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Combination of Ultra-Dense Networks and Other 5G Enabling Technologies: A Survey

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ABSTRACT Recently, to address the astonishing capacity requirement of 5G, researchers are investigating the possibility of combining different technologies with ultra-dense networks (UDNs). However, the ultra-dense deployment of small cells in the coverage area of conventional macrocells known as UDNs introduces new technical challenges such as severe interference, unfairness in radio resource sharing, unnecessary handover, a significant increase in energy consumption, and degraded quality-of-service (QoS). To overcome these challenges and achieve the performance requirements in 5G, there is a need to combine UDNs with other 5G enabling technologies and then, design intelligent management techniques for better performance of the overall networks. Hence, in this paper, we present a comprehensive survey on different generations of wireless networks, 5G new radio (NR) standards, 5G enabling technologies and the importance of combining UDNs with other 5G technologies. Also, we present an extensive overview of the recent advances and research challenges in intelligent management techniques and backhaul solutions in the last five years for the combination of UDNs and other enabling technologies that offers the visions of 5G. We summarise the mathematical tools widely exploited in solving these problems and the performance metrics used to evaluate the intelligent management algorithms. Moreover, we classify various intelligent management algorithms according to the adopted enabling technologies, benefits, challenges addressed, mathematical tools and performance metrics used. Finally, we summarise the open research challenges, provide design guidelines and potential research directions for the development of intelligent management techniques and backhaul solutions for the combination of UDNs and other 5G technologies.

INDEX TERMS Macrocells, small cells, ultra-dense networks, QoS.

I. INTRODUCTION

The mobile traffic on traditional cellular networks is experiencing explosive growth and the demand for mobile data continues to increase in an exceeding manner as a result of the emergence of smart-phones, tablets, laptops, as well as wearable devices with powerful multimedia facilities and recently introduced applications [1], [2]. Lately, it is predicted in [3] by CISCO that globally, between 2017 and 2022, the mobile data traffic will rise at a compound annual growth rate (CAGR) of 46%, which will reach 77 exabytes per month by 2022. In effect, only video will represent 82% of the total traffic by 2022. Presently, the industry is getting ready for an astonishing 1000-fold of data traffic growth by 2020 and beyond [4]. Additionally, the report in [5] shows that the future wireless communication systems will have to accommodate about 100 billion connected devices, which include both human and machine communication devices. The main goal is to have a connected society, where drones, cars, sensors, medical and wearable devices will all connect with one another, through cellular networks, interacting with end users to offer different innovative services such as smart cities, smart homes, smart cars, advanced security and telesurgery. Moreover, it has also been shown that in the not so distant future, indoor/hotspot traffic may approach 90% [4]. Furthermore, the mobile data applications such as Internet-of-things (IoT), high definition video, social networking, machine-to-machine (M2M) communication, augmented and virtual realities, as well as financial and wearable technologies are being accessed mainly in indoors, and they require

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broadband connectivity. Unfortunately, end users in indoor environments experience very low received signal strength (RSS) because the transmitted signals from the macrocells also known as macro base stations (MBSs) are weakened by high penetration losses by the time they get to indoor area [6]–[9].

On the other hand, the unprecedented rise in mobile data traffic results in ever increasing carbon footprint and energy consumption in mobile communication industry. Hence, this causes an escalation of carbon dioxide (CO_2) emission indirectly, which is presently considered as a major environmental hazard [8]. Likewise, the high operating expenditures (OPEX) and the enormous amount of greenhouse gas emission can be attributed to huge energy consumption in wireless networks [10], [11]. In particular, according to the report in [11], more than 80% of the energy consumption in mobile telecommunications happens at the radio access network (RAN), especially, at the base stations (BSs). Therefore, the heterogeneous deployment of small cells (SCs) (e.g., microcells, picocells, femtocells, remote radio heads (RRH) and relay nodes) in the coverage area of macrocells is one of the most important and cost-effective solutions **(1)** to cope with the future exponential traffic emanating from indoors/crowded areas and **(2)** to ensure spectrum efficiency (SE) and energy efficiency (EE) enhancement due to the decreasing transmission distance [9], [12].

Heterogeneous network (HetNet) can be described as a mixture of different types of cell (e.g. macrocell, microcell, picocell or femtocell) and various access technologies (such as long term evolution (LTE), wireless fidelity (Wi-Fi)) to provide a cellular network. As a result, mobile operators can possibly provide a more consistent quality-of-experience (QoE) for end users compared to what could be achieved with a homogenous network [13]. Hence, integrating small cells into the traditional macrocells results in HetNets [14]. The basic idea of HetNets is to bring the access nodes (ANs)/access points (APs) very close to the end users, thereby improving the signal-to-noise ratio (SNR), which provides additional enhancement in capacity. A HetNet comprises infrastructure elements, each of them having diverse constraints, several capabilities, and different operating functionalities [15], [16]. Moreover, HetNets have the capability to improve network coverage and enhance spatial radio resource reuse, consequently, allowing end users to achieve lower energy consumption with higher data rates while maintaining an uninterrupted connectivity and seamless mobility of cellular networks [17], [18]. The fundamental components of HetNets include a core network, BSs/APs, and diverse user equipment (UEs). The BSs/APs serve as the communication bridges for UEs [19]. Conventional HetNet is not capable of addressing the exponential traffic in the coming years. By contrast, ultra dense HetNet simply refers to as ultra-dense network (UDN) is one of the enabling technologies in the fifth generation (5G) wireless networks to address capacity crunch, improve coverage, and ensure green communications in dense urban outdoor and indoor environments. In UDNs, the number of APs and the communication links per unit area are more dense [9], [20]. Moreover, to address the unprecedented high volume of data traffic, the third generation partnership project (3GPP) has initiated the 5G new radio (NR) standardisation process of Release 15, which is, the non-standalone 5G radio specifications. Release 16, which is the phase II has been completed in 2019. The NR is a new air interface, which has been designed to support (i) time-division duplex (TDD) and frequency-division duplex (FDD) at carrier frequencies below and above 6GHz, (ii) massive MIMO, and (iii) scalable numerology [21], [22].

A. MOTIVATION

UDN is considered to be the main enabling technology for the future 5G wireless networks [23]. However, the ultra-dense deployment of small cells in the coverage region of conventional macrocells introduces new technical challenges such as load imbalance, severe interference problem, unfairness in radio resource sharing, unnecessary handover, inefficient utilisation of radio resource, a significant increase in energy consumption, high signalling overhead and degraded quality-of-service (QoS). To overcome these challenges and achieve the performance requirements in 5G, there is a need for the combination of UDNs and other 5G enabling technologies such as massive multiple-input multiple-output (massive MIMO), millimetre wave (mmWave), etc. These combinations can be in two or more. Likewise, network operators must utilise intelligent management techniques such as radio resource management (RRM) schemes (e.g. radio resource allocation (RRA), packet scheduling, link adaptation, radio admission control, cell/user association and radio access technology (RAT) selection schemes) [24]–[29], interference management algorithms [30], [31], mobility management schemes (e.g. handover schemes) [32]–[36], and efficient backhaul solutions [37]. These intelligent management techniques and backhaul solutions play a pivotal role in effective cell/user association, interference control, better fairness in radio resource sharing, radio admission control and flexible switching, load balancing, efficient utilisation of the limited radio resources and EE enhancement with adequate provisioning of QoS/QoE for end users.

In this survey paper, the focus is on UDNs comprising macrocells and small cells in combination with other 5G enabling technologies. A typical example of UDNs is depicted in Fig. 1.

The largest ‘‘dashed’’ circle indicates the macrocell's coverage area whereas each smaller ‘‘dashed’’ circle represents a small cell's coverage region. The macrocell communicates with its attached UEs while each small cell also communicates with its associated UEs. Macrocells usually support high mobility users while small cells provide high data rate for low mobility users [38].

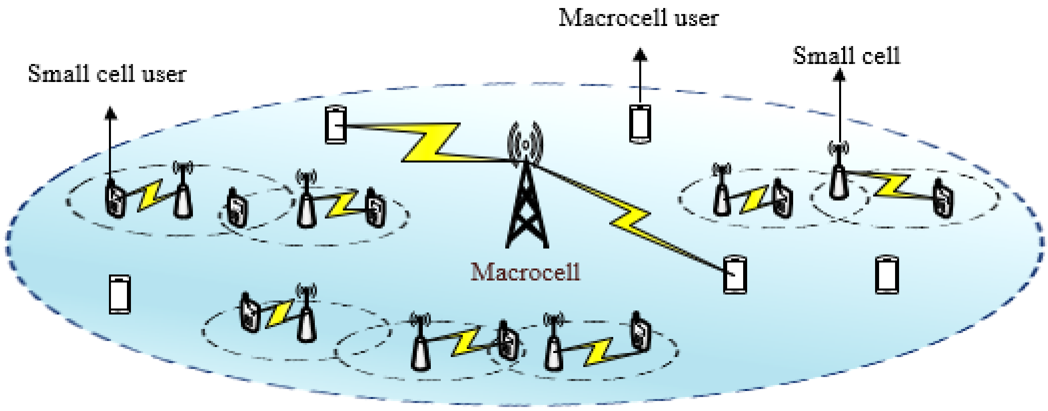

FIGURE 1. An example of UDNs consisting of a macrocell and several small cells.

B. REVIEW OF EXISTING SURVEY PAPERS ON INTELLIGENT MANAGEMENT ALGORITHMS AND BACKHAUL SOLUTIONS FOR HETNETS AND UDNs

A number of surveys have highlighted the challenging issues involved in the designing of different intelligent management algorithms in the literature [5], [14], [18]. In [5], the authors present the analysis, synthesis, and summarise alignments of the conventional radio interference and resource management (RIRM) techniques toward overcoming the technical challenges in 5G RAN systems. In [14], the authors present the aspects of RRM for LTE/LTE-advanced (LTE-A) HetNets with special consideration for radio resource utilisation, interference mitigation, complexity, fairness, and QoS. In [18], the RRA, the cross-layer optimisation, cooperative radio resource and multi-dimensional optimisation are summarised. Moreover, the methods of self-configuration, self-optimisation, and self-healing for self-organised underlay HetNets are surveyed to improve both SE and EE. Additionally, the authors outline the potential open research directions for underlay HetNets when combining with energy harvesting and cloud computing for SE and EE enhancement. Various surveys have addressed the issues of energy-efficient RRM techniques in HetNets [39]–[41], and energy saving by dynamically switching off BSs [42]. The issue relating to fairness in wireless network is discussed in [43]. In [44], the authors present various user association schemes in HetNets, massive MIMO and mmWave technologies. Some authors also surveyed the aspect of mobility management for small cells in LTE-A [45]. The authors focus more on RRM schemes that perform admission control and handover. The aspect of backhaul, which is the connectivity between small cells and radio controllers, its technical impacts, technical challenges and various access modes are discussed in [46]. All the above-mentioned works concentrate on HetNets.

Currently, the authors in [47], [48] revealed that the conventional HetNets consisting of indoor small cells such as femtocells overlaid on the conventional macrocells will not be able to satisfy the imminent traffic demands in the next few years. Hence, UDN, which is one of the key enabling technologies in 5G to tackle the traffic explosion and address the various demands of users, has been referred to by researchers from academia, industry and standardisation communities as an effective and cost-efficient solution for providing enhanced network capacity and coverage by 2020 and beyond [49]–[53]. Consequently, attention has started to shift from the traditional HetNets in the existing fourth generation (4G) wireless networks to UDNs in 5G.

Some authors have investigated various issues relating to UDNs individually [12], [20], [23], [47], [54]–[56]. A summary of the existing survey papers on UDNs is given in table 1 based on the issues discussed, research challenges and suggested techniques. In [12], potential cooperation gains are explored via a cooperative bargaining game to counter challenges of mitigating interference and saving energy, thus improving both SE and EE in UDNs. Moreover, the optimisation and trade-offs of SE and EE are surveyed, and the authors introduce the basics of cooperative game theory. Then, a utility function is presented with SE and EE coupled together. Furthermore, the bargaining cooperative game theoretic framework to explore potential cooperation gains is presented. Moreover, two applications are investigated for the dedicated and co-channel deployment cases, including cooperative relay with spectrum leasing and cooperative capacity offload. A general overview of UDNs has been presented in [20], the authors review the modelling techniques as well as the performance metrics widely exploited to model problems in UDNs.

In [23], the authors provide insights on issues, which are related to UDN deployment, for example, how to determine the density of infrastructure required to support the given traffic load requirements and the advantages of network-wise coordination. The authors in [47], discuss the classification of future network tiers, the drawbacks of the current small cell technologies and three paradigms to enhance network performance in UDNs. Also, they show how network densification contributes to the reduction of multi-user diversity, and how the proportional fairness schedulers will be losing their benefits with respect to the round robin ones.

TABLE 1. A summary of existing survey papers on intelligent management algorithms and backhaul solutions for UDNs.

Ref.	Issues discussed	Research challenges	Suggested techniques
[12]	• Cooperative bargaining game to counter challenges of mitigating interference and saving energy in UDNs • Optimisation and trade-off of SE and EE • Utility function for joint SE and EE • Utility function attaining the optimal trade-off between efficiency and fairness • Dedicated and co-channel deployment cases and cooperative capacity offload.	• Serious inter-tier and intra-tier interference • Load imbalance • High energy consumption • Distributed control with high signalling cost	• Cognitive and self-organised networks • Cell range expansion • Cooperative techniques • A distributed algorithm with low signalling cost • New cooperative scenarios in the 5G era
[20]	• Modelling techniques and enabling technologies for UDNs • Performance metrics for evaluating the designed algorithms • User association and interference management such as interference coordination, idle mode abilities • EE, RRM, spectrum sharing, resource and backhauling in UDNs	• User association • Backhauling • Interference • Small cell discovery • Propagation modelling	• Novel association rules • Effective collaborative-based solutions • Joint backhaul-aware and energy efficient user association • The use of Rician fading model • Range expansion, dual connectivity and multiple association
[23]	• Objectives, progress, analysis, and design methodologies in UDNs • Densification requirements • Scaling laws for UDNs • Coordination benefits for UDNs	• Dynamic RRM, coordination and cooperation capabilities among ANs • Backhaul overhead and computational complexity • Integration of UDN	• Network-wise coordination • 3D modelling in UDNs • Consideration of Nakagami-m and Rician fading models in algorithm designs
[47]	• Categorisation of future network tiers • Current small cell technologies and its drawbacks • Motivation for uncoordinated dense small cell deployments • System model to analyse UDNs deployments • Three paradigms to enhance network performance, i.e., network densification, higher carrier frequencies and multi-antenna transmissions • Impact of network densification in small cell BS schedulers and energy efficiency • Main differences between regular HetNets and UDNs	• Backhaul • Mobility • Reducing costs • Small cell location planning • Smart idle mode capabilities • Modulation and coding schemes • Radio resource management • Spatial multiplexing • Dynamic time-division duplex (TDD) transmissions • Co-existence with WiFi	• Wired backhaul • Accurate mobility state estimation • Massive MIMO multicast • Separating the transmission of the UE data and control planes • Self-organisation capabilities • Higher order modulation deployments and coding schemes • Fingerprinting approaches • Simpler solutions such as round robin
[54]	• Interference • Mobility • Resource management • Potential solutions in UDNs	• Interference, mobility, and cost • Security and privacy • Integrating UDNs with other techniques	• A 3D framework to address the problem of space on interference, mobility, and cost • The investigation of attacks and their impact on UDN
[55]	• Analysis of concepts and challenges of user-centric UDN (UUDN) • Architecture and methodology of UUDN • Joint optimisation of resource management and interference control • Methods for resource management, interference management, mobility management, and security issues	• Further investigation on resource management, interference management, mobility management, and security issues • Backhauling • User's privacy	• Dynamic AP grouping • Co-design and jointly optimisation of mobility, interference and resource management
[56]	• M2M communications and UDNs • The roles of M2M communications in future UDNs. • Different methods to implement M2M communications in UDNs • Security and network virtualisation,	• Energy efficiency • Over the-air signalling • Cost requirements • Computational complexity • Backhaul overhead	• A mode selection scheme • A proper routing scheme for M2M traffic • Simplified modulation and demodulation schemes

Moreover, in their survey, the EE of the ultra-dense small cell deployments is analysed, indicating the benefits of energy harvesting approaches to make the small cell deployments more energy-efficient. The authors in [54], review existing research efforts toward addressing the challenges of interference, mobility and RRM in UDNs. Similarly, in [55], the challenges, methodologies, and directions of user-centric UDNs for 5G are highlighted. The authors provide methods for resource management, interference management, mobility management, and security issues. A survey of M2M communications in UDNs is discussed in [56]. The roles of M2M in UDNs, and different methods to implement the M2M communications in UDNs are also presented. A more general survey on 5G wireless networks, which includes new architecture related to the RAN design, and emerging technologies such as device-to-device (D2D) communications, mmWave, massive MIMO etc. and key techniques such as medium access control (MAC) layer protocol, multiplexing, and interference management schemes is given in [2], [57].

C. CONTRIBUTIONS AND ORGANISATION

Different from [12], [20], [23], [47], [54]–[56], which study UDNs individually, in this paper, we aim to fill the research gaps found in previous surveys by presenting a comprehensive survey on the recent advances and research challenges on the combination of UDNs and other 5G enabling technologies. In addition, various proposals on intelligent management techniques and backhaul solutions for the mixture of UDNs and other enabling technologies in the last five years are presented. However, to the best knowledge of the authors, this is the first survey to investigate the possibility of combining UDNs with other 5G enabling technologies in two or more to explore the potential gains and challenges. In the literature, there are a number of survey papers that have presented different intelligent management techniques and backhaul solutions for UDNs individually. Recently, to address the astonishing capacity requirement of 5G, researchers are investigating the possibility of combining different technologies with UDNs, which is the focus of this paper. Also, joint considerations of various related intelligent management techniques and backhaul solutions are investigated. The contributions of this paper with respect to the existing surveys are summarised below:

- (i) We present a comprehensive study of the different generations of wireless networks, 5G standards released by 3GPP in Release 15, state-of-the-art 5G enabling technologies. Also, the benefits, research challenges and the impact of each technology on UDNs are identified as well as the impact on the network performance. Also, we point out the importance of combining UDNs with other 5G enabling technologies.
- (ii) Moreover, we provide an overview of the key challenges in various combinations and highlight different intelligent management techniques and backhaul solutions to address these challenges. We provide motivation for selecting a tool and how these tools can be applied to solve issues in 5G. We classify the intelligent management techniques according to the adopted enabling technologies and the mathematical tools used and compared with each other in order to underline benefits and challenges. The effects of these technologies on throughput, EE, SE and QoS are also investigated.
- (iii) We highlight the specific implementation of 5G on each intelligent management technique and point out the fundamental aspects that should be carefully considered, when designing different algorithms and backhaul solutions for the combination of UDNs with other 5G enabling technologies.
- (iv) We summarise the mathematical tools also known as modelling techniques widely adopted in solving problems and designing of intelligent management algorithms for various combinations as well as the performance metrics used to evaluate the algorithms.
- (v) Finally, we summarise the open research challenges and provide design guidelines for the development of intelligent management schemes and backhaul solutions for the combination of UDNs and other 5G technologies as well as the lessons learnt.

The rest of the paper is organised as follows: In Section II, the evolution of wireless networks from the first generation (1G) to 5G is given. Also, the main features of 5G wireless networks, which include the performance requirements of 5G wireless networks, 5G NR standards and the enabling technologies in 5G and beyond are presented. The general overview of combining UDNs with other 5G enabling technologies is described in Section III. In Section IV, detailed explanations on the general overview of intelligent management techniques and backhaul solutions related to the combination of UDNs with other 5G technologies are presented such as the functions of each algorithm and different approaches found in the literature for designing the intelligent management algorithms. Additionally, in Section V, a comprehensive review of the existing intelligent management and backhaul techniques for different combinations of UDN and other 5G enabling technologies is presented. In Section VI, the summary of open research challenges, design guidelines and lesson learnt are discussed. In Section VII, a concluding remark is presented.

II. EVOLUTION AND MAIN FEATURE OF WIRELESS NETWORKS

A. EVOLUTION OF WIRELESS NETWORKS

Over the years, different generations of wireless networks (1G–4G) have evolved due to the successive changes and technology innovations in the networks. However, the issue of exponential increase in mobile data traffic and continuous demands is putting more pressure on mobile network operators to provide higher data rates, and lower latency services to end users. Hence, there is a need for an evolution of 5G, which will be deployed by 2020. Additionally, 6G and 7G have been predicted in the literature, which will be deployed in 2030 and 2040 respectively [58]. In 6G, there will be integration of satellites with wireless networks to achieve global coverage. The proposed four global systems coverage are global positioning system (GPS), COMPASS, Galileo, and GLObal NAvigation Satellite System (GLONASS) developed by USA, China, EU, and Russia respectively. The 7G will provide space roaming through these four systems [58]. In this paper, the evolutions of mobile system generations from 1G to 5G are described and a summary of the comparison among them is presented in table 2 to show at a glance the features of 1G-5G.

- **FIRST GENERATION (1G)**
  1G systems, deployed in 1980's, were analog cellular systems for example, the advanced mobile phone services (AMPS), the Nordic mobile telephones (NMT), and the total access communication system (TACS) [57]–[61]. The systems had data rate of up to 2.4kbps but had many disadvantages. Also, 1G systems

TABLE 2. Comparison among mobile system generations.

Features \ Generation	1G	2G	3G	4G	5G	Ref.
Deployment	1980	1990	2000	2010	2020	[57], [61], [63]
Transition	–	2.5G, 2.75G	3.5G, 3.75G, 3.9G	–	?	[57]
Frequency band	800 MHz	850/900/ 1800/1900 MHz	800/850/900/ 1800/1900/2100 MHz	1.8GHz, 2.6 GHz	30-300 GHz	[57], [61]
Speed	2 kbps	64 kbps	2 Mbps	1 Gbps	>1 Gbps	[63]
Latency	N/A	629ms	212ms	60-98ms	<1ms	[64]
Power density (Watt/m^2)	4.0	4.5-9.0	4.5-10	10	10	[61]
Bandwidth	30 kHz	200 kHz	5 MHz	1.4MHz-20MHz	60 GHz	[57]
Technology	Analog cellular	Digital cellular	CDMA, UMTS	LTE-A, WIFI	Muilti-RATs, Wi-Gig	[57], [63]
Applications	Voice	Digital voice, low rate data	Higher quality audio and video calls, mobile broadband	Wearable devices, online gaming, high definition TV	Ultra high definition video, virtual reality, D2D, M2M, IoT	[57], [63]
Access Technology	AMPS, FDMA	GSM, TDMA, GPRS, EDGE	CDMA, UMTS, WCDMA, HSUPA/HSDPA, EVDO	OFDMA/SC-FDMA	BDMA, FBMC, NOMA	[57], [63]
Handover	No	Horizontal	Horizontal	Horizontal/vertical	Horizontal/vertical	[63]
Switching	Circuit	Circuit/packet	Packet	All packet	All packet	[63]
Forward Error Correction	N/A	N/A	Turbo codes	Turbo codes	LDPC	[57]
Core network	PSTN	PSTN	Packet network	Internet	Internet	[63]
Key differentiator	Mobility	Secure, mass adoption	Better Internet experience	Faster broadband Internet, lower latency	Ultra-fast broadband Internet	[8], [13]
Weakness	Poor SE, security issues	Limited data rates, difficult to support demand for Internet/e-mail	Failure of WAP for Internet access, mobile specific architecture and protocols	spectrum crisis, High energy consumption	?	[8], [13]

include a signalling protocol known as signalling system 7 (SS7) [62].

- **SECOND GENERATION (2G)**
  2G mobile communication systems emerged in 1990's. They were digital cellular systems, essentially designed for voice as well as power control methods that offered a fixed data rate of about 64kbps for reliable QoS maintenance. Moreover, 2G systems provide services such as electronic mail (e-mail) and short message service (SMS). The major 2G standards were global system for mobile communications (GSM), interim standard 95 (IS-95) and interim standard 136 (IS-136) [61], [62]. The significant benefit of 2G mobile handsets was the longer battery life due to low power radio signals. Moreover, 2G has two transitions i.e. 2.5G and 2.75G. The major 2.5G technologies were general packet radio service (GPRS) with data rates of 50kbps, enhanced data rate for GSM evolution (EDGE) with up to 200kbps data rates, and code division multiple access (CDMA) [57], [59].
- **THIRD GENERATION (3G)**
  3G systems appeared in 2000's, which provided transmission rate of up to 2megabit-per-second (Mbps) with improved QoS. The 3G standards were time division multiple access (TDMA), wideband CDMA (WCDMA), called international mobile telecommunications (IMT) 2000, standardised by the international telecommunication union (ITU) and universal mobile telecommunications system (UMTS) standardised by 3GPP, evolution data optimised standardised by 3GPP2, high-speed uplink packet access (HSUPA) and high-speed downlink packet access (HSDPA). The services provided by 3G were improved voice quality and global roaming. In addition, 3G systems have three transitions i.e 3.5G and 3.75G and 3.9 (LTE-A Pro) [60]. The main drawback of 3G mobile systems was that they required more power than most 2G systems [61].
- **FOURTH GENERATION (4G)**
  4G wireless systems were designed to fulfil the requirements of IMT-advanced (IMT-A) using the Internet protocol (IP) for all services [8], [63]. In 4G systems, an advanced radio interface is used along with technologies like MIMO, orthogonal frequency-division multiplexing (OFDM), and link adaptation. The existing 4G systems (for example, LTE and LTE-A systems) are capable of supporting data rates of up to 100 Mbps for high mobility, and up to 1 gigabit-per-second (Gbps) for low mobility e.g., nomadic/local wireless access [8], [57]–[65]. Currently, 4G networks will not be able to adequately accommodate the envisioned future traffic because the networks have reached their theoretical limits [65]. The major disadvantage of 4G systems is the excessive overhead which occurs due to the use of

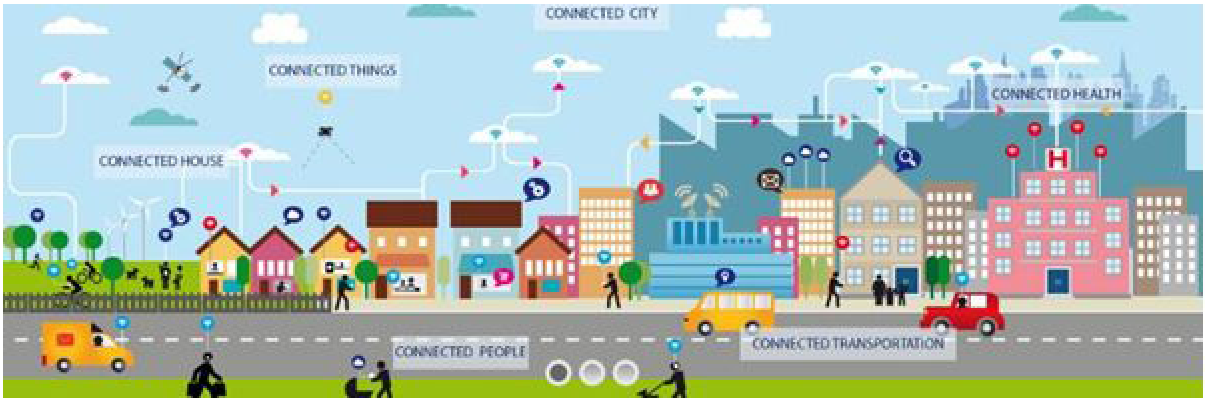

FIGURE 2. An illustration of future 5G networks and infrastructures [67].

cell-specific reference signal (CRS) that decreases the EE of the overall network [61]. Also, there are still some specific challenges that 4G cannot accommodate, for example, huge energy consumption and spectrum crunch [8]. Consequently, a new generation of mobile communication, 5G, becomes necessary.

- **FIFTH GENERATION (5G)**
5G wireless networks will include device densities, extreme BSs with unprecedented number of antennas, ultra-high carrier frequencies with massive bandwidths [49]. The vision of 5G is to ensure that the entire world is connected and achieve ubiquitous and seamless communications between people–to–people (anybody), people–to–machine or machine–to–machine (anything), whenever they need (anytime), wherever they are (anywhere), by whatever services/networks/electronic devices they want (anyhow) [8]. In addition, 5G networks are expected to satisfy different requirements of new services and support vertical markets such as healthcare, energy, automotive, agriculture, etc.
Presently, the attention of mobile industry and research community is moving towards the 5G wireless broadband systems to address the issue of ever-increasing demands of end users. The ultimate objective of 5G is to support 10 to 100× higher user data rate (1 to 10 Gb/s in dense urban areas), 10 to 100× higher number of connected devices, 10× longer battery life for low-power massive machine-type communications (mMTC) and lower end-to-end (E2E) latency as well as 1000× higher mobile data volume per area. Furthermore, to enable the vision of the future Internet, there is a need for E2E latency to be less than 1 ms, while EE and SE will be 10× higher [65], [66]. The 5G technologies include multi-RATs, wireless gigabit alliance (Wi-Gig), filter bank multicarrier (FBMC), beam division multiple access (BDMA) and non-orthogonal multiple access (NOMA). A typical example of 5G networks and infrastructure is shown in Fig. 2, where there will be connection of houses, things, cities, people, vehicles and different smart products. In summary, 5G promises to provide tremendous features as compared with the previous generations of wireless networks.

B. PERFORMANCE REQUIREMENTS OF 5G WIRELESS NETWORKS

In 5G, three use case scenarios have been identified, which are enhanced mobile broadband (eMBB), mMTC and ultra-reliable and low-latency communications (URLLC) [64], [67]. Presently, various major performance requirements have been identified by different research initiatives for 5G wireless networks to ensure optimal performance of the use case scenarios. These requirements are summarised as follows:

- **Higher Data Rate:** Peak data rates of 10 Gbps (uplink) and 20 Gbps (downlink) are required in 5G wireless networks [67]. This amounts to 10-fold increase from the theoretical peak data rate of 150 Mbps of the existing LTE network [2], [13].
- **Reduced Latency**: Lower latency of less than 1 ms is required in 5G wireless networks. This amounts to 10× decrease from the 10 ms round trip time in the current 4G wireless networks [2].
- **Higher Battery Life**: 5G wireless systems will have a longer battery life (up to ten years) to support the emerging applications compared to the 4G wireless systems [13].
- **Higher Bandwidth in Unit Area:** 1000× higher bandwidth per unit area is required to facilitate a massive number of connected devices along with ultra-high bandwidths for longer durations in a particular area [2], [13], [66].
- **Massive Connectivity:** There will be huge number of connected devices to accomplish the vision of D2D, M2M, and IoT technologies, it is essential for emerging 5G wireless networks to provide connectivity to billions of devices [2], [13], [49].
- **100% Network Availability:** 5G envisages that network should be always available everywhere, and everytime in reality [2].

TABLE 3. A list of various proposed 5G enabling technologies as identified in the literature.

Ref.	Year	5G Enabling Technologies
[8]	2014	energy-efficient communications, massive MIMO, VLCs, and CRNs
[20]	2016	SDN, C-RAN, mmWave networks, massive MIMO, D2D, multi-RAT, proactive caching, IoT
[44]	2016	Massive MIMO, energy harvesting, mmWave networks, SONs, C-RAN, D2D, and FD communication
[69]	2015	Dense HetNets, FD communication, energy-aware communication and energy harvesting, C-RAN, wireless NFV.
[70]	2016	Wireless NFV, SDN, mmWave spectrum, network ultra-densification, massive MIMO, big data and mobile cloud computing, IoT, green communications, D2D, and new RATs.
[74]	2014	Denser multi-RAT HetNet, massive MIMO, mmWave networks, D2D, FD communication
[76]	2015	Ultra-dense wireless networks using mmwave communications and microwave, massive and full-dimension MIMO technologies, C-RAN
[77]	2017	Massive MIMO, mmWave, UDNs, D2D
[79]	2018	UDNs,FD, mmWave, massive MIMO, NOMA and DSA

- **100% Coverage for Ubiquitous Connectivity**: Complete coverage becomes indispensable irrespective of users' locations in 5G wireless networks [2].
- **Reduction in Energy Usage:** 100-fold EE is expected in 5G. Development of green technology is already being considered by standardisation bodies to ensure significant reduction in devices' energy consumption [2], [13], [49].
- **Enhanced end-user QoE:** QoE describes the subjective perception of each user as to how well an application or service is working. QoE is highly application- and user-specific with an adequate level of reliability. It is required in 5G to provide end users with better experience and satisfaction in a wireless network [41], [68], [69].
- **Higher Security:** Higher security is another requirement that is very important in 5G for standardisation on authentication, authorisation and accounting [70].

C. 5G NR STANDARDS

NR is the 3GPP effort for outlining and standardising advanced RAT for 5G [71], [72]. The process is on-going. A total of 12 architectural options have been identified in [72] for 5G and beyond. The key features of NR are beamforming and multi-antenna transmission, forward compatibility, spectrum flexibility, higher frequency operation, and ultra-lean design, which aim at reducing the effect of always-on transmissions, hence, enabling higher achievable data rates and network energy performance [73]. Small cell can be enhanced through dual connectivity (DC) and its variants in 5G NR [72].

NR supports a flexible numerology with subcarrier spacings from 15-240 kHz with a relative change in cyclic prefix period. It is based on OFDM transmission similar to LTE [73]. The NR opportunities come with different challenges such as protocol optimisation, channel modelling, mmWave modelling digital interface capability, and antenna complexity. The development of interworking functionality with minimal interfaces between evolved packet core (EPC) and 5G core (5GC) is one of the solutions to address these challenges.

D. 5G ENABLING TECHNOLOGIES: DESCRIPTION, BENEFITS, CHALLENGES AND RELATIONSHIP WITH UDNs

The emergence of each mobile system generation introduces new wireless technologies and services. Similarly, growing interest in very high data rates, high-quality services and scarcity of available frequency resources in mobile communication networks spur exploiting new technologies that can facilitate a significant improvement in spectral and energy efficiencies of the emerging 5G networks. A plethora of new technologies need to be incorporated in the future cellular networks to meet the unprecedented traffic demands and to provide newly conceived services, which can make the 5G systems feasible and business viable [44], [74], [75]. Consequently, there are various enabling technologies that have been identified in 5G namely: UDNs, massive MIMO, mmWave, energy harvesting communication, FD communication, network slicing, cloud radio access networks (C-RAN), D2D communication, NOMA, network function virtualisation (NFV), software defined networking (SDN), cognitive radio networks (CRN), big data and mobile cloud computing, fog computing, multi-RAT, proactive caching, self organising network (SON), IoT, and visible light communication (VLC) [8], [44], [69]–[79]. It must be noted that each enabling technology introduces its own benefits and challenges. A list of various proposed 5G enabling technologies as identified in the literature is presented in table 3.

1) UDN TECHNOLOGY

The UDN technology is presented as a new network paradigm evolution to the 5G wireless systems to address the exponentially increasing traffic demands. Recently, mobile operators are already changing their conventional HetNets to UDNs, in which small cells reuse the spectrum and provide most of the capacity while macrocells provide umbrella coverage for UEs [20]. In UDNs, the number of APs in an area is considerably larger than the active number of mobile terminals [80]. The main features of the UDN are the dense deployment of small cells and short transmission distance [54].

ARCHITECTURE OF UDN

The UDN architecture is made up of MBSs/ANs and UEs [81] as shown in Fig. 3. In LTE, macrocells are also

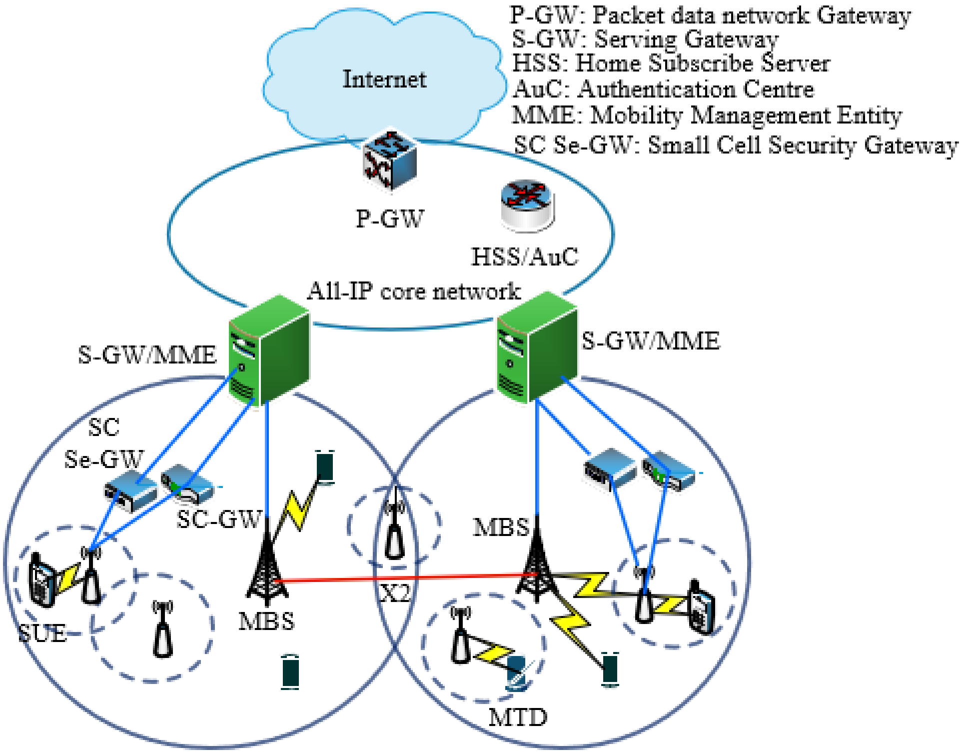

FIGURE 3. UDN architecture [81].

called enhanced NodeBs (eNBs) while femtocell, a common small cell is called Home enhanced NodeB (HeNB). The AN performs scheduling and baseband processing and terminates the radio interface (including physical, medium access, and link layers) toward the UEs. ANs can directly be connected to fixed transport or can be wirelessly backhauled toward other ANs. These physical nodes are aided by several functions responsible for managing various aspects of the UDN including transport and access resource coordination and mobility [82].

The UDN architecture is an evolution of the current HetNets, which is in alignment with the 3GPP LTE-A standards [83]. The core network is also known as the evolved packet core (EPC), which is divided into the packet data network gateway (P-GW), the serving-gateway (S-GW), and the mobility management entity (MME). The P-GW is a layer 3 mobility anchor point, which acts as the channel between the EPC and other IP core networks such as the Internet. It is responsible for the IP assignment of the UE. The S-GW is responsible for routing and forwarding user data packets. The S-GW also act as the mobility anchor during inter-RAT and inter-BS handovers. Moreover, S-GW manages and stores UE contexts. It also possesses the control capabilities to manage clusters of small cells and uses the IP Security (IPsec) tunel to achieve a secured communication between the HeNB and the S-GW [81]. The MME is related to radio bearer management, where a radio bearer is a logical channel or a data flow established between a macrocell and a UE. The functions of MME include IP address allocation to UEs for QoS provisioning, paging procedure, tracking of idle mode UEs, user mobility management, bearer activation/deactivation process, security management, roaming, ciphering/integrity protection and user authentication [14], [83].

The RAN is referred to as the evolved-universal terrestrial radio access network (E-UTRAN), which consists of BSs and UEs. The EPC and E-UTRAN are connected via the S1 interface between the S-GW and macrocells. Each macrocell manages both downlink and uplink transmissions among UEs. Also, a macrocell provides multimedia services to different UEs in their coverage areas. Likewise, macrocells are connected to each other using the X2 interface for direct signalling as can be seen in Fig. 3. The connection allows the macrocells to exchange information that is related to inter-cell interference (ICI) coordination and mobility management. For the SCN, a small cell must connect to a small cell Gateway (SC GW) to reach the mobile network through an Internet fixed broadband connection e.g., optic fibre, digital subscriber line (DSL), or cable. In general, the connection between a small cell and its gateway passes through a small cell Security Gateway (SC Se-GW) to achieve secured communications. The SC Se-GW provides IPsec channels for the small cell, which is also responsible for their authorisation and authentication. The SC GW serves as an accumulator to aggregate the traffic of a large number of small cell to

TABLE 4. Comparison among small cells.

Various Aspects \ Types of small cell	Micro cell	Pico cell	femto cell	Relay nodes	RRH	Ref.
Deployment Location	Outdoor	Outdoor/ indoor	Indoor	Outdoor/ indoor	Outdoor	[20]
Coverage	250m - 1km	< 100m - 300m	< 10m - 50m	300m	Few km	[16], [84]
Installation/Site rental	Operator	Operator	Customer	Operator	Operator	[88]
Deployment configuration	Planned	Planned	Unplanned	Planned	Planned	[88]
Radio/Frequency parameters	Centrally planned	Centrally planned	Locally determined	Centrally planned	Centrally planned	[88]
Access Mode	Open access	Open access	Open/ closed/ hybrid access	Open access	Open access	[20]
Transmit power	30–43 dBm	23–30 dBm	< 23 dBm	30 dBm	46 dBm	[16], [84]
Backhaul	Fibre	X2 interface	IP	Wireless	Fibre	[16]

the core network. SC GW supports some particular functionalities, such as handover control, admission control, and interference management [14], [83].

COMPONENTS OF UDN

Wireless cells can be categorised as macrocells and small cells, with decreasing cell radii and decreasing transmit power levels.

(*i*) ***Macrocells:*** These are conventional operator-installed BSs, which are deployed to provide open access and a wide area coverage typically on the order of few kilometres. Usually, macrocells offer guaranteed minimum data rate under maximum tolerable delay and outage constraints. Macrocells typically emit up to 46 dBm [84], serving numerous customers and using a dedicated backhaul. Different from conventional cellular networks where BSs are placed in the centre of hexagonal grids, the placement of BSs in UDN are usually according to the traffic demands. Therefore, UDN tends to be a random network. The UEs in UDN may suffer from severe ICI from neighbouring BSs due to the random placement of the BSs. A lot of research has been carried out on ICI management and one effective scheme is interference coordination, such as the frequency reuse scheme in macrocell network with regular topology and balanced cell loads. However, this scheme cannot be directly applied in UDN. Firstly, in UDN, the topology is irregular and BSs have different numbers of interfering BSs. Thus, it is difficult to group BSs in UDN and reuse the frequency as in macrocell networks. Secondly, the cell loads in UDN are extremely imbalanced because of the irregular cell coverage and various requirements of user's QoS. Obviously, novel ICI coordination schemes are crucial in UDNs.

(*ii*) ***Small Cells:*** A brief description of small cells, types of small cell, access modes in small cells, spectrum assignment techniques in small cells, and the benefits of deploying small cells are presented in the following:

- **Description of Small Cells:** A small cell also referred to as small BS (SBS) is defined as "a low-cost, a short-range, and low-power cellular BS/AP that operates in licensed and unlicensed spectrum to connect standard mobile devices to a mobile operator's network using cable broadband connections or wireless. Small cells are installed in homes, small business environments, lampposts or streetpoles to boost signal reception [6], [85]. The purpose of small cell deployment is to enhance communication quality when a user is located in the weak signal area such as the boundary of BS coverage or indoors.
- **Types of Small Cell:** There exists different types of small cell underlaid macrocells, which are microcells, picocells, femtocells, RRH and relay nodes. The small cells are differentiated by their propagation characteristics, transmit powers, physical sizes, and backhaul [15], [20]. The detailed comparison among small cells, their transmit power and coverage is given in table 4.
- **Access Modes in Small Cell:** Small cells work in three distinctive access modes namely; closed access, open access, and hybrid access modes [61], [83].

(*i*) ***Closed Access Mode:*** Only the registered users are authorised to access a small cell in the closed access mode. These users are referred to as closed subscriber group (CSG). This access mode offers exclusive service to small cell users in the CSG but the performance can be affected if there are nearby macrocell users that cause severe interference. This is a typical user-deployed scenario [61], [83].

(*ii*) ***Open Access Mode:*** All nearby users can have access to a small cell in the open access mode. This type of access mode offers the highest level of network capacity but QoS degradation occurs when the number of unregistered nearby macrocell users increases rapidly or when they are running bandwidth-consuming applications. Also, this type of access mode is typically deployed by mobile operators, where small cells with open access are deployed in public regions [61], [83].

(*iii*) ***Hybrid Access Mode:*** The hybrid access mode, which is the trade-off between the closed and open access modes offers differentiable services to the registered users in CSG and nearby unregistered macrocell users that are in the coverage area of the small cell. A certain amount of resources is reserved for the subscribed users in CSG while a limited amount of resources is available to all nearby unregistered users [61], [83].

- **Spectrum Assignment Approaches in Small Cells and Macrocells:** There are three possible approaches in allocating spectrum resources between small cells and macrocells, which are dedicated-channel assignment, co-channel assignment and partial-channel-sharing assignment [86], [87].

(*i*) ***Dedicated-channel assignment:*** In the dedicated-channel assignment, small cells and macrocells utilise different frequency bands. This assignment is an effective solution to avoid mutual interference between SCNs and macrocell networks, but the spectral usage is inefficient due to bandwidth segmentation. Therefore, a dedicated-channel assignment is not feasible for the ultra-dense deployment of small cells because one, it leads to resource underutilisation in UDNs and two, BSs may not be able to fully utilise their radio resources with fixed partitioning when the traffic load in the network is fluctuating [86], [87].

(*ii*) ***Partial-channel-sharing assignment:*** The overall bandwidth is segmented into two parts in the partial-channel-sharing assignment. One part is exclusively assigned to macrocell users, and the other part is shared by macrocells and small cells. Macrocell users benefit from ubiquitous coverage on an exclusive carrier frequency and partial coverage (outside the small cell coverage) or sharing carrier frequency. This assignment is efficient without causing much bandwidth loss and mutual interference, but a portion of the spectrum and high-cost carrier-aggregation-capable terminals are required [86].

(*iii*) ***Co-channel assignment:*** Spectral usage is high because both small cells and macrocells share the same frequency bands without bandwidth segmentation but severe interference occurs in this co-channel assignment technique. [86], [87]. The co-channel assignment is preferred to the dedicated-channel assignment and the partial-channel-sharing assignment by wireless network operators since the licensed spectrum is costly and scarce but powerful interference mitigation schemes are required.

- **Benefits of Deploying Small Cells:** These benefits are summarised below:

  (*i*) ***Improved coverage:*** The deployment of small cells in outdoor, or indoor environments would cover the coverage holes of macrocells due to the close proximity of the transmitters (small cells) and the receivers (SUEs) [6], [14], [18], [89]–[91].

  (*ii*) ***Enhanced capacity:*** The deployment of small cells would enhance the network capacity of cellular networks because small cells transmit at lower power, thereby reducing interference and achieving a higher signal-to-interference-plus-noise ratio (SINR). Thus, more users can be grouped into an area to operate on the same spectrum [6], [14], [18], [89]–[91].

  (*iii*) ***Higher macrocell reliability:*** The traffic congestion on macrocells would reduce by offloading the indoor/hotspot traffic to small cells, hence, making macrocells more reliable. Also, traffic offloading from macrocells to small cells improves the overall network performance and service quality [6], [14], [18], [89]–[91].

  (*iv*) ***Longer system battery life:*** The life span of the system battery is prolonged because a lower transmission power is required in small cells [6], [14], [18], [89]–[91].

  (*v*) ***Seamless connectivity:*** A small cell can perform handover to a nearby macrocell. Hence, there is an unbroken service even if a small cell user leaves the coverage area of the serving small cell [6], [14], [18], [89]–[91].

  (*vi*) ***Better QoS:*** Offloading users from macrocells to small cells enhances the satisfaction level of users since a small cell serves a small number of users, each user can get more resources to satisfy its QoS's requirements leading to enhanced QoS [6], [14], [18], [89].

  (*vii*) ***Reduced CAPEX and OPEX:*** A large portion of CAPEX and OPEX is attributed to site acquisition, installation and maintenance of cell tower, energy bills, and backhaul in macrocells. The deployment of small cells reduces the infrastructure, maintenance and operating costs of the mobile operators [6], [14], [18], [89]–[91].

2) MASSIVE MIMO TECHNOLOGY

A massive MIMO (also called hyper MIMO, full-dimension MIMO, large-scale antenna, or very large MIMO) system is a BS equipped with massive antenna arrays. A massive MIMO system is capable of serving various single-antenna users over the same frequency and time resource. It is a special type of multiuser MIMO (MU-MIMO) wherein the number of antennas at the BS is more than the number of devices per signalling resource [2], [92], [93].

The benefits of massive MIMO systems are identified in [8], [92]–[99] as follows:

- Massive MIMO is one of the basic 5G technologies to manage the orders of magnitude more data traffic and can substantially improve SE and EE using relatively simple (linear) processing [8], [92], [95].

- In massive MIMO systems, especially for most propagation environments, the detection methods and the simple linear precoding can be used to mitigate inter-user interference while the effects of fast fading and noise disappear [8], [96].
- The MAC layer design is simplified by using MU-MIMO in massive MIMO systems. Also, complicated scheduling schemes can be avoided [8].
- Computationally, very simple signal processing happens from all the antennas at the base stations because massive MIMO systems are based on phase-coherent technique [92]–[98].
- There is a significant increase in capacity (about 10-fold) when massive MIMO system are used as a result of the aggressive spatial multiplexing. In addition, the radiated EE is improved by 100-fold [8], [99].
- The massive MIMO systems can be designed using low-power and cheap components [92].
- The massive MIMO systems allow remarkably reduction of latency when beamforming is used [92].
- The multiple access layer is simplified because each subcarrier in the massive MIMO systems has similar channel gain [92]–[99].
- The massive MIMO systems have a lot of potentials to eliminate harmful signals.
- Massive MIMO is a scalable technology, which can provide uniformly good services for end users [92].

There are still some challenges that must be addressed to make massive MIMO technology feasible, which are:

- **Propagation models**: In the literature, most work on massive MIMO show that as the number of antennas increases, under favourable propagation conditions, each user channels are spatially not correlated and their channel vectors asymptotically become pairwise orthogonal [92]. The authors in [100] demonstrate that the antenna correlation coefficients are extensively greater than what should be expected under independent and identically distributed (i.i.d.) channel assumptions. Hence, this implies that user scheduling scheme should be an essential part of massive MIMO systems.
- **Pilot contamination:** In a multi-cell massive MIMO system, users from neighbouring cells can use non-orthogonal pilots because the number of orthogonal pilots is lesser than the number of users. The problem of pilot contamination occur when non-orthogonal are used, which results in ICI. Various precoding, channel estimation, and cooperation techniques have been proposed to solve this problem. However, more efficient techniques with good performance, low complexity, and zero or limited cooperation between BSs need further intensive study [92].
- **Antenna Arrays:** In massive MIMO systems, there are numerous issues regarding antenna arrays. First, the configuration and deployment of the antenna arrays. Second, a system, where antennas are placed in 3D and distributed array structures. Third, the mutual coupling effect among antenna elements. This effect can be neglected only when the antennas are well separated from each other. Thus, for massive MIMO systems, antennas may be compactly arranged, and, the coupling effect cannot be neglected. Fourth, the increased hardware and computational costs as a result of using large-scale antenna arrays is another issue. In general, issues relating to antenna array design and implementation are to be addressed to achieve an optimal performance of the massive MIMO systems [92].
- Other open problems include development of novel channel tracking algorithm, low-complexity interference coordination schemes and user grouping optimisation [94].

The massive MIMO technology can be combined with UDNs to address the problems of load imbalance and severe interference, if intelligent management schemes can be developed for this combination.

3) MILLIMETRE WAVE TECHNOLOGY

The mmWave communication is envisioned to provide orders of magnitude capacity improvement due to the large bandwidth available at mmWave bands [101]. Today, mobile communication systems generally use sub-3 GHz spectrum. However, this band is becoming crowded, as the traffic demands grow, whereas a substantial amount of spectrum in the range of 3-300 GHz remains unutilised. An obvious approach of enhancing the throughput will be through bandwidth expansion [65]. The major difficulty of mmWave communications is the severe propagation attenuation caused by pathloss (specifically with non-line-of-sight propagation (NLOS)), shadowing and blockages. Commonly, mmWave spectrum has mainly been used for carrying high resolution multimedia streams for short-range services or for outdoor point-to-point backhaul links due to lack of cost-effective components and high propagation loss. Hence, suitable models for using these frequencies are needed [102]. Currently, it has been shown in [103] that these frequencies can be introduced into mobile systems after intensive analysis of the propagation characteristics.

The authors in [104] have applied mmWave beam steered fibre wireless systems to 5G indoor coverage, in terms of network architectures, key emerging devices and fibre-wireless links to ensure link reliability and improve bandwidth efficiency. Also, in [105], the propagation characteristics of 28 GHz and 38 GHz frequencies are studied in different environments, which can be used in 5G systems. UDNs are expected to operate in the mmWave band, where wide bandwidth signals needed for high data rates can be designed, and will rely on high-gain beamforming to mitigate pathloss and ensure low interference [82], [106]. Furthermore, the large beamforming gains allow the mmWave inter-BS backhaul link to be deployed in the same frequency as the mmWave access link [65]. In [107], the authors present a preliminary analysis and solution framework to support NLOS and an inband, point-to-multipoint, mmWave backhaul. In addition,

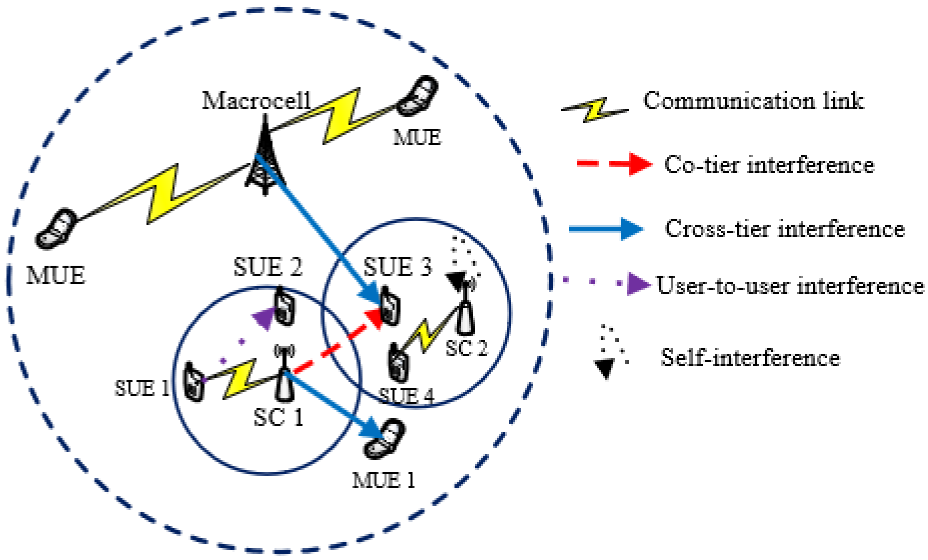

FIGURE 4. Different types of interference in FD-based UDNs.

the obtained results show that an in-band solution is viable at mmWave frequencies for tolerable losses in access capacities when the authors assume modest hardware capabilities. Moreover, the two major characteristics of the mmWave technology are very small wavelengths leading to massive antennas in a particular area and massive bandwidth, which enables ultra-high coverage throughput. In [38], a digitally controlled phase shifter network based hybrid precoding algorithm is proposed for mmWave massive MIMO to reduce the complexity and the required cost of a transceiver with a negligible performance degradation. Also, the possibility, benefits and the challenges of mmWave massive-MIMO-based wireless backhaul for 5G UDNs are discussed to facilitate performance enhancement.

4) FD COMMUNICATION

The term "duplex" in a wireless network describes the capability of two systems to communicate with each other, i.e., both systems have the ability to transmit and receive data [109]. FD transmission is an emerging technology with simultaneous transmission and reception on the same carrier and it is a promising way to boost SE. Also, recent studies show that in-band FD technology, where a terminal is capable of receiving an incoming frame and simultaneously transmitting an outgoing frame exhibits better performance for low-power transmission, which makes it suitable for UDNs [110]. Therefore, FD communication in UDNs is expected to offer tangible enhancements in uplink and downlink transmission rates as compared to the traditional half-duplex (HD) systems but hindered by complicated interference problems. Recent breakthroughs in analog and digital signal processing make it possible for FD communications to demonstrate nearly doubled SE for point-to-point links. However, it has complicated interference environments [111]. Hence, advanced interference cancellation schemes and new scheduling algorithms are crucial, to maximise the EE and capacity gain in a FD cellular system [112].

There are four types of interference, which could arise due to the ultra-dense deployment of small cell overlaying the existing macrocells and when the small cells are equipped with FD capability, which are self-interference (interference that arises as a result of the signal leakage and imperfect isolation between transmit and receive antennas), user-to-user interference (the uplink signal of one user causing serious interference to the downlink signal of another nearby user), cross-tier interference (interference between macrocells and small cells) and co-tier interference (interference between small cells). These possible scenarios of interference are illustrated in Fig. 4 as follows: When the small cell 1 (SC 1) is communicating with small cell UE 1 (SUE 1), SC 1 can cause co-tier interference to the SUE 3. Also, when the macrocell in the network is communicating with its associated MUE, the macrocell can cause cross-tier interference to the SUE 3. Likewise, when SC 1 is communicating with the SUE 1, the SUE 1 can cause user-to-user interference to the SUE 2. Moreover, when SC 2 is communicating with the SUE 4, there can be self-interference at the SC 2. Hence, advanced interference management schemes in FD equipped small cells in UDNs are crucial to tackle the problem of interference.

In [113], a duplex mode selection algorithm is proposed for FD SCNs based on channel allocation and stable roommate matching theory. The various challenges of FD communication such as self-interference are presented in [114]. The authors in [115] studied downlink spectrum allocation for in-band and out-band wireless backhauling of FD small cells. The work in [116] considered joint backhaul-access analysis of FD self backauling HetNets. Also, an application of FD communication to UDNs is presented in [117].

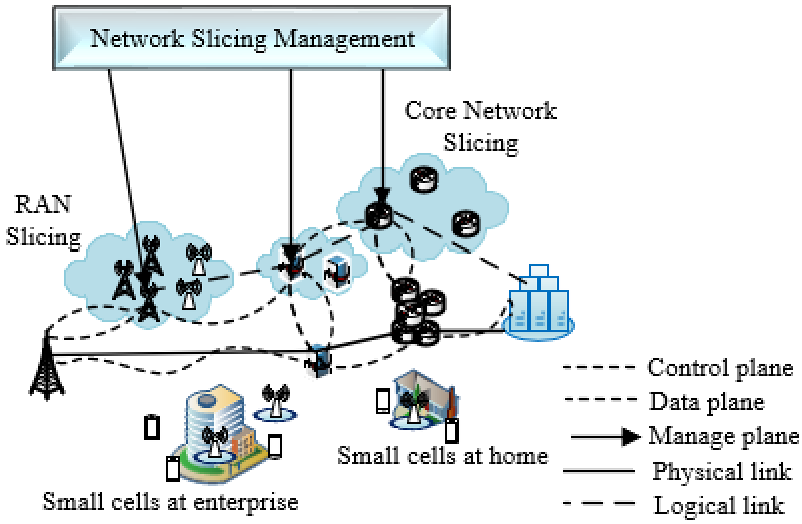

FIGURE 5. Implementation of network slicing in 5G UDN [118].

The combination of UDN and FD technologies leads to minimisation of the load of MBS and mitigation of interference.

5) NETWORK SLICING

Network slicing means slicing a common underlying physical network into multiple E2E logical networks. These logical networks are mutually isolated, managed independently and created on demand [118]. Network slicing is a fundamental technology to facilitate future 5G networks for a cost-effective deployment and operation of multiple logical networks over a common physical network infrastructure. In this way, each network is customised to efficiently serve the needs of certain applications such as IoT applications and mobile broadband and/or special purpose service providers for different sectors (e.g., automobiles, utilities, public safety, and smart city) [119]. An example of implementation of network slicing in UDN is shown in Fig. 5, where the core network and RAN solutions bring the benefits of core network only and RAN only solutions. In the implementation, a UE does not need to select the slice of a core network once it has secured an access to the RAN. The network slicing management provides E2E slices for diverse service demands.

The deployment of ultra dense small cells has been adopted for effective radio resource slicing. The aim of this conceptual change in network architecture is to meet the rapid growth in mobile data traffic as well as connected devices. In CR communications, the small cell solution is driven by the theoretical approach of intensive network slicing provided with new spectrum coexistence techniques for efficient spectrum utilisation [118]–[120]. The proposed approach in [121] can be applied to design algorithms for a variety of application scenarios, including the optimisation of the network operation of a mobile virtual network operator (MVNO) in terms of OPEX minimisation or network slicing, and the optimisation of spectrum sharing among multiple operators of collocated UDNs. There are open challenges and issues that have been identified in network slicing such as network reconstruction and cooperation with other 5G enabling technologies [122].

6) ENERGY HARVESTING TECHNOLOGY

Energy harvesting enables wireless nodes to store energy physically or chemically from natural or man-made phenomena. Different types of energy sources are solar/light, motion/vibration, thermoelectric energy sources and electromagnetic radiation [108]. Energy harvesting is an effective solution for prolonging the battery life of wireless devices and for improving the overall EE of the networks [69], [123]. It has been revealed in [69] and [124] that the stochastic nature of environmental sources (e.g wind, thermal, solar) makes the harvested energy levels of a UE to vary over time or location. Hence, harvesting energy from these sources will not provide reliable and QoS-constrained wireless applications. Instead, the suggested strategy is to harvest energy from ambient radio signals (e.g., radio broadcast or TV). Usually, energy harvesting devices utilise the strategy of either harvest-and-use (HU) or harvest-store-use (HSU).

Recent advances in energy harvesting technology have made the dream of self-sustaining BSs and devices possible [44]. Moreover, another suggested solution is simultaneous wireless information and power transfer (SWIPT), which is envisioned as a promising technology for improving EE in 5G wireless networks [44], [108], [124]. The combination of UDNs and energy harvesting can solve the problem of user association and improve the EE of the overall networks. The problem of distributed user association for energy harvesting ultra-dense small cell networks (SCNs) has been investigated in [29]. Moreover, an approach based on the mean-field multi-armed bandit games is proposed in the work to solve the uplink user association problem for energy harvesting devices in UDNs in the presence of uncertainty.

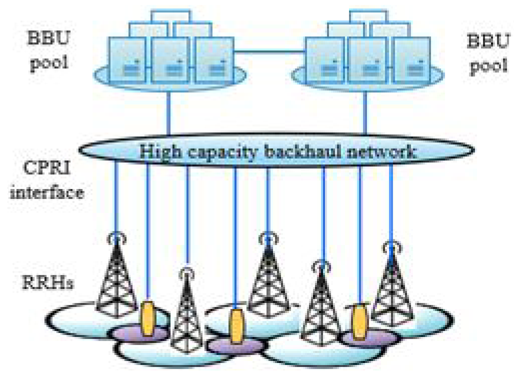

FIGURE 6. The cellular architecture of C-RAN [129].

7) C-RAN

C-RAN is a prevalent centralised RAN architecture to improve coverage performance, EE and mobility while simultaneously minimising the cost of network deployment and operation [125]. C-RAN is based on fundamentals of centralisation and virtualisation. C-RAN moves the baseband units (BBUs), located at the remote central office to the cloud for centralised processing, which significantly reduces CAPEX and OPEX. In the cellular architecture of C-RAN as shown in Fig. 6, the backhaul between RRHs and BBUs forms a key component to enable a large-size centralised deployment and cooperative communication. In a typical macrocell site, a BBU is directly connected to the backhaul. The IP packet data coming from the core network is being processed and modulated by the BBU into digital baseband signals, where they are transmitted into RRHs. The digital baseband signal travels from the BBU to a RRH through a common public radio interface (CPRI) and a digital radio-over-fibre (D-RoF) connection, which is referred to as fronthaul. The BBU processes and packetizes the digital baseband signal from the RRH and sends it through a backhaul connection to the core network. Solutions that enable connection of BBUs should be reliable, support low latency, very high bandwidth, and low cost with a flexible topology interconnecting different RRHs. Thus, C-RAN can provide a better reliability as compared to optical networks [125]–[129]. To avoid the transport network and the BBU pool from overloading, cells should be clustered to be assigned to a BBU pool. Also, to achieve optimal energy savings of the C-RAN, BSs should be selected in such a way that will optimise the number of active RRHs within the BBU Pool. In addition, to achieve optimal throughput on the cell edges, cooperative intelligent schemes are needed to deal with ICI, thus improving SE [125].

In 5G C-RAN architecture, the three components are RRHs, BBU with a powerful cloud computing in a data centre and fronthaul links that connect the RRHs to the central processing unit [130]. The combination of UDNs and C-RAN has a great potential in mitigating interference in the entire networks. However, as the number of RRHs is excessive in C-RAN, the channel state information (CSI) is difficult to obtain. Hence, a robust transmission design based on the imperfect CSI is necessary. In [131], a robust beamforming algorithm for ultra-dense user-centric FDD C-RAN in the face of realistic pilot contamination and limited feedback has been designed to minimise the total transmit power subject to the constraints of users' rate requirements and fronthaul capacity. Additionally, in [132], a robust beamforming with pilot reuse scheduling algorithm has been proposed to maximise the sum SE of the network, reduce CSI feedback overhead and pilot consumption. Also, a centralised user centric merge-and-split (MAS) rules based on coalition formation game, which can be well supported in the framework of the C-RAN, is proposed in [128] for UDNs to ensure a more effective and accurate interference mitigation.

One of the main challenges of 5G operational models for URLLC is latency, which will support multimedia services, vehicle-to-vehicle communications, tactile Internet and IoT applications. These services and applications have stringent E2E delay requirements [130]. Most of the existing work in C-RAN technology focused on physical layer issues. Hence, research attention should be directed to the upper layers beyond physical layer by considering these delay requirements such as propagation delay, queueing delay and processing delay when designing next-generation transmission schemes. In [130], a low-latency based algorithm for C-RAN is proposed for data link layer considering queueing delay in the BBU pool. In addition, C-RAN uses wireless links for the BBU-RRH connection, but point-to-point wireless links have been considered for UDNs [133].

8) D2D COMMUNICATION

This technology allows direct transmission between devices instead of transversing a BS to improve SE and EE of a network. This means that nearby devices can establish local links so that traffic can flow directly between them without passing through a BS. Thus, D2D communication in combination with UDNs can potentially improve user's QoE by reducing power consumption and latency, while increasing the peak data rates, and creating new proximity-based services (e.g., multiplayer gaming), which leads to dense spectrum reuse [134]. D2D communication can operate in licensed (inband) or unlicensed (outband) spectrum. The former is preferred due to high control over the spectrum. Existing research on D2D communications has shown great potential for 5G networks, which leads to a trend toward the UDNs. However, several important issues, such as interference, the trade-off between deployment cost and EE, are still open [135]. A distributed power control approach for ultra-dense D2D communications underlying cellular communications based on a mean field game is presented in [136].

9) NOMA TECHNOLOGY

NOMA is a fundamental 5G enabling technology to address the heterogeneous demands on high reliability, low latency, high throughput, enhanced fairness, and massive connectivity. The key concept of NOMA technology is to serve several users in the same resource block, such as subcarrier, a time slot, an orthogonal spatial degree of freedom, or spreading code [137]. The authors in [138] review the aspect of resource management in NOMA systems for 5G and beyond. NOMA can be combined with the existing and future wireless systems due to its compatibility with other communication technologies. For instance, NOMA is compatible with traditional orthogonal multiple access (OMA), (e.g., OFDMA, CDMA and TDMA) and it permits two users to be served simultaneously on the same OFDMA subcarrier [137], [139]. Also, NOMA is an important principle in the design of RATs for 5G wireless networks and beyond. Other 5G multiple access techniques are lattice partition multiple access (LPMA), power-domain NOMA, sparse code multiple access (SCMA), low density spreading (LDS), interleave division multiple access (IDMA), and pattern division multiple access (PDMA) [140]–[143].

The main challenge in the combination of NOMA and UDNs is the introduced interference in time/frequency domain, which can be mitigated by exploiting the degree of freedom of other domains. This interference has different characteristics within different propagation regions in UDN. Therefore, the design of NOMA in UDN should fully take into account the complicated interference features. In addition, the implementation complexity of NOMA, such as resource allocation and decoding complexity, is exponentially increasing with the number of users. Therefore, a direct approach to cope with the issue of interference is to use effective interference management techniques. However, existing interference management techniques are basically designed for sparse wireless networks and may not be applicable in UDN. Thus, the authors in [30], have to re-examine the performance of the available interference management techniques and rethink how to effectively implement these techniques in UDNs. The aspect of energy efficient user scheduling and power allocation in UDNs is considered in [144] for both perfect CSI and imperfect CSI to improve the EE of the overall system.

10) NFV

NFV is a network architecture concept, which enables virtualised network functions to run over an open hardware platform. It also allows separation of hardware from software and has become a reality for the mobile industry due to the improved performance of ‘‘common, off-the-shelf’’ (COTS) IT platform [13]. NFV offers flexible provisioning of software-based network functionalities on an optimally shared physical infrastructure. NFV benefits data centres owned by mobile service providers, including mobile core network, access networking and mobile cloud networks. The benefits of NFV in combination with UDNs include OPEX and CAPEX reduction, space reduction for network hardware, easier network upgrades and network power consumption reduction, intelligent use of network data to ensure efficient use of network resources for better QoE provisioning. Wireless network virtualisation accommodates the significant growth in wireless traffic, in which physical resources are abstracted and shared among different parties. With virtualisation, the network infrastructure is separated from the services, thereby providing convenience for the operation in UDNs [145]. In such a virtual network, the RRA schemes need to decide how to distribute the content in the virtual networks, and how to map the virtual networks with the physical ones. The joint content distribution and physical resource mapping problem can be solved efficiently by means of hypergraph matching [146].

11) SDN

In SDN, software can perform dynamic reconfiguration of the network topology of an operator in order to adjust to demand and load, for example, additional network capacity can be directed to where it is needed to maintain the QoE of each customer at peak data consumption times [13]. SDN enables the evolution of Internet with the openflow, network virtualisation and service slicing strategies. UDNs can obtain benefits from the SDN evolution to fulfil the 5G capacity booming. Many studies proposed new network architectures for efficient network resource management in future wireless communication systems [85], [147]. An SDN-based mobility and available resource estimation strategy is proposed in [148] to solve the handover delay arising from the problem of frequent, unnecessary, and back-and-forth handovers, with additional problems related to increased delay and total failure of the handoff process. In [149], a two-layer architecture has been presented, which consists of a network cloud and a radio network integrating small cells, massive MIMO, NFV and SDN, user/control plane split. The proposal addresses data rate and capacity challenges. SDN technology in combination with UDNs is introduced to facilitate optimal use of network resources and flexible network deployment for QoE provisioning.

12) CRN

The CRN is an innovative technology to improve the utilisation of the limited and congested radio spectrum. The motivation for the adoption of CRN arises from the fact that, most of the time, a large portion of the radio spectrum is underutilised. In CRNs, a secondary system can share spectrum bands with the licensed primary system, either on an interference-free tolerant or on an interference-basis. The combination of UDN and CRN has the capability to sense the surrounding radio environment and regulate its transmission based on the sensing outcomes, thereby, improve the SE of the overall network. Also, the application of CRN can greatly reduce the computational complexity and guarantee the requirements of users' QoS when designing the power allocation schemes [8], [137]. In [150], an overview of reconfigurable radio and small cell technologies is presented with an introduction of tentative network architecture for 5G. In addition, two planning methods (i.e., graph-based and genetic-based) are proposed, which accommodate CRN technology to increase user throughput by mitigating communication interference. Since CRN provides frequency allocation with cognition cycle for better SE, the deployment of ultra-dense small cells is addressed with special consideration for the coordination of unlicensed spectrum at the same time. Also, the hypergraph game is applied to solve the spectrum sharing problem in CRNs by formulating the relationship between the primary and secondary users as hyperedges.

13) BIG DATA AND MOBILE CLOUD COMPUTING

The conventional data storage on local devices will no longer be able to handle the exponential increasing data cache in 5G. Hence, the cloud storage has become popular because of the convenient and on-demand services. Users can now upload their data to cloud servers through Internet and save the local storage on their devices. In 5G, the mobile cloud computing will become the main method for big data computing on a higher level [70]. The mobile edge computing (MEC) is another important technique developed for 5G cloud computing, which provides the benefits of high bandwidth at the edge of RAN and low latency. Thus, the ultra-dense cloud small cell network (UDCSCN), which combines massive deployment of small cells and cloud computing, is a promising technology for 5G LTE-Unlicensed (LTE-U) mobile communications because it can accommodate the anticipated explosive growth of mobile users' data traffic and has been extensively studied in [151]. The authors present an overview of the requirements and the challenges of the fronthaul technology in 5G LTE-U UDCSCNs.

14) FOG COMPUTING

Fog computing is a technology that extends computation, storage facilities and communication towards the edge of a network. Fog computing has capability to support delay-sensitive service requests from end users with reduced low traffic congestion and energy consumption [152]. The fog radio access network (F-RAN) has been proposed as an advanced socially aware mobile networking architecture to provide high SE while maintaining high EE and low latency [153]. F-RAN enhances a C-RAN by enabling the RRHs, called enhanced RRHs (eRRHs), with caching and signal processing capabilities. The introduction of local cache to the eRRHs in F-RANs can significantly reduce the traffic overhead and latency [152]. The authors in [154] has combined UDNs with capillary edge cloud, the fog, for optimisation of users' QoE and network performance by addressing the issue of load balancing in fog computing. Also the European project, "TROPIC" proposed a new architecture, in which small cells are characterised by computation and storage capacities. This is an example of fog computing architecture.

15) MULTI-RAT

The coordination between different RATs to provide an adequate level of QoS to end users is referred to as Multi-RAT. Existing mobile systems apply different RATs, such as Universal Mobile Telecommunications System (UMTS), WLAN, WiMAX, and LTE [150]. For example, the cellular networks of one network operator may be operated jointly in combination with the usage of WLAN, to ensure the optimisation of the resource utilisation and to provide the mobile users with the best QoE, reliability and redundancy. The network resources of these multi-RATs can be selected and controlled partially by the end users themselves and by the RANs using techniques such as SDN and NFV [160]. The major challenging issues in multi-RAT technology are RAT selection algorithms, offloading mechanisms, mobility, splitting of data across multiple flows [161], [162]. Likewise, the simultaneous connection of different RATs to UDNs stems as an alternative viable offloading solution [20]. In addition, RAT can generate unnecessary signalling overhead. To overcome this issue in multi-RAT technology, efficient RAT handover decisions and optimised partitioning of common resources have been proposed in [74].

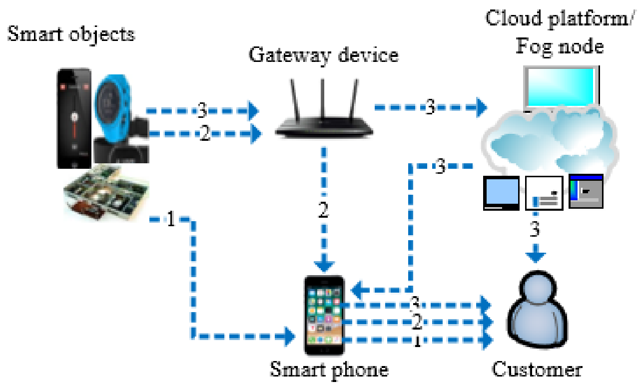

FIGURE 7. Three common communication patterns in IoT applications [155].

16) IoT

IoT is a network of devices with Internet connectivity, which enables direct communication between devices without human-intervention in order to offer smart services to end users. IoT allows connectivity of things (e.g., equipment, devices, computers, and machines). These connected things are embedded with components such as electronics, sensors, and software applications through wired and/or wireless networks for provision of value-added services. Also, the embedded components enable devices to connect and exchange data, which monitors, analyses and controls the smart products. IoT is an important driver for digital and economy transformation, data-driven optimisation, automation, development of new applications, and customer-based innovation. In addition, IoT network management is deployed to ensure that network equipment, devices, and IoT services are properly managed. The main benefit of having efficient network management solutions is to guarantee general management of connected things in the IoT networks. Fig. 7 illustrates the three common communication patterns employed in the IoT networks. In the first pattern, data collected by the IoT solutions (smart objects) may be sent to a customer through a smart phone. In the second pattern, data collected by the IoT solutions may be sent to a customer via a gateway device to a smart phone. In the third pattern, data collected by the IoT solutions may be sent to a customer through a gateway device to a cloud platform/fog node or to a smart phone for further processing, pattern recognition or historical archiving [155].

There are still many challenges to be addressed in order to enjoy the full benefits of IoT technology, such as, the standardisation of the technology for optimal interoperability, identification and addressing of the connected devices, the security of the sensors or actuators, the privacy of information, the provisioning of storage resources and wireless backhaul solutions for high density of connected devices, and the energy efficient deployment of communication nodes and edge-devices [20], [156]–[158]. Also, the following challenges of IoT have been identified, context sharing, security–privacy–trust, automated sensor configuration, acquisition, context discovery, modelling and reasoning, and selection of sensors in ''sensing–as–a–service'' model [156]. Therefore, intelligent management techniques should be designed to address these challenges. The combination of IoT and UDN has the benefit of providing the network with better security and privacy. In [159], the analysis on physical-layer security for IoT in ultra dense HetNets has been presented, which can be modified for better application in UDNs.

17) PROACTIVE CACHING

This technology involves predictive storing of popular content in UEs or BSs to serve the demand of users in peak traffic loads [163]. The content is usually stored in off-peak periods to reduce the load on the wireless and backhaul resources [164]. The design of proactive caching algorithms to be implemented in UDNs requires the understanding of the social and spatial structure of such networks [163]. The benefits of successful prediction of the popular content in the UEs or BSs, are efficient use of storage resources at the network-edge, and achieving the potential gains of caching. However, the basic limitations of the predictive caching need further investigation to assess the role of various parameters involved and to promote effective design techniques. Also, the secured transmission of such content is a crucial part, which must be put into consideration in the design of caching schemes at UEs [20].

18) SON

The features of SON minimise the level of manual work in order to reduce the OPEX. In SONs, there are multiple use cases for network optimisation such as load balancing, coverage and capacity optimisation [44], [165]. These features of SON can be combined with UDNs to achieve higher performance in 5G wireless networks. However, the major limitation of ultra dense small cell deployment results primarily from the fact that, small cells can be installed by subscribers without any network planning and site-specific system configuration settings. Therefore, small cells are required to be plug-and-play with self-configuration features. The self-organising features of UDNs can be categorised into three as follows:

- Self-configuration: A scenario where newly deployed cells are automatically configured by downloaded software before entering into the operational state.
- Self-optimisation: A situation where cells constantly monitor the network status and optimise their settings to reduce interference and enhance coverage.
- Self-healing: A scenario where cells can automatically perform failure recovery or execute compensation strategies whenever failures happen.

19) GREEN COMMUNICATION

There will be a significant increase in carbon footprint by 2020 due to large amount of traffic that will pass through the Internet. Therefore, it is necessary for the cellular networks to revolutionise, and head towards green communication. The term ''GREEN'' in wireless networks stands for globally resource optimised energy efficient network [166]. Energy-efficient wireless communication (green communication) is imperative. In order to fulfil user traffic demand and improve network EE in UDNs, the work in [167] focuses on the adaptive cell zooming scheme to achieve the optimised user association through adjusting cell coverage. Then, the cell sleeping scheme is further applied to turn off light traffic load cells for BS power saving.

E. IMPORTANCE OF THE MIXTURE OF UDNs WITH OTHER 5G ENABLING TECHNOLOGIES

The main purpose of these above mentioned technologies is to facilitate a dramatic capacity increase in the 5G wireless network with efficient utilisation of all possible resources [8]. Also, UDNs in combination with other enabling technologies can potentially help to achieve the performance requirements in 5G and beyond and improve the performance of the cellular networks. These performance requirements include higher data rate, reduced E2E latency, higher battery life, better security, higher SE and EE. In addition, the combination of UDNs and other technologies will enable 5G to tackle the expected increase in mobile data volume while expanding the range of application domains that mobile communications can support beyond 2020 [66]. A summary of the performance requirements and the respective technologies in 5G is presented in table 5 in terms of desired values and applications.

III. GENERAL OVERVIEW OF COMBINING UDNs WITH OTHER 5G ENABLING TECHNOLOGIES

A. CHALLENGES OF UDNs IN COMBINATION WITH OTHER 5G ENABLING TECHNOLOGIES

The application of UDNs in combination with other 5G enabling technology has great potential to provide the required coverage and increase the data rates of the end users. However, there are numerous challenges that arise when UDN is combined with other 5G enabling technologies in two or more. These challenges are: mobility issue, backward compatibility, RRM, transmit power management, interference management and backhaul management.

TABLE 5. Performance requirements and the respective technologies.

Requirements	Desired value/ Description	Applications	5G Technologies	Ref.
Higher data rate	1-10 Gbps (uplink), 1-20 Gbps (downlink)	Virtual reality	UDNs, mmWave, massive MIMO, C-RAN	[2], [13], [66], [70], [67]
Reduced E2E latency	1 ms latency	IoT, M2M	UDNs, D2D, FD communication, C-RAN, Big data and mobile data computing	[2], [13], [63], [66], [70], [67]
Higher battery life	One decade	Health care devices and wearables	UDNs, Energy harvesting, massive MIMO	[2], [13], [63], [66], [70]
Higher SE	> 4G values	Financial technology, Augmented reality	UDNs, Full duplexing, New waveforms (e.g. FBMC, NOMA), massive MIMO	[2], [13], [63], [66], [70]
Massive number of connected devices	300, 00 devices per AP, accommodating 100 billion devices	IoT, M2M	UDNs, D2D, massive MIMO, Mobile cloud computing	[2], [13], [63], [66], [70]
Mobility	Faster user speeds	IoV, Smart grids, smart cities, smart homes	UDNs, massive MIMO, mmWave	[2], [13], [63], [66], [70]
Reduced energy consumption	1000x decrease in energy consumption per bits	Smart grids, smart cities, smart homes	UDNs, massive MIMO, mmWave	[2], [13], [63], [66], [70]
QoE	99.9% availability and reliability, and 100% coverage	Video conferencing, online transaction, online gaming	UDNs, massive MIMO, mmWave, SON	[2], [13], [63], [66], [70]
Better security	Higher than the existing security	online transaction	UDNs, SDN, Big data and mobile data computing	[70]

1) MOBILITY ISSUE

An important challenge is to offer seamless mobility within the UDNs in combination with other technologies to prevent any service interruption or degradation in user's QoE. As the number of small cells increases, handovers become more likely. It is important to avoid excessive handovers to reduce signalling load to the core network and also optimise handover performance. A small cell also has to maintain its neighbour list to ensure proper handovers of UEs to other cells. Any incorrect or incomplete neighbour information can cause UEs to have call drops as they move away from their serving small cells. Effective mobility management is essential for the viability of a network with hyper-dense small cell deployments essentially when combined with other 5G enabling technologies such as SDN/NFV. Such dense small cell deployment creates more cell boundaries and potentially more handover events.

The mobility management problem basically boils down to avoiding excessive handovers while ensuring robustness of necessary handovers for all mobiles, including the legacy ones. Handovers are vital in the case when users move in or out of the cell coverage, so as to provide a seamless uniform service. Also, handovers are essential to ensure traffic load balancing, by moving users at the edge of overlapping/ adjacent cells from the more congested cells in the same wireless network (vertical handover) or different wireless networks (horizontal handover) to the less congested ones. However, this approach comes at the expense of system overhead, which will be significant when UDNs are combined with other 5G enabling technologies due to the ultra-dense deployment of small cells and the different types of backhaul links available for each cell. Additionally, the probability of handover failure increases the probability of user outage [16]. Therefore, effective schemes for handover management and admission control for users need to be developed to realise the desired network objectives of UDNs in combination with other 5G enabling technologies and to minimise the ping-pong effect, which occur in wireless networks when two or more handovers occur between the incumbent user and the target point of attachment [168], [169].

2) BACKWARD COMPATIBILITY

It may not be feasible to significantly modify the existing wireless infrastructure to accommodate newly deployed small cells integrated with other 5G enabling technologies. Therefore, the operation of existing macrocells and UEs should not be affected by these newly-introduced small cells. Thus, the design of co-existence techniques is necessary for small cells to provide backward compatibility with the conventional systems. It has been suggested in [168] that CR technology for dynamic spectrum access can be deployed in small cells to address the challenge of backward compatibility. Consequently, self organisation capabilities for small cells may be achieved via spectrum monitoring and cooperation among the neighbouring small cells. Therefore, the operation of small cells is transparent to the macrocells, and backward compatibility with the macrocells is maintained. For the cognitive small cells to be robust and adaptive to topological changes, the design parameters should be independent of the topology and account for topological randomness [26], [168].

3) RRM

RRM techniques such as interference coordination, fairness enforcement and load balancing are important to optimise capacity and user experience. Due to the increasing capacity demand and limited wireless spectrum, both small cells and macrocells will share the same frequency band, which is universally used across the entire network. The universal frequency reuse enhances efficient utilisation of spectrum at the expense of increased mutual interference. For practical deployment of ultra-dense small cells, the challenge of RRA optimality among the different network tiers (i.e., among macrocells and small cells) depends on the network topology, which may vary across the service area must be tackled. For OFDMA-based small cells, subchannel and power allocation for macrocell users and small cell users need to be performed to achieve the QoS requirements of all users while maximising the utilisation of radio spectrum. For NOMA-based small cells, power control and interference management for users in the different network tiers will be the most critical issue. Therefore, efficient and cost-effective RRM schemes must be designed to properly manage radio resources.

4) TRANSMIT POWER MANAGEMENT

In addition, transmit power management of small cells equipped with other 5G enabling technologies is needed to optimise capacity offload while minimising pilot pollution under dense small cell deployments. Reducing the transmitting power of some of the small cells reduces pilot pollution but on the other hand can impact the capacity offload to small cells. Hence, intelligent transmit power management algorithms are needed to optimise the capacity offload while minimising pilot pollution. Furthermore, joint transmit power management, scheduling and resource coordination among multiple small cells can further optimise the system capacity. Also, transmit power management should also take into account backhaul limitations. For example, a small cell with lower backhaul capacity should in general transmit at a lower power to avoid attracting many users and hence, causing congestion due to limited backhaul [53].

5) INTERFERENCE MANAGEMENT

Interference management is very important in the seamless combination of UDNs with other 5G technologies. In UDNs, the co-channel deployment of several layers of network introduces severe interference. Generally, there are two types of interference associated with the co-channel deployment of UDNs comprising macrocells and small cells, which are cross-tier and co-tier interference. Cross-tier interference occurs between small cells and macrocells and their respective UEs when they share the same set of frequency bands. Co-tier interference occurs among small cells and their respective UEs when neighbouring small cells reuse the same set of frequency bands [83], [90]. The uplink co-tier interference is caused by surrounding, co-located SUEs creating interference to nearby SBSs while the downlink co-tier interference is caused by the SBS transmission interfering with neighbouring SUEs [170]. The uplink cross-tier interference occurs when an SUE acts as the source of interference to an MBS while the downlink cross-tier interference is caused by a SBS transmitting close to an MUE. Employing effective measures to avoid interference issues are the major keys to the successful deployment of ultra-dense small cells [171]. Coordinated multipoint operation is considered as a promising technique for addressing the challenge of interference, especially for users at the edge of the cell coverage area.

6) BACKHAUL MANAGEMENT

Existing backhaul leveraged by small cell may be shared by other devices and may not be properly dimensioned for small cell traffic, it is thus necessary to design the SON features to account for backhaul-limited scenarios and preserve the small cell user's experience. Small cells may leverage on existing backhaul, the quality of which varies widely. For example, backhaul in residential buildings based on home broadband service may be consumer-grade and shared by multiple users. Provisioning of customer's backhaul open to all users presents interesting opportunities and challenges for the operators. It is possible for the total traffic from the users on a small cell and other traffic from the owner to exceed the available capacity of the backhaul. When a small cell runs into backhaul limitations, it will offload user(s) to other cells in the vicinity if possible. The small cell owner needs to be prioritised by handing over other users to the macrocell network or limiting the backhaul usage of other users via RRM and scheduling. Small cell coverage can also be adjusted based on long-term backhaul usage statistics. In addition to these, the total backhaul usage by a small cell may need to be monitored and controlled in order to prevent impact on other home devices sharing the same backhaul. The small cell may need to estimate the backhaul availability and limit its backhaul traffic in order to prevent any impact.

B. MATHEMATICAL TOOLS FOR SOLVING PROBLEMS DUE TO THE COMBINATION OF UDNs AND OTHER 5G ENABLING TECHNOLOGIES

Generally, searching for mathematical tools that are suitable for handling a variety of problems that emerge because of an ultra-dense deployment of small cells as well as a massive number of end-user devices becomes imperative [29]. The fundamental features that must be considered when selecting a mathematical tool are: low complexity and fast convergence, easy implementation, attaining optimal solution and suitability for large-size network. These features show the effectiveness of a particular tool. The mathematical tools for solving problems when UDN technology is combined with other 5G enabling technologies as identified in the literature are discussed as follows:

- **Low-complexity Methods:** These methods are used to solve problems such as resource allocation problems for UDNs, D2D communications, and heterogeneous cloud-based RANs. Examples of low-complexity algorithms include: game theory, utility theory, greedy algorithm, water-filling, iterative-based method, contract theory, complex theory, graph theory, stochastic geometry/process, artificial intelligence (AI) and reinforcement learning (RL).

- **Game theory** is a sub-field of applied mathematics that describes and analyses interactive decision situations among different players [172]. It can be used to solve the problems of RRM, mobility, and interference. It achieves optimal solution, low computational complexity and suitable for large-sized networks. However, more variables are involved and solution models can be sometimes complex. Game theory has been applied to model, analyse, and design various problems in wireless networks for decades. Basically, it is used to analyse the potential conflict of interest that may arise when more independent players interact with each other. Two main kinds of strategic games have found wide applications in wireless networks: the non-cooperative game and the cooperative game [173], [174]. The main difference between them is that a non-cooperative game is concerned with the analysis of strategic choices. It explicitly models the decision making process of rational but selfish players to maximise their individual payoffs in a self-interested manner without considering the strategic impact on the other players. In a cooperative game, multiple players first make cooperation formations, and then target socially efficient and fair bargaining utilities for each of the participating players. Cooperative games emphasize collective rationality and social optimality, which means that no one node can improve its own performance at the cost of degrading the other nodes' performance. With the emergence of a cooperative paradigm in wireless networks, cooperative game theory has received considerable interest in recent years [12], [175], [176]. Moreover, many different game based schemes have been proposed in the literature such as Stackelberg game [52], coalition game [175], and Nash bargaining game.
- **Stochastic geometry/process:** Stochastic geometry is the investigation of arbitrary spatial patterns that can likewise be used to capture the effect of explicit system properties, for example, cognition. It can be used to solve the problems of RRA, interference, fairness in resource sharing, load imbalance, SE and EE. Its features includes: low computational complexity, easy implementation, optimal solution attainment and suitability for large-size network. Stochastic geometry is the mathematical tool used in [177] to analyse the heterogeneous structure of emerging wireless networks in FD communication. In [178] and [179], the tool of stochastic geometry has been applied to ensure EE of BSs and cross-tier interference mitigation respectively. The tractable resource management with uplink decoupled mmWave overlaying UDNs has been analysed by using the stochastic geometry in [180].
- **Graph Theory**: Graph theory is the study of graphs, which are used to model pairwise relationship between objects. It can be used to solve the problem of RRM, interference and user association. A graph is a mathematical structure that is made up of nodes, vertices, or points, which are connected by arcs, edges, or lines. Graphs can be used to represent networks of communication, data organisation, computational devices, the flow of computation etc. Graph colouring is a special case of graph labelling in graph theory; it is an assignment of label colours to elements of a graph subject to specific constraints. Graph colouring is a way of colouring the vertices of a graph such that two adjacent vertices cannot share the same colour; this is called a vertex colouring. Likewise, an edge colouring assigns a colour to each edge so that two adjacent edges cannot share the same colour, and a face colouring of a planar graph assigns a colour to each face or region so that two faces that share a boundary cannot have the same colour. Examples of graph-theory based schemes can be found in [181], [182]. Also, there are various forms of graph theory such as hypergraph theory, which is a generalisation of a graph, in which any subset of a given set can be an edge. In [145], the hypergraph theory has been used to effectively tackle RRA problems in an UDN to minimise ICI and optimise network performance.
- **Matching Theory:** Matching theory is a mathematical tool for studying the formation of dynamic and mutually beneficial relationship among different types of rational and selfish agents. It has been widely used to develop low complexity, high performance, and decentralised protocols in [183]. Matching theory is a promising strategy for wireless resource allocation, which can overcome some shortcomings of game theory and optimisation. It provides mathematically tractable solutions for the combinatorial problem of matching players in two distinct sets, depending on the individual information and preference of each player [184].

- **Optimisation tools**: Optimisation tools are used to solve the problems of resource allocation, user association, network instability etc. and these tools ensure that a network performs optimally while guaranteeing the QoS of end users. Other benefits include network reliability and stability. Examples of such tools are simplex method, BnB, Langragian method, convex programming, probabilistic optimisation, Lyapunov optimisation, sequential quadratic programming, Hungarian method, multi-armed bandits and Heuristics but the high computational complexity of these tools is the great challenge that must be overcome. Hence, low-complexity algorithms must be designed when using these tools. The vast majority of the RRM techniques can be formulated as

RRA optimisation problems, with an objective function that must be minimised or maximised and optimisation constraints that correspond to physical limitations in the network. In addition, some of these optimisation problems can be multi-objective optimisation. Multi-objective optimisation is the optimisation problem that involves more than one objective function to be optimised simultaneously and it is concerned with the minimisation/maximisation of a vector of objectives subject to a number of equality and/or inequality constraints. The procedure for the formulation of various optimisation problems can be summarised into four essential steps as follows [185]:

- **A clear statement of each user's requirements in the network:** It is very essential to take the requirements of all users into consideration in the formulation of a problem. This will guide the decisions to be made and the choice of performance metrics by which such decisions are evaluated.
- **Identification of the decision variables:** The decision variables that measure the amounts of radio resource to be given to each user must be identified, which can be set as threshold values.
- **Definition of the objective function:** The objective function of the optimisation problem is defined, once the requirements and the decision variables have been identified. An example of an objective function includes capacity maximisation and power minimisation.
- **Inclusion and definition of a set of constraints:** The constraints need to be specified in order for the optimisation model to find the optimal operating rules, which reflect the restrictions in the network.

Furthermore, different optimisation tools can be employed in solving optimisation problems. Some of these optimisation tools are more suitable than the others. The choice of any optimisation tools depends on some factors, for example, the formulation of the optimisation problem itself, the nature of the variables involved, the possibility of linearisation of the objective function and the possibility of relaxation of the optimisation constraints. Moreover, when it is very difficult to find the optimal solution of an optimisation problem, some sub-optimal methods can be adopted. Some of the most common methods found in the literature are listed below:

- **Relaxation of constraints:** The concept of this method is to relax some of the constraints so as to make the problem easy to provide a solution. However, it must be noted that after solving the relaxed problem, the relaxed solution has to be re-evaluated [186]. The authors in [187] exploit the approach of relaxation of constraints to make the formulated optimisation problem tractable.
- **Problem splitting:** This method employs the idea of "divide to conquer", i.e. splitting the complex problem into two or simpler sub-problems so that a sub-optimal solution close enough or an approximation to the optimal solution can be found. This method is applied in [188] to split the formulated optimisation problem into two so that it can be easy to solve.
- **Problem Reformulation:** This approach is used to obtain solutions to non-deterministic polynomial-time (NP)-hard optimisation problems in UDN. By a careful consideration of the structure of a problem, certain distinct properties of the problem can be used to arrive at a reformulation of the original problem. An application of this approach is found in [189].
- **Probabilistic optimisation:** An example of probability optimisation is stochastic programming, which has been used in [190], [191], to solve an optimisation problem and simulated annealing used in [192] to solve cell-clustering resource allocation problem. Also, this class of optimisation tool comprises genetic algorithm (GA). GA is a well-known stochastic search method based on the Charles Darwin's theory of natural selection. GA is an effective tool for solving combinatorial optimisation problems. GA is effective because of its capability to utilise favourable features of previous solutions and successively generate better solutions. Moreover, another advantage of GA is that it is not compulsory to know if the objective function is differentiable or continuous, and it is very easy to implement. An example of the application of GA can be found in [193].

Table 6 presents a summary of the benefits and limitations of different mathematical tools for solving problems in UDNs.

C. PERFORMANCE METRICS OF NETWORKS WITH UDNs IN COMBINATION WITH OTHER 5G ENABLING TECHNOLOGIES

The evaluation of different networks has been commonly characterised by considering only one or two performance metrics while neglecting other metrics due to high complexity. In 5G wireless networks, more performance metrics should be considered for a complete and fair assessment of the networks. These include SE, network throughput, EE, fairness of users, QoS, and network complexity. Thus, a general framework should be designed to evaluate the performance of various combination of UDNs and other 5G enabling technologies, taking into account as many performance metrics as possible from different perspectives. Also, the trade-off among all performance metrics should be considered in the design of various intelligent management algorithms.

1) SE

The spectrum obtainable by any mobile operator is limited compared to the growing capacity, which will occur in 5G wireless networks. Spectrum bands are conventionally allocated to BSs and UEs by a centralised radio network controller. In a SCN in combination with other 5G enabling technologies, this approach will not be applicable because of the expected ultra dense deployment of small cells.

TABLE 6. A summary of mathematical tools for solving problems in UDNs with other 5G technologies.

Mathematical Tools	Benefits	Limitations	Ref.
Simplex method, BnB, Langragian method, convex programming, Lyapunov optimisation, sequential quadratic programming, Hungarian method	• Gives optimal solution • Suitable for large networks	• High computational complexity • Proving convexity is challenging	[188], [195], [196], [197], [199]
Decomposition, relaxation of constraints, approximation, reformulation, problem splitting methods	• Gives sub-optimal solutions • Low computational complexity • Suitable for large-sized networks	• More decision variables are involved • Some components of the original may be difficult to find	[188]– [190], [200]
Heuristic, utility theory, greedy algorithm, water-filling, iterative-based method, contract theory, complex theory, graph theory	• Give sub-optimal solutions • Low computational complexity • Suitable for large-sized networks	• Difficult to analyse numerically • Solutions are problem-specific	[145], [198], [200]
Probabilistic optimisation, Genetic algorithm, stochastic geometry/process, simulated annealing, evolutionary algorithms, matching theory	• Achieves optimal solution • Low computational complexity • Easy to implement • Suitable for large-sized networks	• More variables are involved	[184], [191]–[194]
Multi-objective optimization, game theory, Pareto optimisation, Stackelberg game, Nash bargaining game, coalition game, Multi-armed bandits	• Achieves optimal solution • Low computational complexity • Suitable for large-sized networks	• More variables are involved • Solution models can be complex	[9], [29], [32], [176], [177]
Fuzzy-logic, Reinforcement learning, and artificial intelligence	• Achieves optimal solution • Use of intelligent and very powerful techniques. • Low computational complexity • Suitable for large-sized networks	• Difficult and complex to develop	[200], [201]–[205]

Therefore, the architectures and distributed intelligent algorithms are required for various managements of the entire networks. The dynamic spectrum access of CR technology is a promising approach to simplify spectrum management and to improve SE in ultra-dense SCNs [205]. There are various forms of SE: average SE, which is the average number of transmitted bits per second per unit bandwidth; area SE (ASE), which is the average achievable data rate per unit bandwidth per unit area and cell SE, which is used to measure the performance of a single cell [20].

2) NETWORK THROUGHPUT

The network throughput of UDNs in combination with other 5G enabling technologies is the average number of successfully transmitted bits per second per Hertz per unit area. In the evaluation of the ASE, the coverage probability also known as success probability, the outage probability, the probability of active BSs, and the link capacity are considered. The coverage probability is defined as the probability that the SINR of a randomly selected user is above a pre-defined threshold while the outage probability is the probability that the SINR of an arbitrary user falls below a specific threshold.

3) EE

The BSs consume a large part of the energy, which generate a large amount of electricity bill. Therefore, obtaining EE has the significant economic and ecological benefits, which represent social responsibility in fighting climate change [206]. EE is defined as transmission bits per unit of transmit energy [12]. The design of 5G wireless networks will have to consider EE as one of its key performance metrics [207]. Indeed, 5G systems will serve an unprecedented number of devices, providing ubiquitous connectivity as well as innovative and rate-demanding services. The EE of 5G networks is expected to be increased by 100× from 1000 mW/Mbps in IMT-2000 to 10 mW/Mbps in IMT-Advance and future IMT [208]. Hence, increasing the EE of UDNs in combination with other 5G enabling technologies is very crucial. Energy-efficient hardware design, intelligent energy management techniques, and low-power backhaul, especially in UDNs, to put BSs to sleep when not in use can all contribute to reducing the cost of operating a 5G network [149]. In [61], three different techniques have been presented for EE, which are energy-efficient architecture (e.g. optimisation of cell sizes, relay and cooperative communications), energy-efficient RRM (e.g. joint power and resource allocation) and energy-efficient RAT (e.g. multi-RAT, SWIPT). In [209]–[212], the authors have proposed various energy-efficient resource allocation strategies in ultra dense small-cell networks to maximise the EE of the overall networks.

4) FAIRNESS

Fairness is related to the amount of achievable throughput in a wireless network [83]. An intelligent management scheme such as RRM is required to prevent a user with a favourable channel from greedily utilising the whole radio resource and ensure at least minimum radio resource is allocated to each user in the network. Also, the efficiency of radio resource sharing increases when deploying small cells within macrocell networks. Moreover, efficient radio resource sharing is very important in such a network. In fact, fairness in radio resource sharing is not unique to only SCNs but is also applicable to macrocell networks. There are different metrics defined for fairness in wireless networks. Examples of such metrics include Jain's index, temporal fairness and utilitarian fairness. An example of fairness application can be found in [213]–[215] with respect to femtocell.

5) QoS

QoS management for wireless networks is a set of standards and mechanisms for ensuring high-quality performance for all applications or services [83]. The objective of QoS management is to ensure sufficient bandwidth, control latency, jitter and reduce data loss. QoS can be managed if the number of UEs served by a small cell is small so that available radio resource would be adequate to satisfy the QoS requirements of each UE. An efficient intelligent management algorithm must be designed to satisfy each user's QoS requirements for real time, non-real time, and best effort services. An examples of QoS management can be found in [216]. Also, in [217]–[219], QoS has been taken into consideration in the design of the proposed intelligent management schemes. However, an adequate modification of the schemes is crucial to accommodate the features of UDNs in combination with other 5G enabling technologies.

6) NETWORK COMPLEXITY

Network management is another challenge in the small cell architecture. This architecture requires complex algorithms to manage radio resources. However, the management of information brings heavy overheads (complexity), which reduces network performance. Therefore, intelligent management algorithms with self-organisation and low complexity capabilities are required to tackle the challenge of network complexity in the future 5G wireless networks. An example of low complexity algorithm is presented in [217], and [220].

IV. GENERAL OVERVIEW OF INTELLIGENT MANAGEMENT TECHNIQUES AND BACKHAUL SOLUTIONS FOR THE COMBINATION OF UDNs AND OTHER 5G ENABLING TECHNOLOGIES

In recent years, research related to various intelligent management techniques and backhaul solutions for the combination of UDNs and other 5G enabling technologies is on-going by researchers in academia and industry. Fig. 8 illustrates the different intelligent management techniques and backhaul solutions found in the literature.

A. RRM ALGORITHMS

An RRM algorithm can be described as a series of tasks that control the amount of radio resources such as power, frequency or time that should be allocated to each user in a wireless network to either maximise or minimise some network performance metrics [221]–[223]. Also, an RRM algorithm ensures optimal utilisation of the available radio resources, interference mitigation based on the QoS requirements of each user and channel information, overall stability of network, users' satisfaction enhancement, and increase in operators' revenue [224]. Efficient RRM algorithms are very important to provide substantial gains in capacity, coverage, and QoS for broadband wireless networks. Moreover, in a commercial wireless network, enhanced coverage, capacity, and QoS represent better investment return costs and better services. For the end users, RRM algorithms provide enhanced services, higher fairness and better QoS levels with ubiquitous availability at possibly reduced prices. Therefore, it is of the utmost importance to study novel RRM algorithms that deal with the radio resources in UDNs with other enabling technologies in 5G. An example of an RRM framework can be found in [171], where the authors present the design foundations of an agile RRM framework for 5G RAN by describing essential building blocks (BBs). Overall, the presented RRM framework provides holistic RRM solutions that consider and exploit the novel aspects of 5G systems.

1) FUNCTIONS OF RRM

RRM algorithms have different functions such as RRA among macrocells and small cells, packet scheduling, link adaptation, radio admission control, and cell/user association [14], [91], which are summarised as follows:

- RRA: The radio resources are allocated to users based on a number of considerations with the overall aim of improving the cell throughput. For instance, joint subcarrier and power allocation takes place at the MAC layer of LTE-A systems and allocation is performed among UEs according to the location of the BS and its attached UEs [195]. The objective is to maximise cell throughput while considering the QoS requirements of each user, channel quality indicator of UEs and interference levels [91]. In [25], a dynamic resource allocation scheme has been proposed to address the challenges of interference, QoS and high communication overhead by considering real time interference and traffic characteristics of the small cells in a cluster.
- Packet Scheduling: Packet scheduling is one of the main RRM functions at the MAC layer of LTE-A systems. It performs physical resource block (PRB) allocation among UEs with the objective of maximising the cell throughput and SE. The decision regarding scheduling is based on the channel quality indicator, the QoS requirement of each UE, or CSI of the UEs, and the interference level [14]. Hence, in UDNs, packet scheduling algorithms can be incorporated into small cells to allocate PRBs to their connected UEs. The most common scheduling algorithms are the following:
    (i) Round-robin scheduler: This scheduler is fairness conscious and user-centric. Conventional round-robin scheduler does not always guarantee an

FIGURE 8. Different intelligent management techniques and backhaul solutions for UDNs in combination with other 5G enabling technologies.

adequate level of QoS since, it neither utilises the queue state nor exploits the channel variability in the scheduling policy, thus sacrificing the inherent achievable network capacity and multi-user diversity [43], [215], [221].

(ii) Max-SINR scheduler: This scheduler is a network-centric scheduler and it is the best in terms of total capacity maximisation, as it fully exploits multi-user diversity inherent in the network [221].

(iii) Proportional-fair scheduler: This scheduler offers an intermediate solution that realises the multi-user diversity gains while maintaining fairness across UEs [43], [221].

(iv) Opportunistic scheduler: This scheduler takes into account information such as the channel quality in terms of QoS metrics that allows the scheduler to find the proper transmission resources for each user. It allocates radio resources based on the flow of QoS requirements. A survey of opportunistic scheduling has been presented in [225].

- Link Adaptation: This is an important RRM function in the MAC layer to achieve higher user throughput performance with a given target block error rate [195]. This approach is also referred to as bit loading [226]. It uses the frequency and time diversities in order to assign the most appropriate modulation and coding scheme (MCS) to each subchannel according to its SINR threshold. The functions of link adaptation include transmission power control, adaptive modulation and coding (AMC), etc. In AMC, a higher order MCS is allocated to UEs with good channel quality. The transmission power coordination typically operates jointly with AMC to enhance cell throughput. In [189], RRM algorithm for UDNs based on joint RRA and AMC has been presented to provide an adequate level of QoS for users.
- Radio Admission Control: According to the LTE-A protocol stack, the radio admission control entity can be found at the radio resource control entity in layer 3, which decides whether a new user request should be accepted. The decision is made based on the QoS requirements of the requesting user and the availability of radio resources [14]. In order to admit a user into a network, the available radio resources must be enough to satisfy the QoS requirements of all users. Decision making can also be based on whether the user is a new user coming from the cell itself or a handover user

from a neighbouring cell. Also, pricing schemes have been used to manage and reduce the increase in data consumption. However, as customers are willing to pay for the provisioned service, pricing models may not be effective to suppress traffic in the future [149].
- User/Cell Association: In order to alleviate congestion at the macrocells in a multi-tier RAN, users' traffic can be offloaded to the small cells, which tends to be underloaded. Therefore, traffic offloading and load balancing are achieved by cell/user association and RAT selection approaches in conjunction with radio admission control schemes [129].

The functions of RRM are not completely independent and are often jointly considered in the RRM design for UDNs. For instance, in [227], the author propose a novel technique for joint optimisation of user association and resource allocation in the uplink cognitive femtocell network. Femtocells are deployed to serve a set of femtocell UEs by reusing subchannels used in a macrocell in the network. The issue of joint user association, power allocation and subchannel assignment is formulated as an optimisation problem, in which the goal is to maximise the overall uplink throughput while the macrocell protection, data rate requirements of the served femtocell UEs, and femtocells overloading avoidance are guaranteed. A distributed technique based on the matching game is proposed to model and analyse the interactions between the femtocells and femtocell UEs. Also, distributed algorithms are developed to enable the cognitive femtocell network to make decisions about user association, transmit power, and subchannel allocation using the proposed schemes. The convergence of the algorithms to a stable matching is shown with a low computational complexity.

RRM algorithms can be classified into two categories, i.e. classification according to processing requirements and classification according to the output objectives [221].

2) CLASSIFICATION OF RRM ALGORITHMS ACCORDING TO PROCESSING REQUIREMENTS

The three classifications of RRM algorithms based on the processing requirements are centralised, semi-distributed and fully-distributed approaches [14], [221].

- In the centralised approach, each network has a central entity, which gathers information from the serving BSs and executes RRM functions based on the information obtained. This central entity needs global knowledge of interference and the CSI for all BSs and UEs in the network. This approach can yield optimal solution for cellular networks, but the amount of signalling may be very high. Therefore, centralised approaches are only feasible for small-sized SCNs. An example of a centralised algorithm can be found in [228].
- In the semi-distributed approach, a central entity performs specific global RRM functions, such as the collection of information about traffic and channel, while local RRM functions, like packet scheduling, are distributed to macrocells and small cells. The RRM algorithms require a limited global knowledge of network link conditions. This approach is suitable for moderately large networks. The authors in [229] adopt the semi-distributed approach in the design of an RRA algorithm for a dense small cell deployment.
- In the fully-distributed approach, a central entity is not required. Both macrocells and small cells determine the RRA policies among the associated UEs by themselves. This method is attractive because of its low signalling overhead and low implementation complexity. In addition, the method is more appropriate for large-sized networks [14], [221]. A fully distributed algorithm is developed in [230] for power allocation in UDNs.

3) CLASSIFICATION OF RRM ALGORITHMS ACCORDING TO OUTPUT OBJECTIVES

RRM algorithms sometimes are classified according to their output objectives as network-centric and user-centric.

- In network-centric based RRM algorithms, high capacity is achieved from the perspective of the service providers [221].
- In user-centric based RRM algorithms, reliable service and fair share of resources to the end users are provided. An example of user-centric QoS-aware interference coordination for UDNs has been presented in [182]. Similarly, an application of user-centric UDNs with NOMA is presented in [231] to provide very high area throughput density and flexible access service for users.

4) PHYSICAL LAYER MODELS FOR RRM DESIGN

In the design of RRM algorithms, the following physical layer models are considered: pathloss model, shadowing model, fading model, SINR model and achievable transmission model and these models are discussed as follows:

- Pathloss model: The pathloss model is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. Pathloss is a key component in the analysis and design of the link budget of a telecommunication system. The pathloss specification is given in [232], [233] by 3GPP for different scenarios of UEs.
- Shadowing model: Shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path between a BS and UE.
- Fading model: Fading is the variation or the attenuation of a signal with various variables. These variables include radio frequency, geographical position, and time. Fading is often modelled as a random process. In wireless systems, fading may occur due to shadowing from obstacles affecting the wave propagation, weather (particularly rain), or multipath propagation. There are various types of fading model, which are Lognormal fading, frequency-selective fading, Nakagami fading, Rayleigh fading and Rician fading. For example: Rician fading is considered in an indoor environment.

It is assumed that a random fading effect of 5 dB for LOS and −60 dB to 5dB is used for NLOS component overlaying on the average value of signal [234].
- SINR Model: SINR is a quantity used to give the theoretical upper bounds on channel capacity in a network.

5) KEY RRM DESIGN CONSIDERATIONS

The key RRM design considerations identified based on the early phase of the study on scenarios and requirements for next generation access technologies, which provides the latest considerations for RAN designs are different service requirements, co-existence of multiple air interface variants such as LTE, WiMaX, dynamic radio topologies, communication modes, interference management techniques for ultra-dense and dynamic deployments, dynamic traffic steering methods that aim to achieve the optimum mapping of 5G services to any available resources, sharing of a common RAN by multiple network slices, RAN moderation mechanisms for improved EE gains [171].

B. INTERFERENCE MANAGEMENT ALGORITHMS

Interference is a fundamental nature of wireless communication systems, in which multiple transmissions often take place simultaneously over a common communication medium. Co-channel interference management has driven recent LTE releases, and important features, such as ICI coordination (ICIC) and coordinated multipoint (CoMP) communication. Basically, the interference management in 4G LTE is mostly a network-side operation and transparent to receivers. Network-side interference management is beneficial to ensure backward compatibility with legacy users and easy to deploy by extending the legacy network. Also, the coverage of a cell is controlled to a certain geographic area and adjacent cell using orthogonal radio resources to avoid ICI by RAN planning and optimisation. Hence, radio resources can thus be reused at a sufficiently far away location to improve system capacity. However, the ultra-dense small cell deployment will have to abandon the cell planning and optimisation method for interference management and adopt denser spectrum reuse patterns to further boost capacity. Different techniques such as adaptive on-off power control method [30], resource allocation schemes [31], [175], [235], graph-based interference topology control [181], QoS-aware interference coordination [182], distributed scheduling and power control [236], and semi-clustering of victim-cells [237] have been considered in the literature to reduce interference in UDNs.

C. MOBILITY MANAGEMENT ALGORITHMS

Mobility management plays a significant role in the current and the future wireless mobile users on the move. It involves location management and handover management. Location management enables the system to track the attachment points of UE between consecutive communications. Handover management enables the network to maintain a user's connection as the UE continues to move and change its AP to another network. Current EPC technique for handover management is based on tunnels connecting devices from a macrocell to an anchoring point. When a mobile user moves, a sequence of messages is exchanged among the EPC entities to update the tunnel information, to reroute the mobile user's device traffic to and from the new location. This model is not suitable to handle the unprecedented amount of control signalling that emanate from small cells. Hence, there is a need for intelligent mobility management solutions.

The handover procedures are performed as follows [36]:
- The reference signal received quality (RSRQ) or reference signal received power (RSRP) is measured by a UE from the serving and neighbouring cells. The UE waits to check whether the entering condition will be held for that time (this is called time-to-trigger (TTT)), if an entering condition of the handover is fully satisfied.
- The UE will then send a measurement report (MR) that includes the measured RSRQ or RSRP values, if the entering condition remains satisfied during TTT. Hence, based on the MR, the serving macrocell decides whether to perform the handover and sends a hand over request to a selected target macrocell.
- The target macrocell considers whether or not it can accommodate the UE and responds to the handover request from the serving macrocell.
- The serving macrocell will send a handover command to the UE, if the handover is accepted.
- The UE then executes the handover on the basis of information in the handover command, which includes the configuration for the UE in the target cell.
- After completing the above steps, the UE sends a handover confirmation to the target macrocell.

In the past years, mobility management solutions have been proposed that employ SDN and NFV technologies. These solutions can be divided in two categories. One involves proposals that maintain almost all EPC control signalling and entities. They use virtualised EPC entities, as virtual network functions, and the SDN controller to flexibly manage the transport network. The second category has solutions changing the signalling and the entities of the control plane. In this case, the functionalities of EPC are maintained but they are redesigned following an SDN approach based on SDN applications [238].

There are two types of mobility management, which are centralised mobility management (CMM) and distributed mobility management (DMM). DMM is regarded as one of the alternatives to CMM, facilitating the anchoring of traffic closer to the user's point of attachment, contributing to the flattening of the mobile networks architecture. It allows a mobile node (MN) to be associated with multiple mobility anchors, optimizing packet routing as the MN changes its point of attachment. In [32], a novel user-centric energy-aware mobility management (EMM) scheme is proposed, in order to optimise the delay due to both radio access and computation, under the long-term energy consumption constraint of the user. EMM works in an online fashion

TABLE 7. Major backhauling solutions for small cells [129].

Types of solution	Backhaul solutions		Frequency band	Link capacity	Link distance
Wired	Fibre	OTN/WDM	1.31 μm laser, WDM	Up to 100 Gb/s	$>$ 10 km
		Uni-PON	1.31 μm laser, WDM	10 Gb/s/wavelength	$<$ 10 km
		PtP fibre	1.31 μm laser	10 Gb/s	$\sim$ 20 km
	Copper	xDSL (ITU G.99x)	Up to 30 MGz	Up to 100 Gb/s	$<$ 3 km
		G.fast	Up to 212 MHz	Up to 1Gb/s DL + UL	$\sim$ 20 km
	Major backhaul multiplexing		Varies	Varies	$<$ 1 km
Wireless	LOS	FSO	1.31 μm laser	Up to 10 Gb/s	$<$ 5 km
		Microwave	60 MHz, 6-42, 70/80 GHz	Up to 5 Gb/s/wavelength	$<$ 5 km
	NLOS	PtMP	Sub 6 GHz	Up to $\sim$ 500 Mb/s	$<$ 1 km
	Massive MIMO + mmWave		mmWave band	Up to 10 Gb/s	$<$ 1 km

without future system state information, and effectively handles the imperfect system state information based on Lyapunov optimisation and multi-armed bandit theories. In [33], a spatial-domain scheduler adapts to the users' mobility that coordinates its decisions within a coordination area composed of several access-nodes is proposed. Similarly, the authors in [34] present efficient localised mobility management schemes considering small cell deployments and backhaul topology based on newly proposed network architectures for UDN. In [35], the authors show that the optimisation-based mobility protocols cannot achieve long-term optimal energy consumption, particularly for UDNs. A non-stochastic online-learning approach is proposed to address the complex dynamics of UDN, which does not make any assumption on the statistical behaviour of the small cell activities. In addition, a handover cost to the overall energy consumption is introduced, which forces the proposed solution to explicitly minimise frequent handovers.

D. BACKHAUL SOLUTIONS

In the rollout of the future 5G cellular systems where a very large number of small cells will be deployed, developing efficient backhaul management solutions for small cells is considered as one of the most substantial challenges [38]. In UDN, a macrocell with large coverage usually control user scheduling and resource allocation, while in small cells, better frequency reuse can be achieved, and EE can also be improved significantly due to the reduced pathloss. To enable UDNs in combination with other 5G enabling technologies, a cost-effective backhaul connecting the macrocell and the associated small-cell BSs is very important. It has been demonstrated in [38] that backhaul with 1-10 GHz bandwidth is needed to efficiently support UDN.

There exist two types of backhaul data transmission between macrocells and small cells, a wired connection or a wireless connection. Although a wired backhaul is more stable and supports high data rate, a wireless backhaul is desirable in terms of low cost, flexible configuration, and easy implementation. Moreover, when the macrocell is equipped with massive antennas, a high data rate is achievable between macrocell and small cell through the wireless backhaul. Fibre optic backhaul is the most preferable solution in terms of both delay and capacity. For wireless backhaul, with LOS communication path up to several Gbps highly directional wireless links are supported by free space optical communications or point-to-point microwave. The NLOS solutions typically offer several hundreds of Mbps link capacity and flexible deployment. Combining the two technologies in wireless backhaul significantly boosts the backhaul performance with adequate antenna array. It is therefore considered as a candidate technology for small cell backhauling. Different techniques have been adopted in the literature for designing effective backhaul solutions. For example, in [129], the authors present a simple case study of joint cell association and bandwidth allocation with a massive MIMO-based in band wireless backhauling technique to demonstrate the performance gain with backhaul-aware RRM in multi-tier cellular RAN. A summary of the major backhauling solutions for small cells is presented in table 7 based on the analysis in [129].

In [239], a joint access and backhaul resource management scheme has been presented to maximise the area throughput of UDNs. In [38], the possibility, benefits and the challenges of mmWave massive-MIMO-based wireless backhaul for 5G UDNs are discussed. In addition, the in-band backhaul for UDNs based on massive MIMO systems in sub-6 GHz is proposed. In [240], a scheme for allowing simultaneous downlink transmissions in backhaul and access network on a single frequency band that exploits a novel combination of the state-of-the-art practical transmit and receive beamforming techniques is proposed. A novel frame structure for allowing a co-existence between massive MIMO-based backhaul and UDNs is also proposed. Moreover, a solution for in-band uplink transmissions that exploits TDD and spatial multiple-access is also provided.

V. REVIEW OF EXISTING INTELLIGENT MANAGEMENT AND BACKHAUL TECHNIQUES FOR DIFFERENT COMBINATIONS OF UDN WITH OTHER 5G ENABLING TECHNOLOGIES

METIS builds on the fact that a single new RAT will not have the capability to fulfil all the requirements of 5G and beyond or replace today's networks. Rather, METIS's vision is that 5G networks will respond to the new and diverse requirements as well as the expected traffic volume explosion through a flexible aggregation of different enabling

TABLE 8. A summary of intelligent management techniques based on year of publication, enabling technologies, benefits, and issues discussed for the combination of udns with other 5G enabling technologies.

Ref.	Year	Combination of Enabling Technologies	Intelligent Management Schemes	Benefits	Issues Discussed
[29]	2017	UDNs and Energy harvesting	User Association	• Opportunistic ambient energy harvesting with UDNs is energy-efficient and environmental-friendly. • No reliance on CSI availability	• Interference management through user association • Capacity maximising user association • Energy-efficient user association • Distributed uplink user association for energy harvesting devices in SCNs
[128]	2018	UDNs and C-RAN	RRA and interference management scheme	• Network throughput and SE improvement • High level of cooperation and communication between BSs	• A centralised user-centric merge-and-split coalition formation game for interference coordination • Graph-based resource allocation • Computational analysis
[154]	2015	UDNs and Fog computing	Load balancing scheme	• Better users' QoE and network performance • Access to greater computational resources and storage capacity	• A joint optimisation of radio and computational resources for minimising the overall power consumption in small cell clustering. • Optimal multi-user small cell clustering
[180]	2016	UDNs and mmWave	Resource management scheme	• Improved data rate • Dual RAT operations • Mitigation of severe distance attenuation due to physical blockages	• mmWave UL RRA strategy • SE of mmWave overlaid UDNs • UL/DL resource management in mmWave UL decoupled UDNs • 3D blockage and channel models
[187]	2016	UDNs and CRNs	RRA and interference management scheme	• Coverage improvement • SE and traffic offloading enhancement • Interference reduction • Better QoS provisioning	• Development of a novel spectrum-efficient optimisation framework by jointly considering capacity maximisation, fairness, interference • Convergence analysis
[194]	2017	UDNs, massive MIMO, mmWave, and FD	Joint user association, user scheduling, and interference management with wireless backhaul solution	• Lower latency • Increase in network capacity • Load balancing • Interference mitigation • Reduction in deployment cost • Minimisation of power consumption	• Design of a hierarchical precoder schemes and control of SC transmission • Wireless backhaul solution, traffic offloading, beamforming design and power allocation • Downlink transmission signal, pilot training, channel aging and convergence analysis
[241]	2017	UDNs, massive MIMO and mmWave	Interference management scheme	• Network capacity and coverage enhancement • Cross-tier and co-tier interference mitigation	• User terminal architecture • Hybrid decoder and equalizers design • Distributed hybrid analog-digital architecture
[118]	2017	UDNs and network slicing	Network slicing management scheme	• Enhanced capacity • Improved utilization of radio resource • Flexible and dynamic radio resource sharing	• Network slicing architecture and complex network theory • Network slicing management, which involves deployment policy, resiliency and security
[244]	2017	UDNs mmWave and energy harvesting	Interference management scheme	• Improved SE and EE • Better QoE • load balancing • High-speed broadband wireless access	• User association and interference mitigation • Graph-based resource allocation • Computational analysis
[246]	2018	UDNs and green communication	Interference management scheme	• High SE and EE • Enhanced capacity • Load balancing • Better users' QoE	• Energy efficient association, which includes cell selection and cell activation • Complexity analysis

technologies [66]. Therefore, current research trends have shown that combination of these technologies in two or more can accomplish the objectives of 5G and beyond [54], [66]. Hence, the combination of UDNs and other enabling technologies in 5G provides great opportunities for cost-effective and high performance networks. These technologies will jointly contribute to the design of new intelligent management algorithms and backhaul solutions. Several solutions have been developed for UDNs but share the same aim of achieving certain objectives. Therefore, a different

TABLE 9. A summary of intelligent management techniques based on research challenges, existing solutions and research directions.

Ref.	Research Challenges	Existing Solutions	Research Direction
[29]	• Irregular deployment of small cells • Introduction of uncertainty in the network operation • Limited computational capabilities • Frequent recharge of devices	• Wireless energy transfer (power beacon) • Opportunistic ambient energy harvesting with intelligent user association schemes for EE maximisation	• Uplink distributed user association for energy harvesting devices in SCNs. • Joint user association and mode selection in D2D enhanced SCNs • User association for FD transmission in SCNs • User association for SC caching and multicast in the presence of energy harvesting
[128]	• Co-channel interference • High computational cost • Broadband access in extreme crowded area • Inefficient utilisation of radio resource • Huge power consumption	• Colouring-based cluster RRA method • Distributed RRA algorithm based on evolutionary game theory	• Improving system satisfaction when users operate different types of services • Efficient utilisation of radio resource to satisfy the requirements of users • Design of low-complexity algorithms for interference management • Energy-efficient RRA schemes to satisfy the requirements of users
[154]	• High power consumption • High latency • Multiple user requiring computational offloading • Load imbalance	• Associating each user to a small cell and a small cell clustering • Joint distribution of computational and radio resources for mobile terminals and the local cloud.	• A low complexity small cell clusters establishment and advanced RRM for fog clustering in UDNs with consideration for latency constraint. • Dynamic load balancing and task assignment to mobile end devices to address scalability issue.
[180]	• Mitigation of severe distance attenuation due to physical blockages • Disjunction between downlink and uplink rates power dissipation at DACs	• Investigation of the blockage-vulnerable drawback of mmWave and interference reduction • mm-μWave RRM	• Impact of DL transmission outage on mmWave-based UDNs • Resource allocation schemes to support ultra-reliable applications such as the tactile Internet
[194]	• Limited backhaul • Imperfect CSI due to to mobility • Load imbalance • Cross-tier and co-tier interference	• User scheduling • User offloading • Beamforming design and power allocation • Interference management schemes	• Consideration for uplink transmission signal • Imperfect SIC and mobility support • Joint load balancing and interference mitigation for EE optimisation • Bidirectional topology FD communication • Partial duplex communication
[241]	• Limited backhaul • Hardware limitation • High deployment cost • High power consumption • Interference issue	• Hybrid beamforming algorithms • Interference alignment • Joint signal alignment and physical network coding	• Dual band small cells, • Optimisation of antenna selection • Design of mobility management schemes • Development of advanced interference management schemes • Hybrid analog-digital sparse transmit and beamforming scheme
[244]	• Irregular deployment • Interference • Load Imbalance	• Channel-access-aware association scheme • RRA scheme in SWIPT	• Load aware energy efficient user association and power allocation • Low-complexity energy-efficient intelligent management schemes
[246]	• Huge energy consumption • Severe network interference	• Interference coordination approach	• Energy-efficient radio resource allocation • Joint cell selection and interference mitigation schemes

classification can be made for these solutions based on their combination with other 5G enabling technologies. In the following, the detailed discussions of each of the surveyed schemes for UDNs in combination with other 5G technologies are summarised. A summary of these schemes based on research challenges, existing solutions and potential research directions is provided in table 8 while in table 9, a qualitative comparison based on the mathematical tools and the performance metrics adopted is presented. A summary of the intelligent management techniques based on the year of publication, different 5G enabling technologies adopted, the benefits of each algorithm and the issue addressed in the paper is presented in table 10.

A. COMBINATION OF UDNs, MMWAVE, FD, AND MASSIVE MIMO TECHNOLOGIES

UDNs reduces the distance between the users and the small cells, thereby provides excellent QoE for users. However, using the existing cellular bands introduces severe intercell cochannel interference (CCI). Also, there is a problem of load imbalance in UDNs. Hence, mmWave bands are good solutions to address the problem of intercell CCI, while FD

TABLE 10. Qualitative comparison between different intelligent management schemes for the combination of UDNs and other 5G enabling technologies based on the mathematical tools and the performance metrics adopted.

Ref.	Mathematical Tools Adopted	Performance Metrics							
		Network Throughput	Interference Mitigation		EE	SE	Fairness	QoS	Complexity
			Co-tier	Co-tier					
[29]	Mean field multi armed bandit game	✓	x	x	✓	✓	x	✓	✓
[128]	Game and graph theories	✓	✓	✓	x	✓	x	✓	✓
[154]	Heuristic method	x	✓	✓	✓	✓	x	✓	✓
[180]	Stochastic geometry	x	✓	✓	✓	✓	x	✓	✓
[187]	Lagrangian dual decomposition	✓	✓	✓	x	✓	✓	✓	✓
[194]	Utility theory, Lyapunov framework and SCA	✓	✓	✓	x	✓	x	✓	✓
[231]	Matching and Convex programming theories	✓	✓	✓	✓	✓	x	✓	✓
[241]	Optimisation technique	✓	✓	✓	x	✓	x	✓	✓
[118]	Complex Network theory	x	✓	x	x	✓	✓	✓	x
[244]	Lagrangian dual decomposition method	✓	x	✓	✓	✓	✓	✓	x
[246]	Bisection and dual decomposition methods	✓	✓	✓	✓	✓	x	✓	✓

capability can be incorporated in small cells to achieve load balancing. To further enhance the data rate performance of the mmWave small cell users, the mmWave signal should be directional, which can be achieved by using mmWave technology [79]. The authors in [194] study the problems of load balancing and interference mitigation in UDNs, where a massive MIMO MBS is equipped with several antennas, overlaying the wireless self-backhauled, FD enabled small cells to minimise the load of MBS and to mitigate both cross-tier and co-tier interference. In [241], low complex hybrid analog-digital receive and transmit beamforming methods for ultra-dense uplink massive MIMO and mmWave heterogeneous systems are proposed to efficiently mitigate interference.

B. COMBINATION OF UDNs, ENERGY HARVESTING, MASSIVE MIMO, AND FD TECHNOLOGIES

In this type of combination, the major problems are user association, interference and load imbalance. Hence, the intelligent management schemes that can be used to solve these problems are user association techniques, joint load balancing schemes and interference management algorithms. In [29], the distributed user association problem for energy harvesting UDNs is investigated. After reviewing the state-of-the-art research, the major challenges that arise in the presence of energy harvesting due to the uncertainty (e.g., limited knowledge on energy harvesting process or channel profile) as well as limited computational capacities are presented. Finally, an approach based on the mean-field multi-armed bandit games to solve the uplink user association problem for energy harvesting devices in a UDN in the presence of uncertainty is proposed. In [194], the issue of joint load balancing and interference mitigation in UDNs is studied in which massive MIMO MBS equipped with a large number of antennas, overlaid with wireless self-backhauled small cells, is assumed. Small cell with self-backhaul capability and FD communication using regular antenna arrays serve both MBS users and small cell users by employing the wireless backhaul from MBS in the same frequency band. The joint load balancing and interference mitigation problem is formulated as a network utility maximisation subject to wireless backhaul constraints. Moreover, the problem is decoupled into dynamic scheduling of MBS users, small cells backhaul provisioning, and offloading MBS users to small cells as a function of interference and backhaul links using the stochastic optimisation tool. The performance gains of the proposed scheme under the impact of number of BS antennas, small cells density, and transmit power levels at low and high frequency bands is demonstrated via numerical analysis. Moreover, the authors in [241] propose hybrid analog-digital receive and transmit beamforming frameworks with low complexity for ultra-dense uplink massive MIMO mmWave HetNets to effectively mitigate interference. The hybrid analog-digital receive beamforming/equalizer is computed in a distributed fashion at the small cells, while the digital part is performed at a central unit for joint processing. The authors consider the metric of distance relative to the fully digital counterpart induced by the Frobenius norm, to optimise the analog part of the hybrid equalizer and the precoders used at the UEs. In the optimisation problem, the constraints inherent to the distributed nature of the APs are imposed. The digital parts of the precoders employed at the SUE are designed to cancel interference at the MBS. The research directions in hybrid beamforming include dual band small cells, optimisation of antenna selection and mobility management [242].

C. COMBINATION OF UDNs AND IoT TECHNOLOGIES

The intelligent management schemes that can be used to solve problems that involve the combination of UDNs, and IoT technologies are user association techniques, joint load balancing and interference management algorithms.

In [78], "by means of simulations, the authors evaluate the UL performance of IoT capable UDNs in terms of the coverage probability and the density of reliably working UEs. From the study, the benefits and the challenges that UL IoT UDNs will bring about in the future are provided. In more detail, for a low-reliability criterion, such as achieving a UL SINR above 0dB, the density of reliably working UEs grows quickly with the network densification, showing the potential of UL IoT UDNs. In contrast, for a high-reliability criterion, such as achieving a UL SINR above 10dB, the density of reliably working UEs remains to be low in UDNs due to excessive ICI, which should be considered when operating UL IoT UDNs. Moreover, considering the existence of a non-zero antenna height difference between BSs and UEs, the density of reliably working UEs could even decrease as more BSs are deployed." This calls for the usage of sophisticated interference management schemes and/or beam steering/shaping technologies in UL IoT UDNs. Other potential research directions in IoT-based UDNs include, network management, security and privacy.

D. COMBINATION OF UDNs, C-RAN, AND FOG COMPUTING TECHNOLOGIES

The intelligent management schemes that can be used to solve problems that involve the combination of UDNs, C-RAN, and fog computing technologies are RRA, user association techniques, load balancing schemes and interference management algorithms. In [128], a centralised user-centric merge-and-split technique is proposed based on C-RAN using the tool of coalition formation game. The proposed technique makes it possible to utilise the information of users such as distance to estimate inter-user interference for more effective and accurate interference mitigation. Also, a novel RRA algorithm based on the graph theory is presented, which gets rid of intra-tier interference successfully by means of allocating users who may significantly interfere each other in the conflict-graph with orthogonal subchannels. Furthermore, a supplementary allocation algorithm is proposed to allocate the rest subchannels so that the system SE performance can be enhanced. In [154], the authors concentrate on enhancing users' QoE by addressing the problem of load balancing in fog computing. The challenging case of several users requiring computation offloading, where all requests have to be processed by means of local computation clusters resources is considered. Also, a low complexity small cell clusters establishment and RRM algorithm development for fog clustering is investigated.

E. COMBINATION OF UDNs, SDN AND mmWAVE TECHNOLOGIES

The challenges of this combination are traffic offloading/load balancing and resource allocation problems. Therefore, intelligent management schemes such as traffic offloading/load balancing and resource allocation schemes should be developed. The work in [180] focuses on maximising the total downlink rate subject to a minimum uplink rate constraint. The authors conclude that mmWave tends to focus more on DL transmissions while μWave has high priority for complementing UL, under TDD mmWave operations. Such UL dedication of μWave results from the limited use of mmWave UL bandwidth due to excessive power consumption at mobile users. To tackle this UL bottleneck, the authors propose mmWave UL decoupling, which permits each μWave BS to receive mmWave signals. Hence, its effect on mm-μWave RRM is provided using a novel closed-form mm-μWave SE derivation. In an UDN, the derivation shows that mmWave (or μWave) SE is a logarithmic function of BS-to-user density ratio. Stochastic geometry tool is used for the analysis in conjunction with real three-dimensional building blockage statistics in Seoul, South Korea. In [243], a mobile traffic offloading and resource allocation in software defined wireless networking (SDWN)-based UDNs is proposed, consisting of different MBS and SBSs. A scenario where the capacities of small cell are available is explored, but their offloading performance is not known to the SDWN controller. To address this challenge, incentivized traffic offloading contracts are developed to encourage each small cell to select the contract that achieves its own maximum utility. The characteristics of large numbers of small cells in UDNs are aggregated in an analytical model, allowing the selection of the small cell types that provide the offloading, based on different contracts, which offer rationality and incentive compatibility to different small cell types. This leads to a closed-form expression for selecting the SBS types involved, the monotonicity and incentive compatibility of the resulting contracts is proved.

F. COMBINATION OF UDNs, AND NETWORK SLICING TECHNOLOGIES

RRM, EE and security are the major issues in this combination. Hence, intelligent management algorithms must be designed to address these issues. In [118], the authors propose a network slicing management technique for 5G UDN based on complex network theory. In the technique, a multilayer network model is used to represent the topology of multi-slices and infrastructure network from a global perspective. With the model, the topological information of infrastructure network is put into consideration in the deployment policies of slices. Furthermore, they analyse the potential of complex network theory to be applied appropriately in network slicing management from the aspects of improving the resilience and guaranteeing security. Energy-efficient RRM is still an open issue in network slicing technology due to the massive deployment of small cells.

G. COMBINATION OF UDNs, C-RAN, NOMA TECHNOLOGIES

The challenges of this combination are interference management, resource allocation and load imbalance. Hence, effective intelligent management schemes must be designed to address these challenges. In [187], a resource allocation scheme for OFDMA-based cognitive femtocells is proposed.

The aim is to maximise the overall capacity of all FUEs under the constraints of QoS and co-tier/cross-tier interference with imperfect channel sensing. The minimum and maximum numbers of subchannels occupied by each user are considered, to achieve the fairness among FUEs. Also, the subchannel and power allocation problem is modelled as a mixed-integer programming problem, and then, transformed into a convex optimisation problem by relaxing subchannel sharing and applying co-tier interference constraints, which is finally solved using a dual decomposition method. Moreover, an iterative subchannel and power allocation algorithm is proposed based on the obtained solution. In [231], a user-centric access framework for providing efficient access service and the flexible resource management in NOMA-based user-centric UDN is proposed. Under the proposed framework, the authors investigate the access scheme that organises multiple APs into respective AP group (APG) cooperatively to provide access service for each user, aiming at maximising the system EE. Firstly, considering the users' requirement and network environment, a grouping evaluation model is set up to organise APG efficiently. Then, the resource allocation problem of APG is formulated as a mixed-integer nonlinear programming problem, which is hard to tackle. For tractability purpose, the problem is transformed and low-complexity algorithms are proposed based on matching and convex programming theories to obtain a feasible solution.

H. COMBINATION OF UDNs, AND mmWAVE TECHNOLOGIES

The intelligent management schemes that can address the challenges of this combination are user association and RRM schemes. In [244], a user association and power allocation in mmWave-based UDNs is considered with focus on load balance constraints, energy harvesting by BSs, EE, user's QoS requirements, and cross-tier interference limits. The joint user association and power optimisation problem are modelled as a mixed-integer programming problem, which is then transformed into a convex optimisation problem by relaxing the user association indicator and solved by Lagrangian dual decomposition. An iterative gradient user association and power allocation algorithm is proposed and shown to converge rapidly to an optimal point.

I. COMBINATION OF UDNs, AND SON TECHNOLOGIES

The issues that arise due to this combination are resource allocation problem, load imbalance, how to maximise EE and SE. Hence, intelligent management techniques such as RRM, user association techniques and low-complexity algorithms must be designed. In [245], a self-organised resource allocation scheme is proposed to enhance the system performance, which can coordinate resource allocation within small cell clusters. Also, the users' access distribution as a constraint weight when conducting downlink cooperative power adjustment, aiming to adapt system resource consumption corresponding with the current traffic load is considered. It has been shown that the proposed strategy improves system performance in hotspot and can maximise the system EE in UDNs. In [246], the authors jointly perform cell activation and selection to maximise the network EE under users' long-term rate constraints. The formulated problem is in a mixed-integer fractional form and hard to tackle and needed to be transformed into a parametric subtractive form, by which its solution is obtained through a three-layer iterative algorithm. The first layer searches an EE parameter using a bisection method; the second layer alternately optimises cell activation and selection indices; the third layer solves cell selection and cell activation problems using dual decomposition and fixed point iteration respectively. At last, the complexity and convergence analyses for the designed algorithm are given, and the impacts of different network parameters on system performance are investigated.

VI. SUMMARY OF OPEN RESEARCH CHALLENGES, DESIGN GUIDELINES AND LESSONS LEARNT

A. SUMMARY OF OPEN RESEARCH CHALLENGES

In summary, research trends and challenges in the 5G enabling technologies have to be pointed out and solved before combining them with UDNs. For example, in massive MIMO system, a large amount of CSI is required in beamforming, which is not convenient for the downlink transmission. Therefore, the massive MIMO technology can be applicable in the TDD domain but not feasible in the FDD. In addition, massive MIMO suffers from pilot contamination and thermal noise produced by neighbouring cells [97]. Hence, these challenges must be overcome before integrating massive MIMO technology into UDNs.

Moreover, the handover and coverage issues between neighbouring small cells and its impact on EE especially in UDNs in combination with other 5G enabling technologies need further investigation. The aspects of EE, SE, QoS requirement of a particular application and time varying channel condition and its relation for the combination of UDNs and other 5G technologies need to be developed. Furthermore, joint interference management as well as handover between various networks with respect to SE and EE needs further studies. The trade-off between EE and SE for load balancing in UDNs with other enabling technologies also needs further investigation. Also, the issues relating to joint uplink, distributed user association and mode selection in D2D enhanced UDNs need further analysis. The EE of massive MIMO network with FD relay channel needs to be studied for the combination of UDNs, massive MIMO, and FD communication to eliminate the effect of interference. Further research also needs to be carried out for efficient implementation of BS with FD capability, sleep modes, energy harvesting ability to minimise interference and save maximum possible power simultaneously. The selection of APs, interference control and power consumption reduction with low complexity strategy and its impact on the SE, EE, QoS requirement of the network need further investigation. Likewise, the power control strategy and efficient intelligent management algorithm for the combination of UDNs and other technologies to minimise interference at the same time ensuring optimum SNR need to be developed. The impact of multiple antennas at the BS and joint resource and power allocation is also a possible future work in this regard. The trade-off between power consumed by hardware and power saving of the network by using massive MIMO with beamforming in the mm-range also needs to be investigated along with the overall EE of the network. Novel ICIC and resource allocation mechanisms are required for bidirectional topology FD communication when combining it with UDNs. Also, a good balance of FD communication and HD communication must be investigated in the combination of UDNs and other 5G enabling technologies.

B. DESIGN GUIDELINES IN UDNs WITH OTHER 5G TECHNOLOGIES

To realise the goals of 5G, design of intelligent management schemes for the combination of UDNs and other technologies must involve consideration of the following:

- general understanding of the combination of UDNs and other enabling technologies
- a reliable, gigahertz bandwidth, and cost-effective backhaul connecting ultra-dense small cells and macrocell. For example, mmWave can provide the potential Gbps traffic for wireless backhaul. Moreover, mmWave can easily be combined with massive MIMO for improved link reliability [38] in UDNs.
- use of high frequencies and other spectrum option such as pooling.
- design of new multiple access schemes that can be optimised for latency reduction and massive connectivity. For example, new schemes such as NOMA, sparse SCMA, and FBMC can further be utilised to enhance SE.
- maximisation of EE across all network entities
- use of an intelligent agent to manage QoE, mobility and resource allocation.

C. SUMMARY OF LESSONS LEARNT

- Fairness will not be a major issue in UDNs since there are not many UEs per cell to be fairly served and channel fluctuation may be low due to LOS channel conditions. According to [47], simpler solutions may be more appealing such as round robin.
- Joint intelligent management schemes and backhaul solutions with consideration for latency, SE, interference mitigation, load balancing, and EE will be more appropriate in the combination of UDNs and other enabling technologies.
- Distributed and low-complexity intelligent management techniques as well as backhaul solutions will be crucial to attain better overall network performance.
- Self-organising and user-centric solutions will be necessary in the combination of UDNs and other 5G enabling technologies.
- Small cell can also be enhanced through the NR technology

VII. CONCLUSION

The evolution of the cellular and wireless networks is leading to 5G wireless networks. Therefore, in this paper, a comprehensive survey on various generations of wireless networks from 1G to 5G has been pointed out. Also, the 5G enabling technologies, the basic requirements of 5G wireless systems and the importance of the combination of UDNs and other technologies in two or more are described. Moreover, the intelligent management techniques, backhaul solutions and holistic research advances for the combination of UDNs and other technologies are presented. There are several technical challenges, which must be addressed in order to make the combination of UDNs and other enabling technologies viable to have a positive impact on the end users in terms of improving the EE, SE, fairness and QoS performance. These major challenges have been described to enable a clear view of the main requirements of the technologies. Moreover, some existing intelligent management algorithms and backhaul solutions have been presented. Furthermore, the functions of the algorithms, the mathematical tools for solving the related problems, the performance metrics to evaluate the algorithms and the potential future research directions have been presented in the paper. Finally, it can be concluded that the research in UDNs in combination with other 5G enabling technologies is still in its infancy and there are many challenges to be overcome to fully achieve excellent network performance in the coming years.

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