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Review

Ultra-Dense Networks: Taxonomy and Key Performance Indicators

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Abstract: One major influence on the future deployment of cellular networks will be a continuous increase in traffic inside mobile broadband systems. Moreover, traditional macrocell-based mobile communication networks will struggle to keep up with the enormous expansion in the demand for communications services in the future. Densification of networks is required if we are to meet the comprehensive needs for end terminals for a wide range of applications. One of the leading concepts in this competitive environment is the Ultra-Dense Network (UDN) where the access nodes and/or the communication links per unit area are densified, with the aim of improving overall network performance. The location of the UDN nodes meets the criteria for symmetry with a high probability. Ultra-dense cell deployment aims to reduce the physical distance between the transmitter and receiver in order to boost system performance and generally optimize the values of a wide variety of key performance indicators (KPIs). This paper aims to provide a taxonomy of UDNs and specifically of UDN-related KPIs. Initially, we address the complex questions "What is the current understanding of what ultra-dense networks are and what they should be, and how can we measure their performance?" by shedding light on the fundamental characteristics of UDNs.

Keywords: ultra-dense networks; key performance indicators; network-centric connectivity; user-centric connectivity; asymmetric connectivity

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1. Introduction

The wireless networks of the future will be required to provide completely new levels of applications and experiences, ranging from multi-sense communication to super-smart cities and communications outside the terrestrial domain, for instance underwater or in space. Adaptability, being able to cater to a vast number of diverse applications, energy efficiency (EE), etc., will become crucial factors in developing the wireless communication of the future. The next generation of networks—6G—will grow and upgrade in all aspects to transform not just human life but society as a whole. There will be a significant improvement in network performance, including greater data rates (up to Tbps), reduced latency (sub-ms), ubiquitous 3D coverage (at sea, in space, below the sea), increasingly precise localisation (reaching centimetre-level), and stricter privacy and security. Improving the capacity of the network is a major method of meeting these challenges. It can be accomplished in three ways: purchasing more spectrum, improving the efficiency of that spectrum, and "densifying" the network. In respect to mobile networking, densification represents the operation of incorporating additional cell sites to increase the amount of available capacity and to also offload traffic from nearby sites. According to the 3GPP [1], densifying communication links and access points (APs) shows great promise as a way of catering for the ever-growing demand for capacity and the explosive surge in data traffic. Increased AP density [2] indicates that, despite the numerous transmission modes, wireless networks are fundamentally following a route from a standard network to a denser network, to an extremely dense network, and onwards to a UDNs. As a result, rather than being a completely new design, UDNs are a novel pattern of network that has evolved from the previous dense networks.

There are many publications that review UDNs but, to the best of our knowledge, none of them contains a taxonomy of UDNs nor clearly defined specific KPIs through which one could evaluate and compare their overall performance. In this context, [3] and [4] are some of the first papers to attempt to address the fundamental issues relating to the deploying of UDNs and demonstrating the utility of UDNs in 5G wireless networks, such as establishing what density of infrastructure is needed to cope with specified traffic loads and what benefits accrue from network-wise coordination. Generally, many of the papers focus on the compilation of a list of recent achievements, research findings, potential challenges and enabling technologies in the context of UDNs [5–11]. Additionally, [12,13] present a comprehensive survey of security issues in UDNs, focusing on physical layer security issues and security-based resource management. There are also several papers which consider diverse areas of UDN evolution. Softwarization paradigms embedded in densely distributed radio access networks (RANs) are presented in [14]. Ref. [15] outlines big data methods for UDN deployment from the perspective of several data science approaches which can lead to the improvement of UDN deployment and operations. The deployment of a high number of small base stations (BS) can increase system performance and resource usage in UDNs. However, BS in UDNs are quite close to each other, often causing significant interference between them. Some papers approach this problem by providing surveys of several intelligent interference mitigation techniques, as well as resource allocation and mobility management strategies and approaches [16–18]. A survey of base station sleep mode techniques in UDNs can be found in [19]. Sleep mode approaches can greatly reduce the power consumption of UDNs by selectively turning either entire access points, or just their transceivers, to sleep mode. Several papers discuss the implementation of machine-to-machine communications in UDNs [20–22]. These focus mostly on various implementation challenges, security and privacy, network virtualization and usage of Non-Orthogonal Multiple Access (NOMA) in machine-type communications-enabled UDNs.

It is of major importance for a classification of UDNs, together with respective KPIs, to be proposed, so as to reach a better definition and understanding of the characteristics of the different types of UDNs, which in addition will allow them to be easily related to specific use cases and scenarios. Although no consensus on the definition of UDNs has yet been reached, there are two widely acknowledged variations considered in the literature. One is from the perspective of cell density, or the number of cells in relation to user density. In this sense, a UDN is a cellular network with more cells than active users or with a cell density of greater than 10^3 cells/km^2 [5,23]. In this situation, APs that are densely distributed put cells closer to users, allowing each user's quality of service (QoS) to be considerably enhanced. The second definition is from the perspective of technical realisation—a UDN can be considered as a flexible complex communication network that combines a variety of emerging technical features, including user-centric beamforming, network corporation, network virtualization (NV), caching, computation, and energy harvesting (EH).

In this paper, we consider that a UDN is ***a network with a spatial density of APs (or base stations) identical to or larger than the number of active end devices—EDs (user equipments (UEs) or physical devices (PDs))***. However, this definition does not go into the details and does not offer a holistic idea of the different types of UDNs. Using this general definition of a UDN we will build up a taxonomy based on the responses to questions such as: (i) "How can a UDN architecture be defined?"; (ii) "What type of connectivity characterizes the network—is it symmetric or asymmetric?" (iii) "What types of devices may the UDNs consist of?"; (iv) "Do all UDNs consist of different types of APs (heterogeneous UDNs) or can they be homogeneous?; (v) "Can UDNs be seen as mobile only?"; and (vi) "Can every network evolve into a UDN?".

The design, and analysis of the performance, of a UDN poses challenges as a UDN differs fundamentally from a current 4G/5G sparse/dense network. To elaborate on this, we first summarize and comment on some UDN-related basic topics. This list is by no means complete; however, it does include the main characteristics and requirements that should be considered as essential in the design of any type of UDN.

- **3D densification**: There are two variations of network densification: horizontal and vertical. As the name indicates, horizontal densification requires the access nodes to be concentrated horizontally, such as on roadways or in hotspots. Vertical densification, on the other hand, occurs in the elevation plane, so APs can be put in apartments, offices, buildings' interiors, or even outdoors, for instance—in the air. The deployment of various types of EDs and APs in this context can provide not only terrestrial, but also air-to-ground and air-to-air wireless connectivity. A summary of EDs and APs is presented in Figure 1. By improving the wireless link quality and spectral efficiency, 3D UDNs based on mobile radio access nodes can provide enhanced coverage and connectivity.
- **AP and ED density:** The typical feature of UDNs is the ultra-dense deployment of APs and end devices, which in mobile networks are, respectively, denoted as BSs and UEs. Usually, the number of APs is greater than 1000 units/km^2 and the number of active end devices is greater than 600 units per km^2. In order for a network to be designated as a UDN, the density of different types of devices must be above the mentioned values in a given area. These metrics can be also defined in a volumetric context (3D space) because the different types of devices can be located not only on the ground but also in the air, for example unmanned aerial vehicles or satellites.
- **ED-AP and AP-AP distance:** Ultra-dense deployment leads to reduced distance between the ED and the AP, and between the APs. Clearly, this results in an enhanced probability of connection for each user, due to the improved communication and coverage range.
- **Traffic volume and connection density:** UDNs need to be able to handle the very high traffic loads resulting from the enhanced connection probability. For this reason, the network topology should be adaptable to the specific communication environments and user requirements.
- **Line-of-sight probability, coverage and outage probability (service continuity):** As a result of the high number of APs, the likelihood of line-of-sight communications is very high, resulting in a very high coverage probability, and very low outage probability tending to zero. Moreover, ultra-dense deployment leads to the opportunity for improved service continuity when the users are located, or moving, within the coverage areas of the APs. The transmission power of each AP can be adapted according to its geographical position and user requirements so as to improve the overall network coverage.
- **Multi-antenna/multi-AP joint transmission:** An ultra-dense network should be able to intelligently recognize users' wireless communication environments, and implement flexible multi-antenna/multi-AP joint transmission in order to serve the user. Furthermore, the UDNs are characterized by specific ED-to-AP association policies, due to the enhanced number of devices. In this context, an association of one user to multiple APs is an option which is not only possible but highly desirable. However, this operation is very challenging, especially when a high mobility of APs and users is considered.
- **Asymmetric connectivity:** Ultra-dense networks in general are characterized by asymmetric connectivity. This means that the data are sent and received through different nodes and/or with varying parameters; the asymmetry can be characterized in terms of important characteristics such as bandwidth, and packet error rate. Between EDs and APs, more bandwidth is available in downlink than in uplink, which causes bandwidth asymmetry. Other asymmetries, including latency, are mostly brought on

by the bandwidth asymmetries. Furthermore, when upstream packets follow different routes than downstream packets, this can result in routing asymmetry. Finally, load balancing algorithms are highly desirable in UDNs, due to the asymmetric data loads which are handled by the different types of APs.

Obviously, there are several important characteristics and design aspects which must be considered when a network is classified as ultra-dense. Furthermore, according to the literature, UDNs can be seen as a network paradigm which can be implemented in the context of various kinds of wireless networks, such as sensor/IoT (Internet of Things) networks, mobile networks, aerial networks, and even satellite networks. Here, UDN is related to the specific types of devices, such as end devices and access points, which can be used (Figure 1). In addition to the most commonly used end devices today, the list in Figure 1 contains different types of aerial vehicles and 6G network paradigm-related devices, such as eXtended Reality (XR) equipment and diverse types of on- or in-body wearables. In relation to access points, in addition to the widely known APs, we also mention Visible Light Communication-based LEDs, denoted as VLC LEDs. These are discussed in section II. The list does not claim to be exhaustive and as technology develops it will inevitably grow larger.

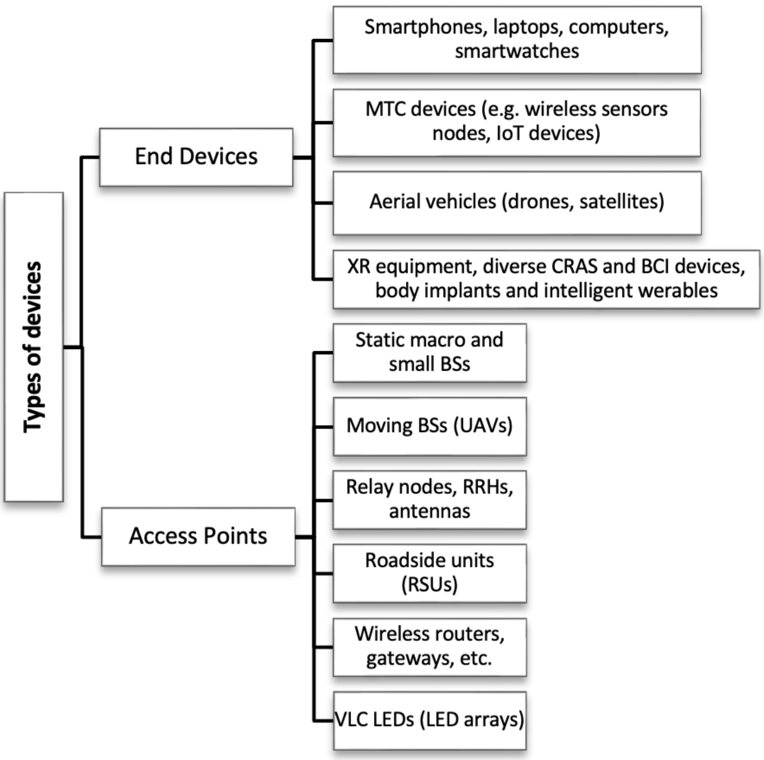

Figure 1. Types of devices in UDNs.

The contributions made by this present paper are summarized as follows:

- A taxonomy of UDNs is proposed, based on two main criteria—network connectivity paradigm and network access. For both, HUDNs and user-centric UDNs, several implementation challenges are summarized, focussing mostly on heterogeneity/densification-based issues and clustering/grouping and security/privacy-related challenges. Furthermore, several important network access-related technologies which can be implemented in UDNs to enhance overall network performance and user experience are outlined.
- The most important UDN design-related KPIs are defined and discussed. Among them, there are several standard KPIs for network performance evaluation, such as

energy/spectral efficiency, coverage/outage probabilities, and end-to-end latency. We also discuss a number of metrics which have the potential to be significant for the UDNs. Some of these are related to the high densification nature of UDNs. Others are related to assessing the complexity and intelligence of the network. These two are important due to the availability of a wide variety of EDs, APs and network technologies. Finally, a UUDN-related metric is proposed in order to evaluate the potential gain of dynamic APG grouping implementation.

The rest of this paper is organized in the following manner. Ultra-dense network taxonomy is presented in Section 2 to outline different types of UDNs in regard to several criteria. Common metrics for assessing the performance of UDNs—KPIs are described in Section 3. Finally, Section 4 concludes this paper.

2. Ultra-Dense Networks Taxonomy

Our taxonomy of UDNs is based on two main criteria: (i) network connectivity, which is related to the specific connectivity paradigm used; (ii) network access, which covers diverse access technologies and architectures (Figure 2).

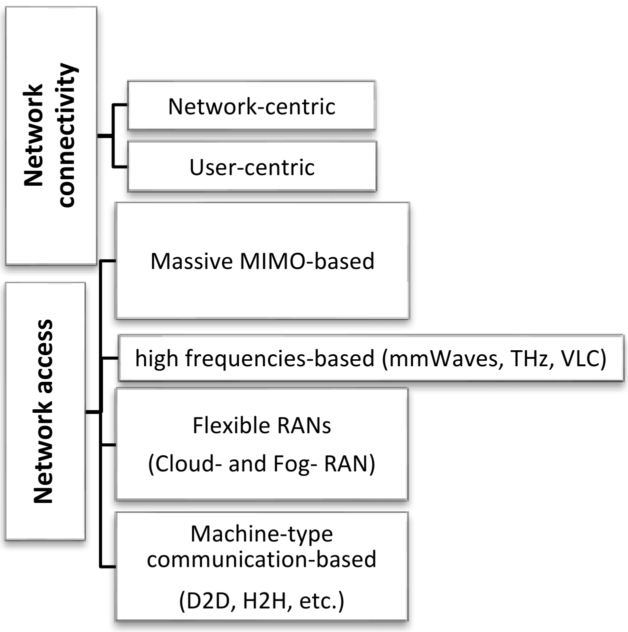

Figure 2. Taxonomy of ultra-dense networks in regard to several criteria.

2.1. Network Connectivity

In this paper, we consider two major types of UDN connectivity concepts—network-centric and user-centric.

2.1.1. Network-Centric Connectivity

Heterogeneous Ultra-dense networks (HUDNs) are the most important example of the realization of a network-centric connectivity concept (Figure 3). HUDNs are made up of a variety of access technologies, each with its own set of capabilities and limitations. This allows for efficient spectrum reuse over the region of interest, which is one of the major approaches to boosting the capacity of next-generation wireless networks [24–26]. Generally, there are three types of cells in an HUDN: (a) fully functional, high-power macrocells (legacy cells); (b) fully functional small cells (picocells and femtocells) which can perform the functions of macrocells, in a smaller coverage area and with low power; and (c) macro extension APs, for example remote radio heads (RRHs) and relays.

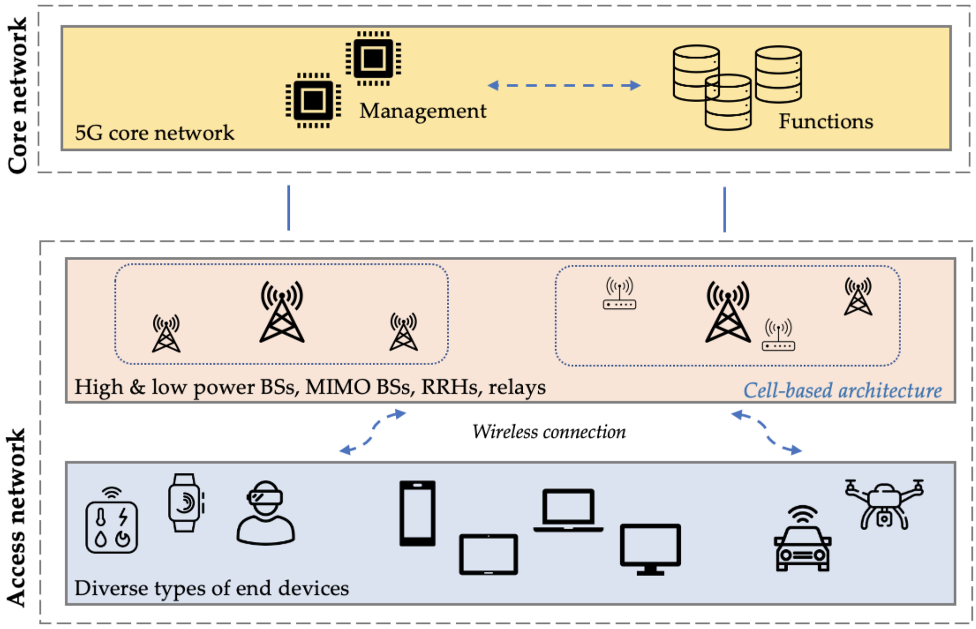

Figure 3. Network-centric connectivity architecture.

The following Table 1 briefly presents the specifics of various AP/cell types.

Table 1. Different types of APs in HUDNs.

Type of AP/Cell	Deployment Scenario	Coverage and Power
Macrocells (fully functioning)	outdoor (planned)	few kilometres, 43–46 dBm
Picocells (fully functioning)	indoor/outdoor	up to 300 m, 23–30 dBm
Femtocells (fully functioning)	indoor	10–50 m, up to 23 dBm
Relays (macro-extension)	indoor/outdoor	up to 300 m, 30 dBm
RRHs (macro-extension)	outdoor	300–500 m, ≥30 dBm

Macrocells are composed of exterior eNodeBs (eNBs) that are strategically positioned by the operator to provide open public access and cover a large area, usually several kilometres. On the other hand, picocells are low-power fully functioning eNBs, usually distributed by a provider following a particular plan, both outdoors and indoors. Picocells share the same backhaul and access features as macrocells, allowing for low latency and high bandwidth. Indoors, femtocells are commonly used (in homes, offices, and meeting rooms, etc.). They are ad hoc low-power access points with a typical transmit power of 100 mW or less. A femtocell can function in one of three modes: open, closed, or hybrid, depending on the access it has. In the same way as with macro extension access points, relays are access points installed by the operator and used to cover dead zones and low coverage regions in macrocells. The data of the users are sent back and forth between the macro cell and the relays and in this case the latter are extensions of a macro eNB rather than fully functional APs. Finally, the RRHs are light-weight RF units installed outside macrocells to allow the core eNBs to cover a larger area. There is no baseband unit (BBU) on the RRH. High-speed fibre or millimetre waves are used to link RRHs to the Macro eNB (MeNB) or BBU pool. All signal processing is handled by central eNBs or BBU pools. As a result, instead of distributed densification, RRHs are used to provide centralized densification. RRHs can be simple and inexpensive to manage.

Unmanned aerial vehicles (UAVs) are another component that may be included in HUDNs. UAVs are predicted to be a major element of the next generation wireless networks, allowing for wireless broadcast and high-speed transfers. In comparison to fixed infrastructure communications, UAVs offer flexibility of deployment, robust line-of-sight

(LoS) connection links, and extra levels of design freedom, due to their controlled mobility. UAVs may be used as airborne communications platforms (i.e., as flying base stations/mobile relays) by equipping them with communication transceivers, in order to supply, or improve, communication services to ground-based targets in areas of high traffic demand or overload situations, a practice known as UAV-assisted communications [27,28].

Another essential component that may be included in HUDNs are satellite networks, particularly LEO (Low Earth Orbit) satellites. These are regarded as APs in HUDNs and have altitudes ranging from 500 km to 2000 km, together with orbital plane inclination angles ranging from 0 to 180 degrees (prograde and retrograde orbits). The ultra-dense LEO Satellite access networks (UD-LEO-SatNets) are typically characterized by the capability to deliver services in isolated and remote, or underserved, locations (e.g., suburban and rural areas). In addition, they can improve the performance of limited terrestrial networks in a cost-effective manner. Finally, UD-LEO-SatNets ensure service availability and reliability in any location, especially when it concerns critical communication systems, as well as railway, shipping, or aircraft requirements [29,30].

LED arrays can be used for APs for indoor users, providing another way to connect to the HUDN [31], as Visible Light Communication (VLC) technology provides an effective connection solution for UDNs due to its LoS propagation properties. With VLC, communication and illumination are available at the same time by regulating the intensity of light emitting diodes (LED) [32]. Furthermore, visible light cannot pass through barriers, resulting in a secure communication environment [33].

In heterogeneous ultra-dense networks with network-centric connectivity, interference and traffic imbalances impede the improvement of system performance. Network collaboration has developed into a promising paradigm, incorporating complex strategies capable of greatly improving performance. In this regard, [34] characterizes the cooperative behaviour of small cells by establishing a coalition game-theory framework and then investigating the advantages of cooperation and the gains due to diversity. [35] investigated 5G HUDNs and provided a system architecture comprising core networks and virtualized integrated ground–air–space radio access networks. Reference [36] is a significant work that focuses on interference management for UDNs using dynamic resource allocation. The downlink precoding investigated in [37] overcomes the issue of co- and cross-layer interference of macro users (MUEs) and FUEs and offers a theoretical framework for the deployment of UDNs and heterogeneous networks. As a result of the random deployment of small cells, the mobility of user equipment, and the preference of small cells during selection/reselection, the load across the small cells is unevenly distributed. To solve this issue, the authors of [38] developed a Radio over fibre-based load balancing method within UDN hotspots. Finally, in [39], a joint strategy of SBSs sleep and spectrum allocation is presented, to address the problem of massive power consumption and spectrum resource tension in heterogeneous UDNs.

To summarize, network-centric HUDNs bring the following new issues for 5G and beyond due to heterogeneity and densification:

- Interference between multiple network tiers is exacerbated by network heterogeneity and densification. To counter this, intelligent methods and algorithms for interference cancellation, mitigation, and management must be designed and implemented.
- Network heterogeneity makes network management and planning more challenging, especially with the emergence of airborne BSs like UAVs and satellites.
- The management of connectivity is also complicated by network heterogeneity. Smart connectivity should be considered, so as to intelligently release redundant connections and ensure reliable wireless communications and service continuity.
- The preference of macrocells during selection/reselection, the mobility of users, and the random deployment of small cells, all lead to unevenly distributed traffic load across the small cells.

- The complexity and overhead of network coordination inevitably increase when network densification takes place. In view of this, achieving optimum network coordination and intelligent cooperative BS clustering is of great importance.
- High-frequency bands, such as millimetre-wave and THz bands, will be used to meet the massive spectrum requirements for 5G, and particularly 6G. Hence, the creation of innovative network coordination for multi-RAT multiband HUDNs is of great importance.
- Clearly, continuous network densification and heterogeneity bring issues for mobility management, particularly when considering network-centric UDNs. Although fixed indoor users handle a significant amount of data, cellular networks' ability for mobility and always-on connection are perhaps their most essential characteristics when compared to Wi-Fi. Thus, the implementation of user-centric ultra-dense networks (UUDN), enabling the smooth transition from a network-centric to a totally user-centric connectivity concept without the need for handover, thanks to its cell-free nature, is of great importance in terms of mobility.

2.1.2. User-Centric Connectivity

The distribution of APs in a UDN is particularly complicated because of the dense deployment, together with a possible significant overlap in coverage. As a result, the traditional network-centric (cell-based) connectivity approach will result in difficulties with resource management, severe inter-cell interference, and significant signalling overhead. Furthermore, due to the inconsistent design of the cells, some users will be located in an overlapping region, causing significant interference, while others may be located at the cell border or in an area without service. Such scenarios will have a significant impact on the overall quality of service.

A paradigm-shifting user-centric UDN is proposed in [40] to better leverage the potential capability of UDNs. UUDNs use the de-cellular technique to move the design concept from a cell-centric to a user-centric paradigm which defines an evolution in the UDN concept [41,42]. Each base station in a UUDN becomes an access point, and the network creates an AP group (APG) for each user to ensure reliable access and data transfer (Figure 4). For this reason, the user-centric connectivity concept can be seen as a cell-less structure where the traditional cell unit is replaced by access point groups. In addition, each of the APs which were considered for HUDN deployment could be used in the context of UUDN.

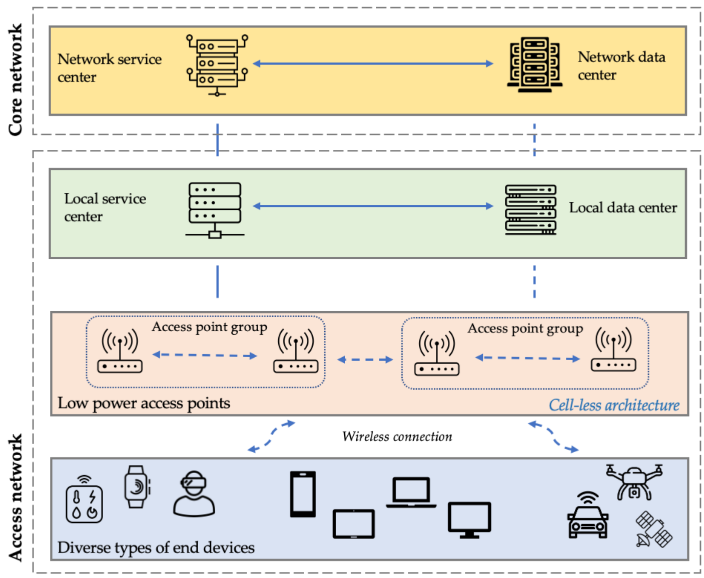

Figure 4. User-centric connectivity architecture.

Several important features of UUDNs can be formulated. Primarily, the UUDN network is capable of recognizing the specific capabilities, requirements and radio environment of the end devices automatically. Moreover, APGs are formed and dynamically updated according to the end devices' requirements and geographical position. In this context, all APs are able to share data and work together in order to enhance energy/spectrum efficiency (EE/SE) and user experience. Finally, network authentication procedures are conducted to ensure high security and privacy levels [40].

A comparison between the traditional network-centric and user-centric solutions is shown in Table 2. It is clear that a user-centric solution has more a dynamic nature and is capable of providing more flexible connectivity options. Moreover, the user-centric approach eliminates the need for handover because the concept of cell creation has been replaced by the dynamic grouping of APs, which constantly monitor the behaviour of EDs. Accordingly, more intelligent cooperation between APs can be implemented, resulting in significant improvement of system performance, resources utilisation and immunity to interference. Finally, as already stated, an asymmetric connectivity is used in HUDNs and UUDNs, due to the different types of APs, point-to-multipoint communications, dynamic access to resources and so on.

Table 2. Comparison between network-centric and user-centric concept.

Aspect	Network-Centric	User-Centric
Network architecture	Network-centric cellular structure	User-centric de-cellular structure
Serving entity	Single serving BS	Dynamic APGs
Mobility management	Handover and terminal involvement	Dynamic grouping of APs without involvement of terminal
Connectivity	Symmetric	Asymmetric
Network sensing	Incapable	Capable
Radio resource management	Independent cell unit	Cooperation, user-centric
Interference management	Independent cell unit	Cooperation, user-centric

In this paper, we consider two important topics and challenges facing the development of UUDNs—clustering/grouping and security/privacy.

1. Clustering and grouping

In essence, UUDN is a cell-free wireless network with an AP density that is equivalent to the user density. To ensure stable connectivity for mobile users and an extremely high level of area throughput, dynamic AP grouping is regarded as a fundamental requirement for these networks. Every user in a UUDN is assigned to a unique dynamic APG and, in theory, is served by a number of APs allocated entirely to that user. As users move, their APG dynamically change to facilitate their movement while preserving connectivity. The APG members' creation and rearrangement will adjust to their needs and their desired services. To this end, the network must first intelligently detect users' wireless communications environments before smoothly organizing the requisite APG and resources to enable extreme, user-centric, spatial resource reuse.

The topic of intelligent AP clustering and grouping in UUDNs has been gaining attention over the last few years. Ref. [43] is a tutorial on user-centric clustering in general, focussing on compelling solutions. A user mobility management strategy for UDNs with UCWA based on dynamic AP grouping is presented in [44,45]. A user-centric dynamic AP grouping (DAPGing) approach in which each UE can design its own APG based on local measurements alone and regardless of other UE's decisions is discussed in [46]. Ref. [47] proposes a maximum data transmission rate oriented Dynamic AP Grouping (MDTR-DAPGing) system. Meanwhile, Refs. [48,49] study a technique in which collaborating APs offer access services for users in a NOMA-based UUDN, with the goal of improving system EE performance. Finally, a unique modularity-based user-centric (MUC) clustering approach for UDNs that relies on a co-designed resource allocation strategy to maximize RB utilization is presented in [50].

From this short overview of AP clustering and grouping, a summary of several significant challenges can be made:

- Resource allocation should be dynamically adapted to APG member changes, with no impact on on-going and new-arrival traffic;
- The distribution of wireless resources and traffic load balance among APGs is a critical challenge, particularly in a high-speed mobile environment;
- Cooperation between APGs and UEs might provide another way for UEs to improve their experience and resource utility.

2. Security and privacy

In UUDNs the APs will be located extremely close to the users, depending on the network architecture, and the users will also be able to install the APs. As a result, ensuring a secure wireless transmission environment is challenging. An attacker could acquire, or duplicate, the APs' digital certificate and the sensitive data stored in them. Following this, the counterfeit APs could illicitly access the UUDN, potentially compromising its security. In addition, the APG's dynamic transformation will pose other security risks to the UUDN. The APs attached to the network will communicate with each other, rendering self-healing, self-optimization, and self-configuration difficult.

There are several publications looking at security and privacy optimization in UUDNs. Ref. [51] examines secure UDNs in relation to their user-centric clustering from a secrecy and energy efficiency standpoint. Ref. [52] summarizes the security aspects of UUDNs' architecture, while also discussing the problems and needs associated with the UUDN's security concerns. Finally, a novel lightweight batch authentication and key agreement (LBAKA) strategy for user-centric UDN scenarios, which also utilizes mutual authentication and one-to-one key agreement to check the communication's trustworthiness on both sides is proposed in [53].

In terms of UUDN security several significant challenges can be summarized:

- Any AP which is becoming a member of a particular APG requires authentication from the network, to ensure that it is not counterfeit. To achieve this, the UUDN must furnish UE and all members of the APG with security guarantees using novel mechanisms.
- A method to more flexibly authenticate is required whenever the APG is refreshed.
- An enhanced key agreement mechanism should be considered to keep UE and all other APG members secure, using a "shared" or inherited key seed.
- The security model selected for UUDN must balance authentication efficiency, communication quality, and computing costs.

2.2. Network Access

In this section the most prominent network access-related technologies are considered in order to clarify their role in the development of UDNs.

2.2.1. Massive MIMO-Based Access

Massive MIMO-capable BSs will contain many hundreds, or even thousands, of antennae. This may be regarded as one means of spatially densifying the network, as projected by 5G use cases. Massive MIMO (alternatively called large-scale antennae systems, very-large MIMO, or HyperMIMO) denotes systems which employ substantial numbers of service antennae across active terminals, and function in the time-division duplex mode using more antennae focussing energy into ever-smaller sectors of space [54]. A larger number of users is able to be supplied by any given resource unit of a particular BS, resulting in significant benefits. Massive MIMO, in comparison to standard MIMO, can deliver ultra-high reliability, enhanced throughput and radiated EE, resilience to deliberate interference, together with decreased latency, by utilising less sophisticated signal processing algorithms with low-cost and low-power components [55].

Massive MIMO technology lends itself to being coupled with UDNs to combat issues of interference and load imbalance. This combination does, however, require the creation of effective management strategies. Among the most significant advantages of Massive-MIMO integration in UDNs are:

- Massive MIMO can easily improve energy efficiency and spectrum efficiency using relatively simple (linear) processing;
- Computationally, because massive MIMO systems are based on a phase-coherent technique, signal processing at the base stations, using all the antennae, is very simple;
- Massive MIMO systems bring substantial capacity increases (of the order of 10 times) due to the aggressive spatial multiplexing used;
- Massive MIMO systems are able to reduce latency dramatically, particularly when beamforming is applied.

2.2.2. High Frequency-Based Access

Since many of the present-day wireless communications systems rely on spectrum scarcity in the 300 MHz to 3 GHz frequency range, mmWave communication is seen as the better option. The 6 to 100 GHz frequency band may give orders of magnitude more spectrum than existing cellular spectrum allocations, allowing for the use of beamforming and spatial multiplexing with a large number of antennas [56]. Thanks to directional antennas, the networks should have more bandwidth, greater isolation, and better coexistence [57]. Although the shift in frequency bands has received much attention, there are many issues, such as high mmWave frequency penetration loss, the link quality and channel condition being highly volatile, together with the severity of cross-link interference [56].

MmWave networks comprise BSs which are transmitting and receiving in the mmWave band, covering particular geographical areas. To guarantee that coverage is adequate, densely deployed mmWave BSs are needed. mmWaves can easily be integrated into UDNs, due to their ultra-dense architecture. However, backhauling a dense mm Waves network can be expensive, due to the number of required BSs. This suggests that some of the mmWave BSs could be connected to the backhaul through other BSs [58].

2.2.3. Flexible RANs

Cloud Radio Access Network (CRAN) comprises an architecture which incorporates cloud technology with cellular systems' radio access networks. Baseband processing operations in CRAN are performed in a centralised BBU pool or central cloud [59]. As a result, the base stations are simplified to basic Radio Remote Heads (RRHs). Fronthaul lines connect the multiple RRHs to the central cloud. The transport network provides communication between the central cloud and the network's core. The RRH and central cloud connection is specified as optical fibre fronthaul in CRAN's initial proposal.

CRAN offers a number of benefits, ranging from simpler BSs to cloud-based processing. In the same way as today's IT cloud computing, cloud operation leads to more resource effective exploitation of available resources. CRAN also allows for the separation of processing and transmission, permitting the use of data plane cooperation methods such as CoMP [59]. A novel attractive network design, termed ultra-dense CRAN, is developed via the dense deployment of the available RRHs in CRANs. Because of the centralization of resource allocation and collaborative signal processing across the RRHs, ultra-dense CRANs may considerably enhance not only spectrum efficiency (SE) but also energy efficiency in comparison to standard cellular networks. Furthermore, in ultra-dense CRANs, mmWave wireless fronthaul might be used for information interchange between the central CPU and the distributed RRHs, lowering costs and increasing deployment flexibility [60].

The benefits of fog computing are proposed to be included in ultra-dense Fog RANs (FRAN) to reduce the constraints of CRAN, which include capacity restricted fronthaul, latency, and high load at the central cloud. In ultra-dense FRAN, a massive number of edge devices, such as RRHs and UEs may be employed for local signal processing, cooperative radio resource management, and content storage, as well as to the central cloud of CRAN. Generally, fog computing is a model for leveraging edge devices for computing and storage that helps to offset the fronthaul and central cloud heavy constraints in CRAN [61].

2.2.4. Machine-Type Communication-Based Access

Massive device connectivity has become one of the hurdles for the IoT to overcome so as to facilitate the growing use of billions of smart gadgets. Meanwhile, a broad variety of high efficiency communication infrastructures, including human-to-human (H2H), human-to-machine (H2M), machine-to-human (M2H), and machine-to-machine (M2M) communications, should be included to deliver ubiquitous IoT services [20]. Simultaneously, future use cases will include smart buildings, smart agriculture, industrial automation, and auto-drive robot interaction, with the network expanding to a large IoT ecosystem. With the help of several new technologies and techniques, such as artificial intelligence (AI), cloud computing, and information sensing [21], it is expected that massive IoT will become a worldwide network of interconnected systems, enabling a wide range of data collection, exchange, and decisions, while also making measurement and management more efficient [21].

With the rise of smartphones and tablets, proximity-based communication that can handle the flow of data has gained a lot of traction. To allow proximity-based communication, D2D-enabled users may communicate data directly without passing via BSs or the main network. A new network structure known as an ultra-dense D2D network has come about as a result of the large number of D2D-enabled users, with consumers benefitting from improved SE and EE, and reductions in communication time, network load, and power consumption [22].

3. Specific UDN-Related KPIs

In UDN planning and deployment, the design of KPIs can be used for a great variety of tasks, such as:

- Monitoring and optimization of the performance of the UDN, so as to ensure a better service quality for end users or to achieve better utilisation of already installed network resources;
- Instant detection of non-acceptable performance-related issues in the UDN. This enables the operator, or the network itself, to react rapidly, so as to maintain the quality of existing network services;
- To provide radio frequency planners with detailed information. This will help them configure the network parameters in order to enhance UDN performance and capacity.

In this section we define the most important KPIs which must be considered when designing UDNs. Additionally, a review of available research is performed to suggest ways to evaluate and improve the values of the indicators. We attempt to answer several questions, such as "Why is a particular KPI important in the context of UDNs?" and "How can particular KPIs be controlled within acceptable limits?". We exclude a few KPIs from the list, such as *area traffic capacity*, *data rate* and *throughput*, because they are directly dependent on other factors which are evaluated by the KPIs presented in this article. For example, the traffic capacity of a UDN and other capacity-related metrics can be enhanced when densification gain and Signal-to-Interference-plus-Noise Ratio (SINR) are optimized. Conversely, more intelligent spectrum utilization (improvement of spectrum efficiency) can lead to significant improvement in data rate and throughput.

3.1. Energy and Spectrum Efficiency

The ratio between the total number of received packets in a destination node and the energy consumed by a communication network to transport these packets is known in communications as **energy efficiency**. The BSs (or APs) consume a significant amount of energy in these networks, resulting in a high power cost. Consequently, maximizing EE offers considerable economic and environmental advantages, particularly in UDNs. The EE KPI can be designed with a focus on three distinct areas: component level, node level and network level. In this article we primarily look at EE at the network level.

The adoption of ultra-dense networks brings with it a number of problems, including the significant energy needs within the networks, and network management concerns. Many attempts to address these issues have been documented in the literature, with an emphasis on the various stages of network implementation and operation. However, due to the complications that come with evolving technology in wireless mobile networks, these solution techniques may become less optimal at some time. The authors of [62] suggest that the existing research on UDNs should focus mainly on system throughput while ignoring energy efficiency. Ref. [63] outlines the essential criteria used to characterize EE performance in HUDNs. Component-level metrics, equipment/node-level metrics, and system/network-level metrics are all bundled together in [64]. The component level metric measures the performance of specific wireless communications equipment such as power supply, power amplifier, and antennae [65]. Equipment level metrics serve to assess the operation of network nodes such as UEs and BSs, and network level metrics assess network access node performance in terms of coverage area and desired QoS [66].

The key to getting high EE in cellular networks is network densification, which can be accomplished by having several BSs or multiple antennas per BS. In this context, the authors of [67] propose a novel bidirectional distributed antenna system with hybrid duplexing, which is characterized by high energy efficiency and low power consumption. Seeking to determine the optimal configuration for a densified network, the authors of [68] formulate a UL EE maximization problem assuming a Poisson point process-based stochastic BS deployment. Because wireless traffic is non-uniform in both the geographical and the temporal domains, *sleep mode techniques* can considerably lower the power consumption of mobile networks by the selective switching into sleep mode of either the base stations or their transceivers. The energy efficiency issue in UDNs is addressed in [69] by proposing a technique to enable small-cell BS awake/sleep mode scheduling to be as efficient as possible. Ref. [70] proposes a genetic algorithm-based centralized dynamic sleep approach for system network cluster management of high-density and large-scale base station groups. Ref. [71] assesses how adaptive baseband unit sharing and small cell on/off can benefit UDNs with centralized/cloud radio access network architecture in regards to energy savings and throughput.

Another approach to improve EE is *power control*. In [72], an ultra-dense UAV network communication downlink power management model is suggested, which will optimize the EE by learning the best power control policy. A power management model is investigated in [73], this time focused on the power control of uplink connections in user-centric ultra-dense HetNets. A unique strategy for combining power control and user scheduling for optimizing energy efficiency in ultra-dense small cell networks in terms of bits per unit power is suggested in [74]. Power control with the goal of interference management in ultra-dense small cell networks is investigated in [75], designed to optimize the sum-rate of all small cells while maintaining tolerable interference for macrocell users.

Throughout every wireless standard, **spectrum efficiency** is an essential element. Any mobile operator's spectrum is restricted in comparison to the increasing capacity that will occur in next-generation wireless networks. A centralized radio network controller traditionally assigns spectrum bands to BSs and UEs. The average number of transmitted bits per second per unit bandwidth defines the spectrum efficiency. Due to the scarcity of spectrum and the high data rate demands, spectrum efficiency is a critical performance indicator in next-generation networks, especially in UDNs. Another way to quantify the performance of a single cell is to use the cell spectrum efficiency metric.

The authors of [76] are the first to use stochastic geometry methods to analyse the spectrum efficiency of densely distributed small cell networks in the downlink. They concentrate on network spectrum efficiency, which is defined as the average aggregate spectrum efficiency per cell, rather than the traditional user-centric link-level spectrum efficiency study. Through the production of 3D interference heat maps, [77] offers an experimental analysis of indoor spectrum occupancy and interference for two prominent wireless technologies for IoT in the unlicensed bands—LoRa and Wi-Fi. Denser networks bring additional issues for flexible and efficient spectrum utilization, particularly when small cells belonging to several networks or operators are deployed in large numbers in the same geographic region. In this regard, [78] proposes a co-primary spectrum sharing technique for multiple operator networks in local area denser deployment.

In ultra-dense networks the EE and SE must be considered as a whole and must be maximized together. To this end, ref. [79] proposes a weighted utility function that takes spectrum, energy, and cost efficiency into account as a benchmark, following which a generic Nash-product form of utility function is defined. Ref. [80] offers a balanced coefficient-related adjustable utility function and a unique bargaining cooperative game framework to examine the possible cooperation advantages to achieve both efficiency and fairness in a unified model, in order to solve the trade-off between SE and EE. Ref. [81] investigates the realistic situation of randomly dispersed femtocell APs (FAPs) in heterogeneous networks and presents a clustering strategy paired with an active FAP selection algorithm to improve spectrum and energy efficiency without manual configuration. Finally, ref. [82] proposes an analytical assessment of the area spectrum efficiency (ASE) and energy efficiency of downlink wireless systems utilizing stochastic geometry theory by modelling the base stations from both macro-cells and small-cells as a homogeneous Poisson Point Process (PPP).

3.2. Coverage and Outage Probabilities

Signal propagation in UDNs becomes significantly more difficult as short-range transmission becomes the norm. Additionally, compared to sparse networks, the interference in a UDN is more unpredictable and difficult to control, due to the dense and unplanned deployment of network infrastructures and users. Because of this, it is unlikely that network densification will have the positive effects that were anticipated, and it is therefore questionable whether network performance can continue to be improved in upcoming UDNs. Characterizing the interference features in a UDN, looking at how interference affects system performance, and, most importantly, looking at effective interference management are all necessary to reap the full rewards of network densification. Furthermore, the use of SINR-based metrics for interference measurement is of great interest. These metrics should be adapted to the applications/services which are used as well as to the particular environment which is available.

As previously mentioned in Section 1, the coverage and outage probabilities are among the main characteristics of UDNs. They are directly associated with SINR. Overall, SINR is a measure of signal quality, focused on the influence of the interference. It can be defined as the ratio of the wanted signal strength to the unwanted interference plus noise levels. In this context, the *coverage probability* is defined as the likelihood that a randomly picked user's SINR is greater than a particular threshold, i.e., the link quality is sufficient for a successful connection. The coverage probability is also known as the success probability and can be defined as:

$$P_{cov}(\tau) = \mathbb{P}\{SINR > \tau\}, \quad (1)$$

where τ is the SINR threshold, or the SINR at which the transmitted signal of an ED can be properly decoded at the BS, hence delivering a predetermined degree of QoS [5].

The *outage probability*, also known as the SINR distribution, is the probability that an arbitrary user's SINR does not exceed the threshold τ introduced above. If the SINR of the link to the serving BS is insufficient for a successful connection, the user is deemed out of service. Finally, the quality of the connection between the user and the serving BS is quantified by the coverage probability, outage probability, and SINR distribution. The first two of these can be controlled and optimised in UDNs, especially when UUDN is considered, since the APs are located very close to the users and they also adapt their operation in order to enhance overall network performance. However, the SINR is a very crucial metric in UDNs. In these networks there are many factors that can affect the SINR, such as the number of EDs, high number of APs, different moving speeds, and different cell ranges (when HUDNs are considered).

Two significant effects of applying a high amount of densification should be mentioned concerning interference. First, an increase in the number of network interference sources for an ED can occur, because the densification of BSs causes a decrease in the link distance between the BSs that are interfering and the ED. This also raises the possibility of a network having an LoS interfering link. Therefore, compared to traditional sparse cellular networks, interference from these nodes is greater in a dense network. Additionally, in a multi-tier network the inter-cell interference is caused by BSs from several tiers (i.e., BSs with differing heights of antennas and powers of transmission). Or put another way, depending on the densification of the BS, the interference received varies according to the tier of the interfering BS. The second effect refers to the fact that the changes in the interfering node set occur frequently because there are more different BSs and EDs with irregular traffic patterns, and a number of BSs may have no associated EDs, i.e., no data to transmit. In contrast to traditional networks, the BS changeover might occur more frequently. The set of interfering BSs can vary more often over time, due to the network's increased dynamism.

Available IM approaches can often be split into three categories, based on how interference is reduced: interference avoidance, interference cancellation, and interference coordination [83]. A full interaction between the network environment and IM should exist in a UDN. In particular, interference avoidance/cancellation/coordination should be chosen and switched dynamically in accordance with the changing levels of interference and distribution, and the IM functions should quickly follow and match the features of interference in the UDN. The majority of existing communications infrastructures fall short of the aforementioned requirements because they lack distinct entities to carry out IM operations. In light of this, the authors of [83] suggest a concept for an IM entity for a UDN that may be integrated into various system topologies. It can be incorporated into the evolved NodeB (eNodeB) in LTE architecture or the centralized controller in a cloud radio access network (C-RAN) architecture.

3.3. Mobility and Mobility Interruption Time

Mobility defines how the wireless system performs when EDs travel at a stipulated speed in km/h. Put another way, the wireless system when moving at a specified speed must meet the needs of the voice or data calls taking place. Clearly, the continuing densification of networks and increasing heterogeneity pose challenges in supporting mobility. Although a substantial portion of data is used by users who are stationary indoors, always-on connectivity and mobility support are perhaps the most crucial features of cellular networks compared to Wi-Fi. The mobility interruption time could be defined as the time duration during which a user device cannot exchange user plane packets with any base station.

There are several papers considering the topic of mobility and its importance in UDN deployment. Ref. [84] proposes a spatial-domain scheduler that adapts to users' movements and coordinates decisions over a coordination region made up of many access-nodes. In [85], the challenge of mobility robustness in a single connection is articulated, with an emphasis on reducing mobility failures and events that cause service disruptions.

The authors of [86] offer two effective localised mobility management techniques that take into account small cell deployments and backhaul topology, based on newly suggested network architectures for UDN. Ref. [87] is another research paper that looks at mobility management in ultra-dense networks and proposes two intelligent handover skipping approaches to lower the rate at which a user switches. Tractable mobility presents a multi connectivity approach with CP/UP split architecture in a 5G UUDN environment to improve mobility performance for mobile users in congested networks.

3.4. Fairness of Resource Allocation

In a wireless network, fairness is connected to the quantity of throughput that may be achieved. Fairness and prioritization considerations are crucial during the resource allocation (RA) process. Instead of focusing on the overall performance of the system or the average level of performance, fair RA schemes make sure that each AP and user receives an equitable part of the resources.

In UDNs, an intelligent management technique is necessary to prevent a user with a favourable channel monopolising the whole radio resource and to guarantee that each user in the network receives at least a minimal amount of radio resource. When small cells are deployed inside macrocell networks, the efficiency of radio resource sharing improves as well. Furthermore, in such a network effective radio resource sharing is critical.

After being scheduled with their respective cell or AP, the fairness indicator defines the allocation of resource quantity across the users. The fairness index α is calculated as follows:

$$\alpha = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{\mathrm{N}\sum_{n=1}^{N} {r_n}^2}\ , \qquad (2)$$

where N denotes the total number of users and r_n gives user rate [88].

Proportional Fair (PF) schedulers' network performance is investigated in [88]. Because the more sophisticated channel-dependent PF scheduling in UDNs provides only a marginal benefit, it is advisable to use less complicated scheduling methods, such as the Round Robin (RR) scheduler to simplify the RRM and minimise network complexity. Several scheduler types at various densification levels, as well as some key network densification considerations are examined in [89]. The closer the UE is to its serving BS, the lower the path loss; nevertheless, the greater the LoS, the lower the multi-user diversity. In [90], resource allocation challenges in ultra-dense MEC-enabled IoT networks with NOMA are proposed to increase fairness and resource efficiency for IoT users.

3.5. End-to-End Latency

The end-to-end (E2E) latency is defined as the time it takes for a particular piece of information to be transferred from a source to a destination, as measured at the communication interface, from the time it is sent by the source to the time it is successfully received at the destination. Another name for this is one trip time (OTT) latency. Another latency metric is round-trip time (RTT), which refers to the time it takes for a data packet to go from the broadcasting end to the receiving end and for acknowledgements to be received.

Delay and latency are proportional to the SINR-determined data rate, which is heavily influenced by inter-node distance. The received strength for the desired signal is determined by the distance between transmitter and receiver in the desired connection. Furthermore, ultra-dense networks are in reality interference-limited, meaning that noise is small relative to interference, making interference a major factor affecting SINR and latency. It is worth noting that the total interference power is proportional to the distance between the interfering transmitters and the target receiver.

Latency is an important QoS indication when there are UAV based access nodes in the UDN. The primary problem with ultra-dense UAV based communication systems is the demand for extremely low latency. Consequently, in [91], the authors aim to lower the overall latency of the system by manipulating the UAVs' 3D location. It turns out that the delay may be reduced in two ways: improving the content-cache-hit-rate by characterising the popularity dynamics of the material, and increasing the backhaul capacity to minimise the delay by minimising inter-UAV interference with flight control. Ref. [92] discusses the interacting queues issue after reviewing the handling of delay in conventional queueing theory.

3.6. Security, Privacy and Reliability-Related Indicators

Network reliability comprises a variety of issues relating to the design and analysis of networks which are subject to random component failure. It is associated with a maximum latency requirement and relates to the continuity of accurate service across time. Reliability especially considers the proportion of packets that are correctly received inside the specified maximum E2E latency dependent on the service. Dynamic simulations are required for their evaluation, and realistic traffic models are recommended. Reliability can be quantified in terms of mean times between failure (MTBF) [93].

There are also two other KPIs which are very close in meaning to network reliability, namely network availability and network retainability. The first KPI represents the amount of time the UDN is in a condition to deliver services, divided by the amount of time it is expected to deliver services in a specific area. The second one is defined as the percentage of time where transmissions meet the target experienced user throughput or reliability. In the context of UDNs these three KPIs can be easily improved by (i) enhancement of the reliability of individual nodes—EDs and APs; (ii) increase in the number of alternative paths available (e.g., usage of a higher number of nodes); (iii) applying intelligent APG creation mechanisms; (iv) enhancing overall network intelligence.

Because of the high density of APs and UEs, which allows for unprecedented information exchange, security and privacy will also become important to the future of UDN development. Similarly, the constrained energy supply in UE devices because of data processing, data roaming, and other tasks opens up new security and privacy concerns that must be considered. Likewise, every time a user connects to an AP in a UUDN, the user and the AP negotiate an information exchange relating to authentication. This communication occurs between users and APGs, as well as between an APG and new AP members of that group, in contrast to conventional networks. Due to the dynamic changing of AP clusters by users in UDNs, this data transmission occurs significantly more often and hence has a large volume [12].

Compared with traditional base stations, in UDNs the AP covers a smaller area. However, the UE and APs will interact more frequently whenever the UE moves. The existing 4G Authentication and Key Agreement algorithm (AKA) is not able to keep pace with such fast-paced requirements for authentication. The problem would be solved should the UE move fluidly within an AP's trusted group, where frequent authentication is not needed. To this end, the authors of [94] propose a security authentication scheme of 5G UDN based on block chaining technologies. Furthermore, the algorithm used is based on block chaining technology with Byzantine Fault Tolerance (BFT). The same authors also propose a new security scheme using an implicit certificate based on the analysis of the security challenge of the UDN [95].

Due to the open nature of wireless channels, transmissions within a UDN are expected to be susceptible to eavesdropping and attacks involving jamming. Anti-jamming communication for ultra-dense networks in unknown and dynamic environments is addressed in [96]. An anti-jamming algorithm based on deep reinforcement learning is proposed which exploits frequency-hopping technology to counter a jamming attack without the need to estimate the mode or parameters of the attack. For secure spectrum-sharing in ultra-dense IoTs, in [97], the authors model the multi-agent anti-jamming decision-making problem as a quality of service constrained Markov game. A new approach aimed at achieving especially robust privacy and security in ultra-dense 5G Distributed RANs

(DRANs) is given in [98]. Combining a centralized Software-Defined Network (SDN) control-plane with deterministic scheduling, this has several advantages in improving performance and security in 5G DRANs.

To date, the following indicators that have the potential to be significant KPIs for UDNs have not been extensively discussed in the literature.

3.7. Densification-Related Indicators

An important densification-related metric, which can be used in diverse types of KPIs is the *densification ratio*. This is defined as the ratio of the number of APs (or BSs) λ_{AN} to the number of end devices (or UEs) λ_{UE}. The densification ratio can be used to distinguish between traditional, sparse infrastructure installations with small densification ratios (usually <1) and ultra-dense infrastructure deployments with densification ratios that often surpass 1. The densification ratio has a major influence on future communication network design since it might suggest unreasonably high densification ratios when excessively high-end devices/UE rates are desired. As a result, there is a practical limit to the advantages of ultra-densification in this regard, which can only be exceeded by other methods such as usage of more spectrum resources and multiple-antenna transmission.

In order to determine the benefits of network densification a densification gain KPI is proposed in the literature. This quantifies the obtainable rates corresponding to the cost of BSs' densities. This metric is defined as follows:

$$\rho(\lambda_1, \lambda_2) = \frac{(R_2 - R_1)/R_1}{(\lambda_2 - \lambda_1)/\lambda_1}, \quad (3)$$

where R_1 is the rate corresponding to a BS density, denoted by λ_1, while R_2 is the rate if the density is increased to λ_2 [25]. In this context, this measure quantifies the payoff ratio in terms of rate relative to the cost ratio in terms of BS density. We may confidently assume that $\rho > 0$ in UDNs. Furthermore, with macro-BS muting considered, ρ rises significantly and can reach a value of 1 both empirically and theoretically, leading to interference minimization. When mmWave frequencies are employed, very high densification gains (greater than 1) may be attainable [19]. Since transmission at these frequencies is often noise-limited, the combination of UDN and high frequency signals has the potential to considerably increase SINR. In general, analysing and optimizing the densification process in a variety of deployment scenarios and network types is a critical area for continued ultra-dense network research.

3.8. Level of Network Complexity and Level of Network Intelligence

As already discussed, UDNs are a fusion of different types of APs and technologies which greatly increase *the network complexity*, especially in the context of dynamic network topology optimisation, and mobility and resource management. Unfortunately, there is no commonly agreed definition of complexity, despite it being a frequently used parameter in network design. There are many research articles that discuss complexity metrics; however, most of them focus on just one feature of a network, such as the complexity of a hardware or software component.

In general, the level of UDN complexity is difficult to determine. The complexity KPI must examine a broad variety of technical characteristics. Various KPIs will be used by different components of the communication network to measure this complexity in UDNs. As a result, direct comparison is not possible. Moreover, the complexity can be measured in terms of the physical network (hardware), the algorithms that run on the network elements, the operational states, etc. Moreover, complexity can be measured based on network configuration, troubleshooting, monitoring and system integration. To address this, one possible way to examine UDN complexity is to break the entire network into many subnetworks. The complexity can then be computed based on the size and number of the subnetworks. Furthermore, another type of complexity—*computational complexity*, becomes an important factor when, for example, resource allocation in UDNs is applied as network densification becomes an unavoidable trend. The RA process also can be divided into different sub-problems or carried out in distributed fashion by using techniques such as stochastic optimization and grouping/clustering methods, graph theory, game theory, convex optimization, stochastic geometry methods, all of which greatly reduce the computational complexity. Finally, in many cases, cost is the most significant feature to consider when evaluating complexity. *Cost KPI* is defined as the resources, such as labour, materials or time, which must be expended to accomplish a certain objective.

Modern intelligent techniques are being used to provide a new approach to address the more complex challenges in next-generation networks, making the network more intelligent and autonomous. Unfortunately, the industry has yet to agree on a single definition of an intelligent mobile network, as well as how to assess its intelligence. In general, the intelligent network may install, configure, and optimise itself to reach goal KPIs based on the network operators' goals, as well as automatically prevent or resolve anomalous occurrences to protect the network's security and stability. In ultra-dense networks, intelligence will play a significant role, extending beyond the classification and prediction tasks that are being studied for 5G systems. When considering user-centric network structure, a high intelligence level is of great importance. End terminals or whole APGs should be able to make autonomous network selections based on the results of prior operations, thus eliminating the need for contact with centralised controllers. Machine learning algorithms may be processed in real time, with a latency of less than one millisecond, as needed by various services, resulting in more responsive network management. To this end, the authors of [99] are the first to introduce a new intelligent learning mechanism via imitation, which assists a user to select the serving BS faster by exploiting their local data and the neighbouring users' learning outcomes. Using this mechanism, rather than exchanging all the users' local data, only the outcomes of the learning algorithms are transmitted. Moreover, the efficiency of swarm intelligence approaches in optimizing dense drone BS deployment is studied in [100]. Obviously, more work needs to be carried out in order to better define the level of intelligence of UDNs considering specific use cases and applications.

3.9. AP Grouping Efficiency (UUDN-Related Metric)

In UUDNs, densely deployed APs in a given area can be dynamically grouped into a "following big AP" which follows users' movements and provides on-demand joint data transmission. As already mentioned in Section 2, the dynamic AP grouping method—DAPGing is proposed as the core function of UUDN, so each registered AP in a UUDN is served by an APG with its own APG-identity (APG-ID); the APG member is then updated adaptively, in accordance with the UE's movement. In this way, the key component of the DAPGing approach is to determine which APs serve which UEs; this is named APG formation. Hence, the way in which an APG is formed can significantly affect the performance of boundary UEs, and this is one of the chief performance metrics which the DAPGing method is aimed at improving.

In this context, a new KPI which can help the evaluation of the DAPGing process must be considered. We define it as AP grouping efficiency. This is a UUDN-related metric and it can be improved if the process of AP grouping results in enhancement of other important KPIs—user throughput, data rate, latency, signal quality-related indicator (such as SINR) at al. DAPGing is also closely related to the network complexity metrics. Here, a trade-off should be considered between the AP grouping efficiency and level of network complexity KPIs to maintain the excellent performance of the entire UDN.

4. Conclusions

This paper provides a survey of the principal types of ultra-dense networks, focusing on user-centric and network-centric connectivity architectures. In addition, most prominent network access-related technologies are outlined to clarify their role in the development of UDNs. Finally, the most important KPIs which must be considered when designing UDNs are defined and discussed. It is clear that research into UDNs, especially in the context of KPIs, is still in its infancy. Numerous novel and already existing categories of KPIs should be designed or redesigned and adapted to take into account the specifics of UDNs—the very high density of EDs and APs, distance between different types of nodes resulting in high connection density, increased traffic volume, etc. We also summarize the diverse types of devices which can be incorporated into different UDN architectures. It transpires that ultra-dense access networks can also be designed by using uniform types of APs, especially when UUDN is considered. Conversely, UDNs can be seen as the evolution of already existing 4G and 5G networks which can be easily transformed in HUDN with multiple types of APs, from low power femtocells, battery-enabled UAVs, and high coverage macrocells. As a result, a UDN can be designed as a mobile network since the greatest impact of these networks in terms of network performance is observed when high mobility scenarios are considered with different radio environment characteristics of EDs. This in turn leads to the conclusion that any mobile network can evolve into a UDN if this is necessary as a result of very high traffic demands or excessive user densities.

As we have already mentioned in this paper, UDNs can be viewed as complex networks with a very high density of nodes, end devices and access points, and asymmetric connectivity. On the other hand, from a network architectural modelling point of view, especially with UUDNs, it is very likely that such networks will be characterized by a high probability of symmetry in the positions and distributions of the ANs in the network. In this case such symmetry could be utilized for efficient AP grouping and efficient power and interference management for network performance enhancement.

In addition to the proposed taxonomy and KPIs overview, there is still more research to be carried out on the different features of ultra-dense networks that have been described in the present paper. Additionally, the development of accurate metrics for the assessment of UDNs may be a topic for future research. Understanding the individual effects of the basic parameters in UDNs, specifically the AP density, the number of antennas per BS, the transmission power, and the idle mode capabilities, is crucial to achieve trade-offs between various performance metrics, such as spectral efficiency, energy efficiency, SINR and a variety of densification-related indicators.

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