2 Ultra-dense Cloud Radio Access Network Architecture

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Ultra-dense cloud radio access network (UDCRAN) architecture, which integrates the capability of cloud computing and edge computing with the massively deployed radio access points, is a promising solution for the fifth-generation (5G) and-beyond mobile communications. In order to accommodate the anticipated explosive growth of data traffic, fronthauling technology becomes a challenging technical issue in the 5G-and-beyond UDCRANs. Moreover, the schemes related to interference management and resource management need to be reconsidered. In this chapter, we will provide a comprehensive review of the current research progress on fronthauling technology. Moreover, we will compare the advantages of various candidate fronthaul schemes.

2.1 Introduction

Driven by the proliferation of data-hungry applications, mobile data traffic has consecutively increased during the past several years [1]. To cope with the ever-increasing data volume, the concept of ultra-dense network was proposed in the 5G mobile communications [2–4]. Moreover, when overlaid with macrocell base stations (McBSs), low-power small-cell base stations (ScBSs) have demonstrated the ability to extend the coverage and enhance the capacity of cellular infrastructure via reusing the already scarce spectrum [5, 6], The ScBSs can also handle the offloaded data traffic of overlaying McBSs, such that the congestion of McBSs can be alleviated or eliminated and more user equipment (UE) can be authorized into the McBSs. For example, the ScBSs can offload at most 80 percent of data traffic in the indoor hot spot scenario. Motivated by the state-of-the-art work in [7], we refer to a cellular network as an ultra-dense network when the density of UEs surpasses 0.2 UEs/m^2 or the data density is greater than 700 Gbps/km^2 in this chapter.

Besides the ultra-dense network, the cloud radio access network architecture is one of the promising candidates for future mobile communications. In a typical cloud radio access network, a baseband unit (BBU) pool performs the centralized computation-heavy tasks, and a set of remote radio heads (RRHs) performs the coarse-grained functions. The BBU pool consists of large-scale BBUs connected by a high-bandwidth and low-latency optical fiber network. Together with system software, the BBU pool can constitute a large real-time cloud, which are computation and control clouds in the

UDCRAN. Since computation-heavy tasks is centralized, the UDCRAN architecture can achieve high processing efficiency and energy efficiency [8, 9].

Beyond-5G (B5G) mobile communications, the unforeseen traffic types and escalating computation power of ScBSs will induce a paradigm shift from ultra-dense networks to incorporating more flexibility in the deployment of network functions. Hence, it is envisaged that the UDCRAN architecture is one suitable candidate for the B5G mobile systems, and such architecture will benefit from the architecture CRAN and ultra-densely deployed ScBSs [8]. For example, the B5G UDCRAN supports plug-and-play BBUs such that the BBUs can be removed, added, and upgraded in real time. In a B5G UDCRAN, the BBU pool performs the centralized computation-heavy tasks for layer 3 and above, such as radio resource control, resource block mapping, and packet data convergence protocol. While a set of ScBSs replaces the original RRHs in order to perform the functionality in layer 1 and layer 2, such as radio link control, media access control, and wireless signal coverage [10].

In the B5G UDCRAN, the data transmission and several control plane (C-plane) functions, such as interference management and mobility handover, management require efficient fronthauling between the BBU pool and ScBSs. Therefore, the fronthauling technology becomes an emerging topic in the B5G UDCRANs. However, three major issues must be solved before the successful application of B5G UDCRAN: (1) the massive deployment of ScBSs requires a significant amount of fronthaul links; (2) current optical fiber may not be deployed in large scale due to the expenditure; and (3) temporary and/or unexpected data demands require rapid response.

Several research efforts have focused on the fronthaul and backhaul links of the B5G systems [7]. Specifically, we define the fronthaul as the communication links between the BBU pool and ScBSs and define the backhaul as communication links between the core network and BBU pool. For example, the authors in [11] studied the system throughput and energy efficiency for two backhauling strategies in small-cell networks. The authors in [12] proposed the use of unlicensed spectra to serve the cellular users via the LTE-U spectrum technology. Based on the coordination among the McBSs, a win-win situation is demonstrated for both WiFi and cellular UEs in [12]. The authors in [13] pointed that applying the millimeter-wave (mmWave) spectrum bands can empower the ultra-dense networks with 10 Gbps level data rate due to the high bandwidth and directional beams of mmWave communications. Due to the lack of literature on characterizing the mmWave links, the authors in [14] figured out six points that pave the way for mmWave communications. Then, the authors in [15] evaluated the application of mmWave spectrum bands (60 GHz band and E band) for both access and backhaul links as a milestone for the B5G systems. Moreover, the authors in [16] discussed the integration of the mmWave into the current optical fiber fronthaul in order to strike a balance between the flexibility and expenditure for the backhaul links. The authors in [17] comprehensively surveyed the recent advances in fronthaul-constrained cloud radio access networks. Notably, several issues related to the capacity-limited fronthaul were investigated, such as spectral efficiency, energy efficiency, and communication quality of service. Moreover, the compression and quantization, large-scale coordination, and clustering in signal processing are also discussed together with the potential feasible solutions. The authors in [18] investigated the application of unmanned aerial vehicles (UAVs) to deliver the fronthaul links. By mounting the free-space optic (FSO) transceivers on each UAV, the authors showed the effectiveness of UAV-mounted fronthaul links.

Motivated by the previous endeavor in the fronthauling technology, we focus on the fronthauling schemes in the UDCRANs for licensed/unlicensed spectra and terrestrial/UAV-mounted scenarios. In this chapter, unlicensed spectra specifically refers to unlicensed spectra used by WiFi. We provide a comprehensive review on the state-of-the-art fronthauling technology in this chapter. We first describe the UDCRAN architecture with both terrestrial and UAV-mounted fronthaul links. Then, we discuss the diverse fronthauling schemes: mmWave, unlicensed spectrum, terrestrial FSO (T-FSO), and UAV-mounted FSO (U-FSO) fronthauling schemes.

2.2 B5G Ultra-dense Cloud Radio Access Network Architecture

Figure 2.1 illustrates the network architecture of UDCRAN, which is comprised of an McBS and a set of ScBSs, both connecting to the BBU pool via diverse fronthaul links. As shown in Figure 2.1, the McBS performs the C-plane functionality, such as mobility management and handover and load balance. The ScBSs perform several coarse-grained user plane (U-plane) functionality, such as signal up/down conversion and clustering

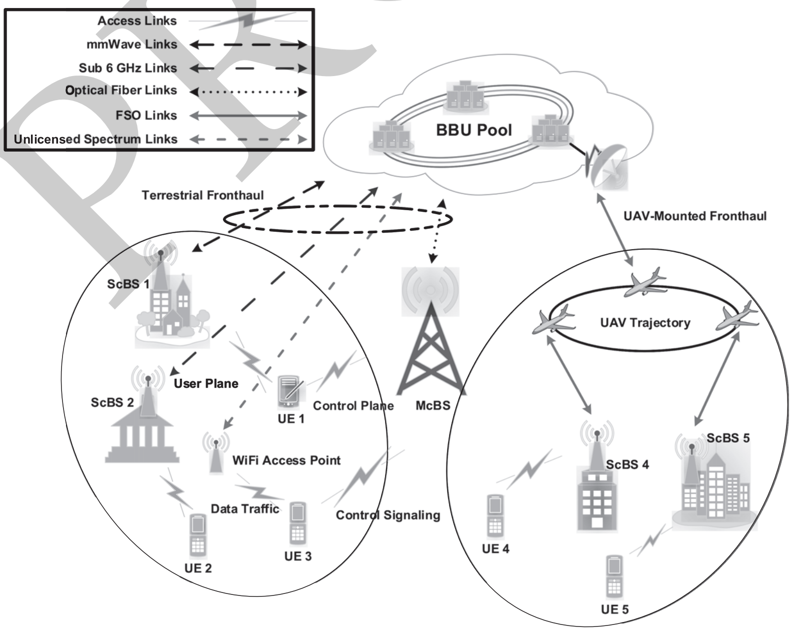

Figure 2.1 An illustration of the B5G UDCRAN architecture

among some ScBSs. The ScBSs can be deployed at the rooftop of buildings or offices to enhance the capacity and extend the coverage of traditional cellular infrastructure. Another use case of ScBSs is the indoor/outdoor hot spot scenario – e.g., a stadium with unexpected events. We need to emphasize that the mmWave communications can be applied to both access links and fronthaul links; therefore, the interference exists with the concurrent transmission of mmWave access links and mmWave fronthaul links. In the next section, we will discuss the mmWave-based access link and fronthaul link in the UDCRAN.

2.3 Fronthauling via mmWave in a UDCRAN with Phantom Cells

By reducing the distance between transmitters and receivers, low-power ScBSs can extend the coverage and enhance the capacity of the B5G mobile systems. Yet, the spectra for second-, third-, and fourth-generation (2G, 3G, and 4G) mobile systems have already been scarce. For example, 4G mobile systems, also named LTE systems, take the spectrum that ranges from 452.5 MHz to 3600 MHz as frequency-division duplex (FDD) mode [19]. Moreover, the several spectrum bands of FDD LTE are reused by the time-division duplex (TDD) LTE as well as the GSM and UMTS systems. Several spectrum bands among the already crowded spectra for GSM, UMTS and LTE may not be available for a specific country due to radio frequency (RF) regulation. In order to compensate the spectrum demands, the mmWave spectrum bands are suggested to be applied in the UDCRAN. Another benefit of mmWave spectra is that mmWave communications usually use narrow beams. A typical mmWave spectrum is located within the RF range between 30 GHz and 300 GHz. Due to the license-free characteristic and significant large bandwidth, the 60 GHz mmWave spectrum band becomes attractive [15].

The ScBSs and McBS can work coordinately to establish a phantom cell, where the ScBSs and McBS perform the functionality of U-plane and C-plane, respectively. Different from, classical cell, the base stations in a phantom cell will not perform the whole functionality of classical base stations. Leveraging the difference in coverage ability of ScBSs and McBS, the C-plane runs on the low carrier-frequency band for wide-range coverage and reliability, while the U-plane runs on different ScBSs with high-carrier-frequency band with high bandwidth in order to guarantee the communication quality-of-service of UEs. One benefit of a phantom cell is that the handover instance will not be triggered as frequently as in classical cells, such that the signaling overhead can be reduced.

Since WiFi access points are part of the ScBSs, the phantom cell can also be extended to split the C-plane and U-plane between the WiFi access points and McBS, as shown in Figure 2.1. Thus, the UEs can obtain the data traffic and control signaling messages from the WiFi access points and McBS, respectively.

Since there may exist a blockage for the ScBS–BBU link, the blocked ScBS cannot connect to the BBU pool directly. Thus, the ScBS with direct access to the BBU pool can serve as an aggregation node and forward the aggregated data traffic of associated ScBSs

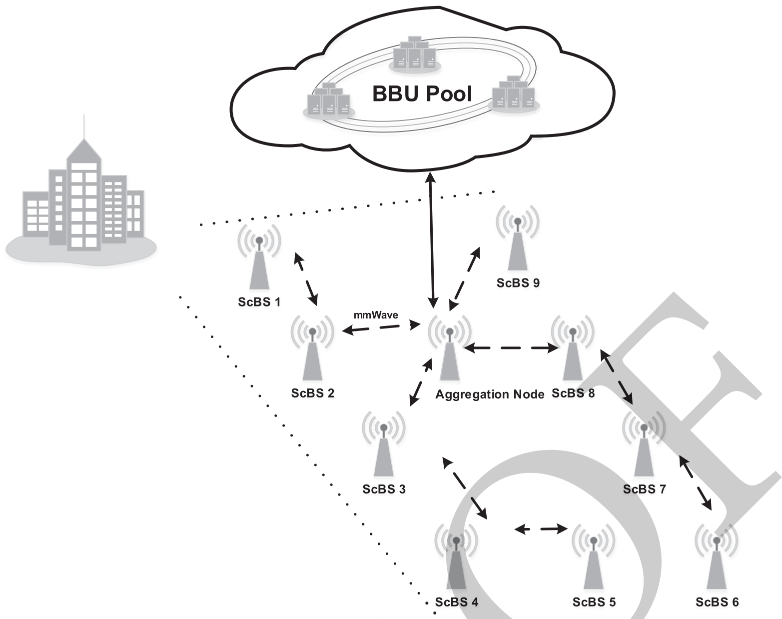

Figure 2.2 A UDCRAN with multihop mmWave fronthaul links

to the BBU pool. For example, in an indoor hot spot area, the fronthaul link between the aggregation node and BBU pool can be an an optical fiber link in the non-line-of-sight (NLoS) case or mmWave link in the line-of-sight (LoS) case. Moreover, the maximum number of hops for the relaying is confined to three hops due to the limitations on delay and routing complexity [13].

Generally, there are two types of mmWave fronthauling: (1) in-band mmWave fronthaul and (2) out-band mmWave fronthaul. In the in-band fronthauling solution, the fronthaul links and access links operate on the same mmWave spectrum band. In the out-band fronthauling solution, the fronthaul links are orthogonal to the access links in the spectrum band [26]. Moreover, the out-band fronthauling solution is more popular due to the backward compatibility of current infrastructure. However, potential capacity improvement can be better exploited by the in-band mmWave fronthauling since the mmWave is directional, and the interference management can be implemented via misaligning interfering beams.

Motivated by the road map of cellular communications, two types of spectrum reuse strategies can be adopted: time-division-multiplexing strategy and frequency-division-multiplexing strategy. In the time-division-multiplexing strategy, the access links and fronthaul links reserve several time slots for fronthaul transmission/reception, which is similar to the transmission in a multihop relaying. Figure 2.2 illustrates system architecture with a multihop mmWave fronthauling solution in a UDCRAN. As shown in Figure 2.2, each ScBS connects to the aggregation node via a direct link or multihop link. For example, ScBS 2, ScBS 3, ScBS 8, and ScBS 9 connect to the aggregation node via direct links in Figure 2.2. ScBS 1, ScBS 4, and ScBS 7 connect to the aggregation node via dual-hop links, and the remaining ScBSs (ScBS 5 and ScBS 6) connect to the aggregation node via three-hop links.

2.4 Fronthauling via Unlicensed Spectrum

Besides the mmWave spectrum bands, the unlicensed spectrum bands with center carrier frequency at around 5 GHz are also suggested to be exploited by several wireless equipment manufacturers, such as Alcatel-Lucent, Ericsson, Qualcomm, and Samsung. Since a significant amount of WiFi access points are operating on the unlicensed spectrum at 2.4 GHz and 5 GHz, several wireless vendors (e.g., Verizon) established a forum in conjunction with the aforementioned wireless equipment manufacturers in order to create specification on the usage of unlicensed spectrum. Meanwhile, 3GPP, which is another standardization institution, is also working on the verification of concurrent transmission of WiFi access points and LTE ScBSs.

Moreover, the unlicensed spectrum bands are also a potential candidate for fronthaul links in the context of UDCRAN. The benefits of unlicensed spectrum fronthaul links are as follows: (1) the license-free spectrum reduces the spectrum expenditure for wireless vendors, and (2) the resilient spectrum management can be exploited when combined with the wireless caching technology. For example, the popular contents can be prefetched into the local cache of each ScBS in off-peak hours [20]. As a result, the traffic burden on the fronthaul links can be reduced, and the system capacity is improved. However, the interference still exists between the access links and fronthaul links. Hence, several enabling techniques can be adopted for the concurrent transmission for the access links and fronthaul links: (1) the access links and fronthaul links operating over orthogonal spectrum bands; (2) the access links and fronthaul links operating over orthogonal time slots; and (3) cognitive/opportunistic transmission of fronthaul links. While the first two methods still require complex synchronization for concurrent transmission, the last method leverages the mature cognitive radio technology such that fronthaul links start the transmission when one of the unlicensed spectrum bands is unoccupied or the interference from the access links is below an acceptable threshold.

2.5 Fronthauling via Terrestrial FSO

The FSO technology is another promising solution to the fronthaul links between the ScBSs and BBU pool to compensate the scarce microwave spectrum bands and the location-constrained optical fiber. Figure 2.3 illustrates an implementation of single/multiple-hop fronthaul links via the FSO communications.

Compared with the previous optical fiber, mmWave, and unlicensed spectrum fronthauling schemes, the terrestrial FSO fronthauling scheme mainly has four advantages: (1) the enriched optical bandwidth; (2) the FSO beams can be narrower than mmWave such that it is inherently free from electromagnetic interference; (3) license-free characteristic; and (4) fast deployment as well as plug-and-play characteristic of FSO

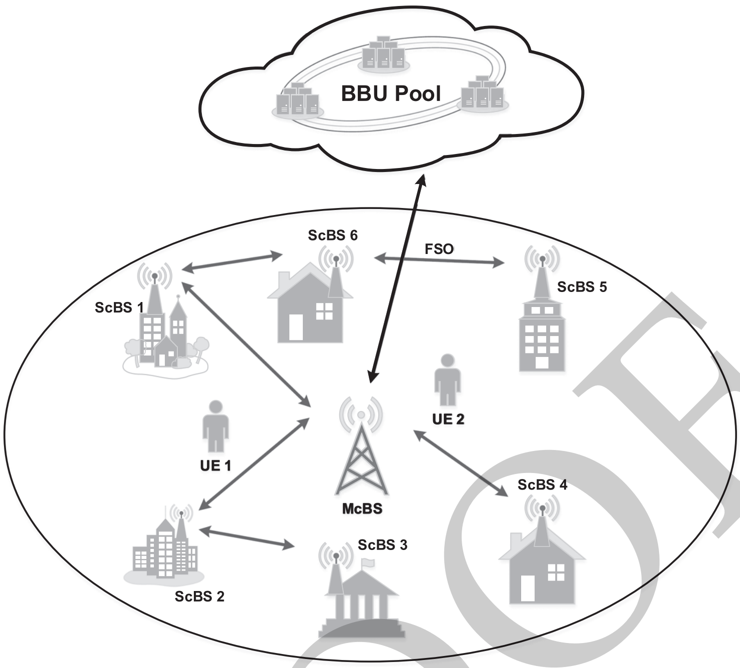

Figure 2.3 A UDCRAN with T-FSO fronthaul links

equipments. Since the FSO beams operate over an unregulated spectrum band with a wavelength range from 750 nm to 1,600 nm, the FSO fronthaul links can provide higher fronthaul capacity than the mmWave fronthaul links to several magnitudes [21]. Moreover, the authors in [22] suggested that the FSO beams operate in wavelength-division multiplexing mode can further improve the fronthaul capacity.

Yet, the weather phenomena can significantly degrade the performance of fronthaul links, especially for the long-distance FSO links. As shown in [18], the capacity of FSO links decreases rapidly when the propagation path suffers from cloud or severe fog. As a result, the FSO fronthauling scheme may not be a reasonable choice when a specific region experiences severe weather conditions, such as dust storms. Since the severe weather conditions induce the ineffectiveness of T-FSO fronthaul links, the hybrid FSO/RF fronthaul links, which use both FSO and RF adaptively, can relieve the weather degradation [23]. A hybrid FSO/RF system can be robust for either rainy or foggy weather. While the RF performance can be degraded in the presence of rain, it can penetrate fog. On the other hand, FSO beams over wavelength 750–1,600 nm cannot be transmitted through thick fog, but the rain will cause little effect on an FSO system. The only weather condition that will affect the performance of a hybrid FSO/RF system is the simultaneous heavy rain and thick fog condition, which rarely occurs. Moreover, when such simultaneous heavy rain and thick fog conditions occur, one can leverage the U-FSO fronthaul links to replace the T-FSO fronthaul links, which will be discussed in the next section.

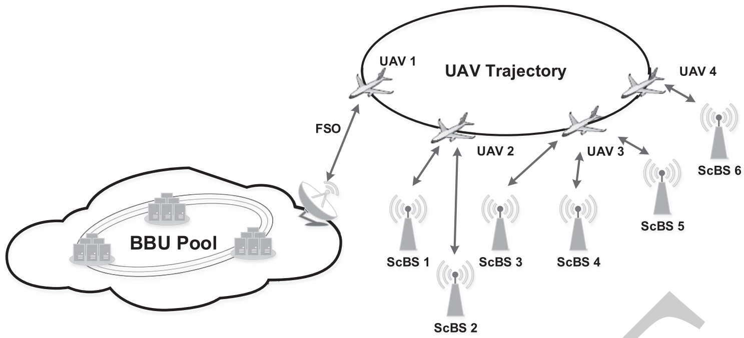

Figure 2.4 A UDCRAN with U-FSO fronthaul links

2.6 Fronthauling via UAV-Mounted FSO

Due to the significant path loss of the mmWave communications and the limited bandwidth of unlicensed spectra, we investigate the FSO-based fronthauling scheme in this section. Since the UAVs usually have a small payload, the FSO receivers in the U-FSO fronthaul links are slightly different from the T-FSO links. As suggested in [18], the retromodulator-based FSO receivers are used due to their small form factor, light weight, and low-power consumption. For example, in the DAZZLE project by Airbus Group Innovations, the size, weight, and power consumption of a typical retromodulator-based FSO receiver are, respectively, $0.55 \times 0.55 \times 0.5$ cm, 200 g, and 200 mW. Leveraging the retromodulator-based FSO receivers, each UAV can receive multiple streams of data traffic simultaneously from the FSO beams with different wavelengths.

As shown in Figure 2.4, each UAV periodically exchanges data traffic with the BBU pool when the distance between the UAV and BBU pool is below a predefined threshold. Since each UAV flies over the ScBSs periodically following the UAV trajectory, the ScBSs connect to the BBU pool intermittently to obtain the intended content from the core network. This setup is motivated by the “power law” of popular contents [18]. For example, the UAV 1 is exchanging the data traffic with the BBU pool; there is no ScBS associated, with the UAV 1. Since the UAVs are cruising over the air, the U-FSO fronthaul links have a higher probability of obtaining the LoS propagation path than the T-FSO fronthaul links. Moreover, when there is cloud in a U-FSO link, the corresponding UAV can reduce its cruising altitude to avoid the blockage of cloud.

2.7 Comparison and Research Issues in B5G UDCRAN

Table 2.1 compares the six potential fronthauling schemes for B5G UDCRAN. We observe that the mmWave, T-FSO and U-FSO fronthauls require LoS propagation paths, while the unlicensed spectrum, sub-6 GHz, and optical fiber fronthauls are still effective without LoS paths. Hence, the mmWave, T-FSO, and U-FSO are good candidates for an LoS fronthaul use case. Since the UAVs operate in the air and the cruising altitude

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Table 2.1 Qualitative comparison of different schemes

	Capacity	Cost	License	Weather	Deployment	LoS/NLoS	Response
mmWave	MediumH̃igh	Low	Unlicensed	Yes	Easy	LoS	Slow
Unlicensed Spectrum	low	Low	Unlicensed	No	Easy	LoS/NLoS	Slow
Sub-6 GHz	Medium	low	licensed	No	Easy	LoS/NLoS	Slow
Optical Fiber	High	High	licensed	No	Hard	LoS/NLoS	Slow
T-FSO	High	High	Unlicensed	Yes	Medium	LoS	Slow
U-FSO	High	Very High	Unlicensed	Yes	Easy	LoS	Fast

is tunable, the probability of obtaining the LoS paths for a U-FSO fronthaul is higher than that of mmWave and T-FSO fronthauls. We also observe that the cost (capital and operational cost) for U-FSO is high due to the manufacturing, and maintaining the UAVs requires professional operations [24]. Thus, the U-FSO can be used for the special event response – e.g., postdisaster recovery. The cost of sub-6 GHz is higher than unlicensed spectra due to the spectrum-licensing process. Since the deployment of optical fiber requires the complicated procedures for authorization, it is the most challenging one in deployment.

The large number of ScBSs in the B5G UDCRAN architecture requires resource management algorithms to balance the effectiveness and computational complexity. The recent progress on the mean field game (MFG) theory enables the development of decentralized communication resource management with reasonable complexity [25]. In the context of B5G UDCRAN, the resource management can be formulated as an MFG under the dynamic system states, where the ScBSs act as the players. The MFG solution allows the ScBSs to require less system information in a decentralized manner with minimum computational effort based on its own states and the long-term average system states. Thus, the MFG solution requires less system state information compared with the solutions based on the conventional game theory.

2.8 Conclusion

Due to the massively deployed ScBSs, the fronthauling technology becomes the key challenge for the B5G UDCRAN. In this chapter, we reviewed the recent advances in fronthauling technology for the B5G UDCRAN. We investigated both T-FSO and U-FSO fronthauling schemes in the context of B5G UDCRAN. Specifically, we discussed the application of mmWave communications in both access and fronthaul links of B5G UDCRAN. It was demonstrated that the interference leakage by the mmWave side lobes results in a degradation in system capacity of B5G UDCRAN. Moreover, the unlicensed spectrum, T-FSO, and U-FSO fronthauls were also investigated for the B5G UDCRAN. Finally, we quantitatively compared the investigated fronthauling schemes and discussed a potential theoretical tool in formulating the resource management problems. Although the optical fiber, T-FSO, and U-FSO fronthauling schemes operate in interference-free scenario, the expenditure on infrastructure can be high. For example, the current manufacturing and maintenance cost of UAVs can be high. For the mmWave, unlicensed spectra and sub-6 GHz fronthauling schemes, the ongoing challenge remains effective interference management.

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