud RANs have difficulties in keeping their latencies within the timing requirements of the Long-Term Evolution (LTE) standard [10]. More specifically, the overall processing has to be completed in 3 ms in order to comply with the Hybrid Automatic Repeat Request (HARQ) timing, which is the most critical timing requirement defined in LTE [18].

2.2 Flexible and Low-Cost Deployment

In [14], the authors investigated millimeter-wave (mmWave) downlink transmission for the ultra-dense cloud radio access network (UD-CRAN). The fronthaul is shared among RRHs via time division multiple access (TDMA). The joint resource allocation over TDMA based mmWave fronthaul and orthogonal frequency division multiple access (OFDMA) based wireless transmission is studied to maximize the weighted sum rate of all users. The authors have specifically considered a system, where user assigned on any sub-carrier frequency can potentially be served by multiple RRHs subject to fronthaul constraint. The numerical solutions showed that the proposed solution for OFDMA based UD-CRAN can achieve throughput gains of more than 150% over a conventional LTE-A where each user is associated with a single RRH and the mmWave fronthaul bandwidth is equally divided among RRHs. However, the authors have assumed a clear line-of-sight for the mmWave link between RRH and BBU, which may not be possible in densely urban or hilly terrain environments.

The authors in [15] proposed a low cost approach to network densification through on demand deployment of mobile small cells using either mobile handsets or remote radio units. The mobile small cell base stations transmit RF signals to UE in downlink or forward baseband signals from UE to BBU pool for further processing in the uplink. The simulation result showed that proposed approach improved throughput and service quality over the coverage of the network. The proposed solution does not require extensive network planning, but there is high potential for inter-cell interferences with the deployment of heterogeneous small cells alongside macro-cells.

2.3 User Access Mode Selection

The authors in [16] proposed an adaptive algorithm for downlink F-RAN users to select between two content access modes: fog access point (FAP) and device-to-device (D2D), by taking into consideration of their locations, cache sizes and fronthaul delay cost. The proposed algorithm is based on the evolutionary game approach and comprises of three entities: players, strategies, and payoff. Players are users who can choose between multiple access modes. Strategies refer to the selection method, and payoff quantifies the performance satisfaction level of a potential player. Simulation results showed that the proposed scheme can achieve better payoffs than a maximum rate algorithm. However, the author have not considered the channel conditions between the FAP, F-RAN and D2D users in their proposed user access mode selection.

The authors in [17] proposed a centralized opportunistic access control (COAC) with user access mode selection. They considered a D2D underlaid cellular network composed of both D2D user equipment (DUE) and cellular user equipment (CUE), i.e. DUEs communicate with each other using the same radio resources as the CUEs. The user access mode selection, i.e. for selecting between cellular or D2D mode, is based on the user's signal-to-interference ratio (SIR) with respect to cellular base station and DUEs, and the achievable spectrum efficiency. The COAC scheme is compared with a distributed random access control scheme (DRAC) where sub-channels are allocated randomly. The simulation results showed that the user access mode for COAC performed better than the DRAC scheme. However, little attention has been given to the study of considering fronthaul delay in the user access mode selection and its impact on the network latency performance.

2.4 Service Node Selection

The authors in [18] focused on achieving ultra-low latency in F-RAN and proposed an algorithm to determine the optimal number of F-RAN nodes (small- and macro-cell BSs) and amount of resources required for a given distributed computing task. The optimisation problem is firstly formulated to tackle the trade-off between communication and computing resources, followed by cooperative task computing to decide how many F-RAN nodes should be selected with proper resource allocation and computing task assignment. Under the proposed scheme, a target user first sends its processing data to a nearby master F-RAN, which then selects an F-RAN node to serve the user, and is responsible for splitting and combining the tasks. Simulation results showed that the proposed scheme can significantly reduce the total service latency and achieve ultra-low latency. However, the authors have not considered the pre-existing computing load of the F-RAN nodes, as well as the load balancing issue, when assigning a new task to them.

The authors in [19] investigated the formation of a femto-cloud (coalition of femtocell access points) for collaborative processing, in order to avoid using remote cloud while enhancing user's quality of experience (QoE). A cooperative game approach to forming the femto-cloud is proposed, such that the available computation resources are maximally exploited while participating femtocell access points are selected based on satisfying the user's quality of experience (QoE) and monetarily rewarded in a fair manner. The femto cell manager (FCM), which is installed and maintained by the network operator coordinates the formation of femto-cloud. The FCM is also responsible for facilitating information exchanging with neighbouring FCMs. The simulation results shows that the execution delay by using femto-cloud can be reduced up to 50% when compared to that by a single femtocell access point. However, very little attention has been given to the load distribution among the femtocell access points.

In [20], the authors proposed an algorithm for selecting small-cell BSs in a small-cell cloud (similar to femto-cloud in [19]) to process offloaded applications from

Table 1. Summary of literature review

Issues investigated	Proposed solutions	Ref.
Limited capacity fronthaul	• Aim: Joint detection and decompression algorithm to minimize the fronthaul transmission rate • Result: Compression efficiency of 350% can be achieved by proposed optimization schemes	[11]
	• Aim: Joint wireless power control and fronthaul rate allocation optimization in the uplink communication of an OFDMA based C-RAN to maximize the network throughput • Results: Joint design achieves significant performance gain compared to optimizing either wireless power control or fronthaul rate allocation	[12]
	• Aim: Joint design of cloud and edge in order to maximize the delivery rate of the requested files while satisfying the fronthaul capacity • Results: Soft transfer mode provides more effective way of fronthaul resources compared to hard transfer mode	[13]
	• Aim: Functional split on the fronthaul capacity and the use of packet-based fronthaul network • Results: Split of functionality can improve significant centralization gain compared to distributed detection methods	[10]
Flexible and low cost deployment	• Aim: Joint resource allocation for both TDMA and OFDMA based UD-CRAN to maximize weighted sum rate of all users using mmWave fronthaul • Results: OFDMA based UD-CRAN can achieve throughput gain of more than 150%	[14]
	• Aim: Low cost on-demand deployment of mobile small cells using either mobile handsets or remote radio units (RRU) • Results: The proposed solutions improved system capacity and service consistency over the coverage of mobile networks	[15]
User access mode selection	• Aim: Evolutionary game approach for user access mode in fog radio access network • Results: The proposed algorithm has a better user satisfaction than the maximum rate algorithm	[16]
	• Aim: Opportunistic selection of sub-channels based on centralized management by cellular base station, and the criteria for selection between D2D and cellular access mode • Results: D2D mode is a suitable candidate for closely located UEs with strong LOS. But as number of D2D links increases, cellular mode is selected to reduce interference among D2D links	[17]
Service node selection	• Aim: An algorithm to determine optimal number of F-RAN nodes and amount of distributed resources for a given computing scenario • Results: The proposed algorithm can significantly reduce the total service latency of the cooperative task computing operation	[18]
	• Aim: Formation of femto-cloud by local femto cell access points (FAPs) equipped with processing power in a UMTS LTE network via a cooperative game theoretic scheme • Results: The proposed scheme shows superior performance in terms of handling latency and incentives provided to FAP owners	[19]
	• Aim: An algorithm for selection of small cell base station to form the small cell cloud (SCC) to process offloaded data by UEs • Results: The proposed algorithm can achieve 100% user satisfaction as long as the task offloading rate is within a certain limit	[20]
	• Aim: An algorithm for application placement problem with the goal of minimizing the maximum resource utilization • Results: The theoretical and simulation results show the proposed algorithm can balance the computation load well	[21]

UEs. The algorithm considers both UE's computation demand and the computation capacity and load of small-cell BSs in order to achieve high user QoS while maintaining relatively balanced communication and computation load among small-cell BSs. The simulation results showed that the proposed algorithm can achieve 100% user satisfaction as long as the task offloading rate is within a certain limit. However, the authors have not considered the dynamicity of the network, such as UE mobility and changing available computation capability during the processing of offloaded application.

The placement of decomposable application components onto physical MEC nodes was investigated in [21]. The user application and physical nodes are modelled as graphs whose nodes and edges represent the computation and communication resource entities, respectively. Several algorithms for placing the application to physical graphs in different scenarios are proposed with the aim of balancing the load and minimizing the sum resource utilisation at the physical nodes. However, the existing work is mainly focused on offloading or placement of application computation to base-station type nodes in MEC. On the other hand, our work addresses the RAN task assignment problem to a virtual group of co-located edge devices, including UEs in F-RAN. A summary of the literature review performed above is given in Table 1.

3 OF-RAN Architecture

The proposed OF-RAN aims to harness the approach of oppnet for opportunistic formation of fogs as local RAN service groups. The concept of v-FAPs is further introduced in which an opportunistic fog is formed by two or more collaborative and local edge devices under the coverage and management of the physical FAPs. Figure 1 shows the proposed OF-RAN architecture with v-FAPs at the access layer.

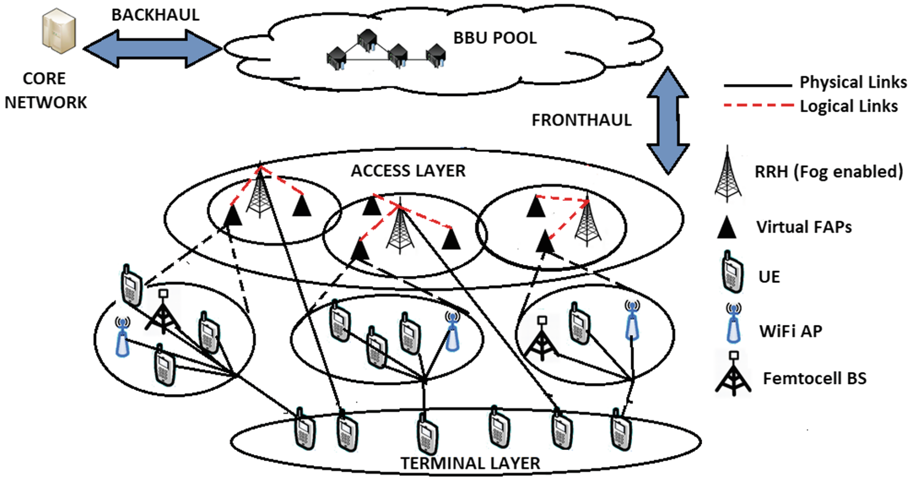

Fig. 1. OF-RAN architecture

As shown in Fig. 1, end-user UEs (hereinafter referred to as client nodes) requests for help from its nearby FAP, which in turn dynamically forms a v-FAP from a set of service nodes (local edge devices) in the client's locality. The FAP decides the set of service nodes to serve the client and the workload assignment to each of the service nodes based on their resource availability. We consider heterogeneous service nodes exhibiting different resource capacities (thus having different costs of utilising resources). The following resource types: computation, storage, communication and energy resources, can be considered when assigning tasks from client node to each service node.

Although the proposed OF-RAN is promising, its performance may be limited by the service nodes that constitute the v-FAPs, which are generally less resourceful than the FAPs or the core cloud. Assigning tasks to service nodes whose resource capacities do not meet the resource requirements of the tasks will result in processing failures. Hence, an important issue is about deciding which service node(s) should be assigned to process what tasks from client nodes in the OF-RAN. The tasks here refer to the client node's radio signal processing tasks that would have normally performed by the FAP or remotely by the cloud. Other important issues that may also need to be investigated include the formation of v-FAP and selection of user access mode (between proposed RAN and conventional RAN).

4 Identified Gaps and Research Questions

In current literature, difficulties have been observed for centralized cloud RANs to keep its latency within timing requirements of the Long-Term Evolution (LTE) standard, and there is still much room for improvement in current F-RAN solutions to effectively address the issues related to cloud RAN. To achieve the best possible outcomes, the following research gaps in both cloud RAN and F-RAN should be tackled.

The capacity limited fronthaul is one of the main challenges faced by current cloud RAN. Although many compression techniques and flexible centralization have been introduced, this requires RRHs to be more sophisticated and capable of handling exponential traffic growth.

The overall processing must be completed in 3 ms in order to comply with the Hybrid Automatic Repeat Request (HARQ), the most critical timing requirement defined in LTE [5]. This tight timing constraint is posing a significant challenge to current cloud-based execution of high-complexity tasks in standard RAN functions such as physical-layer forward error correction (FEC). The excessive load concentration in BBU pool is another issue, as the devices depending on BBU pool for processing are not limited to cellular devices, but also the massive number of Internet of Things (IoT) devices. Current F-RAN mainly comprises of dedicated fog servers, fog-enabled RRHs or macrocell base stations as fog access points (FAPs). Very little attention has been given to the opportunistic expansion of the FAPs through the utilization of a large number of other distributed edge devices such as WiFi access points, femtocell base stations, and resource-rich end-user devices that can be incentivised to lease their resources and collaboratively serve as 'service' nodes to other end-users.

Although the FAPs in the current F-RAN and service nodes in our proposed OF-RAN with v-FAPs resemble the seed nodes, and helper nodes, respectively, in oppnet, but the process of selecting service nodes (recruiting helper nodes) and forming oppnets (v-FAPs) need to be reinvestigated in the specific context of F-RAN. Given differences in the targeted use (e.g. mission-critical application versus RAN service provisioning), type of processing (e.g. application data processing versus radio signal processing), performance requirements, among others need to be considered.

Furthermore, while the OF-RAN seems promising, are there circumstances where the user will still prefer to access the cloud rather than the v-FAP for processing? If so, what the conditions for the user to switch access between the two? The idea of flexible centralization or functional split has so far been only discussed for Cloud RAN, and not for F-RAN. Thus, there is a need to further investigate this concept for F-RAN, particularly under the proposed OF-RAN with v-FAPs architecture. Based on the identified gaps some of the key research question includes:

i. How to efficiently initiate the opportunistic formation of v-FAP and notify the end user? How will information be exchanged between service nodes and seed nodes during the formation process?
ii. What selection criteria should be used for recruiting service nodes in the proposed F-RAN with v-FAPs architecture taking into consideration of finite processing and storage capacity of service nodes, limited energy of battery-operated mobile fog nodes, and 5G signal processing requirements?
iii. What is a feasible way of splitting the radio signal processing function between the BBU and RRHs in an OF-RAN? How can some of these tasks be offloaded to v-FAPs in order to alleviate the burden of RRH and fronthaul?
iv. How should end users (mobile and IoT devices) distribute the 5G signal processing tasks to the v-FAPs, and how will the fog-enabled RRHs collate the processed results of the tasks offloaded to the v-FAPs by the end user?
v. Based on the proposed OF-RAN system model, how to devise a suitable user access mode selection scheme based on both user requirements and available resources?

5 Conclusion

The concepts of Cloud-RAN and F-RAN seems to be very promising for addressing the impact of the exponential growth of the users on the radio access network architecture. However, existing Cloud-RAN and F-RAN solutions are faced by various challenges such as limited fronthaul capacity, load concentration on the centralized BBU, ultra low-latency requirements of 5G and inefficient utilization of the large number of distributed edge devices. In addition, Cloud-RAN may not be suitable for latency sensitive applications.

This paper firstly performed a critical review of relevant literature based on the type of research problems addressed for the existing RANs and their potential solutions. The concept of OF-RAN that features opportunistic expansion and utilization of local edge devices for forming virtual fog access points (v-FAPs) is then proposed and discussed.

Due to the diversity in the multitude of edge devices with respect to their resource capacity and processing capability when it comes to selecting service nodes, a number of important issues need to be investigated. These include deciding which service node(s) should be assigned to process what tasks from end-users in the F-RAN, the formation of v-FAPs, and the selection of user access mode (between OF-RAN and conventional RAN).

The outcomes of this research can benefit both operators and end-users of 5G networks: operator can offload its processing load from the cloud to v-FAPs for more scalable operations; end-users can experience lower latency when served locally by fog devices than remotely by the cloud, thus enhances the provisioning of real-time networked services.

References

1. Tang, J., Tay, W.P., Quek, T.Q., Liang, B.: System cost minimization in cloud RAN with limited fronthaul capacity. IEEE Trans. Wirel. Commun. **16**, 3371–3384 (2017)
2. Peng, M., Sun, Y., Li, X., Mao, Z., Wang, C.: Recent advances in cloud radio access network system architecture, key techniques, and issues. IEEE Commun. Surv. Tutor. **18**(3), 2282–2308 (2016)
3. Checko, A., Christiansen, H., Yan, Y., Scolari, L., Kardaras, G., Berger, M., Dittmann, L.: Cloud RAN for mobile networks - a technology overview. IEEE Commun. Surv. Tutor. **17** (1), 405–426 (2015)
4. Peng, M., Yan, S., Zhang, K., Wang, C.: Fog computing based radio access networks: issues and challenges. IEEE Netw. Mag. **30**(4), 46–53 (2016)
5. Shih, Y., et al.: Enabling low-latency applications in fog radio access networks. IEEE Netw. **31**(1), 52–58 (2017)
6. Hung, S., et al.: Architecture harmonization between cloud radio access networks and fog networks. IEEE Access **3**, 3019–3034 (2015)
7. Dastjerdi, A.V., Gupta, H., Calheiros, R.N., Ghosh, S.K., Buyya, R.: Fog computing principles architecture and applications, Chap. 4. In: Buyya, R., Dastjerdi, A.V. (eds.) Internet of Things: Principles and Paradigms. Elsevier, Massachusetts (2016)
8. Lilien, L., Gupta, A., Kamal, Z., Yang, Z.: Opportunistic resource utilization networks—a new paradigm for specialized ad hoc networks. Comput. Electr. Eng. **36**(2), 328–340 (2010)
9. Wubben, D., Rost, P., Barlett, J., Lalam, M., Savin, V., Gorgogolione, M., Dekorsy, A., Fettweis, G.: Benefits and impact of cloud computing on 5G signal processing. IEEE Sig. Process. Mag. **31**(6), 35–44 (2014)
10. Chang, C.-Y., Schiavi, R., Nikaein, N., Spyropoulos, T., Bonnet, C.: Impact of packetization and functional split on C-RAN fronthaul performance. In: Proceedings of IEEE International Conference on Communications, ICC, Kuala Lumpur, Malaysia, May 2016
11. Vu, T.X., Nguyen, H.D., Quek, T.Q.: Adaptive compression and joint detection for fronthaul uplinks in cloud radio access networks. IEEE Trans. Commun. **63**(11), 4565–4575 (2015)
12. Liu, L., Bi, S., Zhang, R.: Joint power control and fronthaul rate allocation for throughput maximization in OFDMA-based cloud radio access network. IEEE Trans. Commun. **63**(11), 4097–4110 (2015)
13. Park, S.-H., Simeone, O., Shitz, S.S.: Joint optimization of cloud and edge processing for fog radio access networks. IEEE Trans. Wirel. Commun. **15**(11), 7621–7632 (2016)

14. Stephen, R.G., Zhang, R.: Joint millimeter-wave fronthaul and OFDMA resource allocation in ultra-dense CRAN. IEEE Trans. Commun. **65**(3), 1411–1423 (2017)
15. Radwan, A., Huq, K.M.S., Mumtaz, S., Tsang, K.-F., Rodriguez, J.: Low-cost on-demand C-RAN based mobile small-cells. IEEE Access **4**, 2331–2339 (2016)
16. Yan, S., Peng, M., Abana, M.A., Wang, W.: An evolutionary game for user access mode selection in fog radio access networks. IEEE Access **5**, 2200–2210 (2017)
17. Peng, M., Li, Y., Quek, T.Q., Wang, C.: Device-to-device underlaid cellular networks under Rician fading channels. IEEE Trans. Wirel. Commun. **13**(8), 4247–4259 (2014)
18. Chiu, T.-C., Chung, W.-H., Pang, A.-C., Yu, Y.-J., Yen, P.-H.: Ultra-low latency service provision in 5G fog-radio access networks. In: Proceedings of IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, PIMRC, Valencia, Spain, September 2016
19. Tanzil, S.S., Gharehshiran, O.N., Krishnamurthy, V.: Femto-cloud formation: a coalitional game-theoretic approach. In: Proceedings of IEEE Global Communications Conference, GLOBECOM, San Diego, CA, USA, December 2015
20. Vondra, M., Becvar, Z.: QoS-ensuring distribution of computation load among cloud-enabled small cells. In: Proceedings of IEEE 3rd International Conference on Cloud Networking, CloudNet, Luxembourg, October 2014
21. Wang, S., Zafer, M., Leung, K.K.: Online placement of multi-component applications in edge computing environments. IEEE Access **5**, 2514–2533 (2017)