# Ultra-Dense Networks: A Survey

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***Abstract*—The exponential growth and availability of data in all forms is the main booster to the continuing evolution in the communications industry. The popularization of traffic-intensive applications including high definition video, 3-D visualization, augmented reality, wearable devices, and cloud computing defines a new era of mobile communications. The immense amount of traffic generated by today's customers requires a paradigm shift in all aspects of mobile networks. Ultradense network (UDN) is one of the leading ideas in this racetrack. In UDNs, the access nodes and/or the number of communication links per unit area are densified. In this paper, we provide a survey-style introduction to dense small cell networks. Moreover, we summarize and compare some of the recent achievements and research findings. We discuss the modeling techniques and the performance metrics widely used to model problems in UDN. Also, we present the enabling technologies for network densification in order to understand the state-of-the-art. We consider many research directions in this survey, namely, user association, interference management, energy efficiency, spectrum sharing, resource management, scheduling, backhauling, propagation modeling, and the economics of UDN deployment. Finally, we discuss the challenges and open problems to the researchers in the field or newcomers who aim to conduct research in this interesting and active area of research.**

***Index Terms*—UDN, network densification, small cells, cloud-RAN, DAS, D2D, IoT, massive-MIMO, mmWaves, 5G.**

## I. Introduction

THE EVOLUTION of mobile devices and applications in the current decade have drawn a new picture for wireless networks [1]. Where the concept of Ultra-Dense Network (UDN) represents a new paradigm shift in future networks [2]–[4]. The basic idea is to get the access nodes as close as possible to the end users. The realization of this is simply done by the dense deployment of small cells in the hotspots where immense traffic is generated. These small cells are access nodes with small transmission power, and hence, a small coverage. As illustrated in Figure 1, the cells are deployed by the customers in their premises, or by the operators in the streets (e.g., on lampposts, trees, and walls) and hotspots (e.g., airports, metro/train stations, and markets).

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TABLE I
List of Acronyms

| | |
|---|---|
| AE | Antenna Element |
| ASE | Area Spectral Efficiency |
| BBU | Base Band Unit |
| BPP | Binomial Point Process |
| BS | Base Station |
| CDMA | Code-Division Multiple Access |
| CoMP | Coordinated MultiPoint |
| CSG | Closed Subscriber Group |
| CSI | Channel State Information |
| D2D | Device-to-Device |
| DAS | Distributed Antenna System |
| DC | Dual Connectivity |
| DSL | Digital Subscriber Line |
| HetNet | Heterogeneous Networks |
| HCPP | Hard Core Point Process |
| IoT | Internet of Things |
| KPI | Key Performance Indicator |
| LOS | Line-Of-Sight |
| LTE | Long-Term Evolution |
| MFG | Mean-Field Game |
| M2M | Machine-to-Machine |
| MIMO | Multiple-Input Multiple-Output |
| mmWaves | millimeter Waves |
| MTC | Machine-Type Communication |
| OFDMA | Orthogonal Frequency-Division Multiple Access |
| ONF | Open Networking Foundation |
| PCP | Poisson Cluster Process |
| PPP | Poisson Point Process |
| QoS | Quality of Service |
| QoE | Quality of Experience |
| RAN | Radio Access Network |
| RAT | Radio Access Technology |
| RE | Range Expansion |
| RRH | Remote Radio Head |
| RRM | Radio Resource Management |
| RSS | Received Signal Strength |
| SDN | Software-Defined Network |
| SDWN | Software-Defined Wireless Network |
| SINR | Signal to Interference-plus-Noise Ratio |
| TDD | Time-Division Duplex |
| UDN | Ultra-Dense Network |

Thus, UDN deployment scenarios introduce a different coverage environment where any given user would be in close proximity to many cells.

The densification of wireless networks is motivated by the traffic trends measured in the current decade. For instance, Cisco, in the Cisco Virtual Networking Index, predicts a 10 fold increase in the mobile data worldwide for the period 2014-2019 [5]. With the scarce spectrum resources, one vital and long-term solution is to increase the reuse per unit area of the existing spectrum. This spectrum reuse is a two fold gain; the spectrum is increasingly reused, which significantly

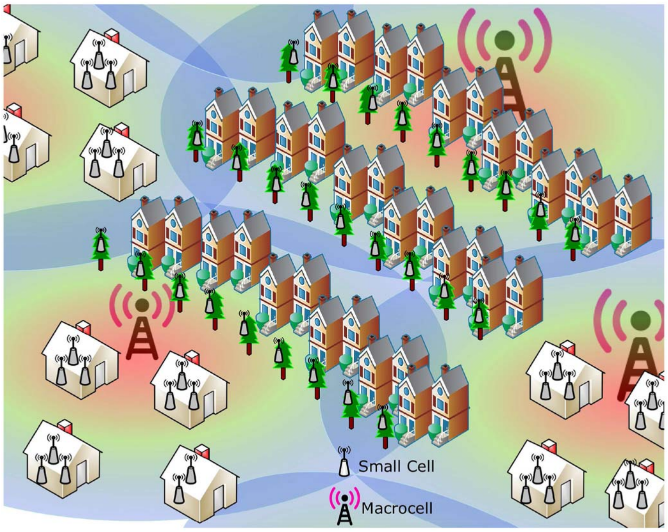


Fig. 1. The network is densified by deploying small cells indoors in buildings and stores, and outdoors on trees, lampposts, and building walls. Small cell networks coexist with macrocells, either in the same spectrum or on a dedicated carrier.

improves the network capacity, and the link to the end user becomes shorter which improves the link quality.

Obviously, the network densification cannot continue endlessly. There would be a fundamental limit for network densification which requires extensive research for realistic system models to capture the reality of dense networks. Andrews *et al.* [6] addressed the question of what are the fundamental limits of network densification. However, some idealizations of the model need further investigations for a complete understanding of these fundamental limits.

### A. State-of-the-Art and Contributions

To the best of our knowledge, this survey is the first to address the ultra-dense network research status in different disciplines. López-Pérez *et al.* [7] conduct extensive simulations to highlight the gains of three paradigm concepts, namely, network densification, exploiting high frequency bands, and the development of high spectrum efficiency techniques on the network throughput, energy efficiency, and signal-to-interference-plus-noise ratio (SINR) distributions. Moreover, they develop a common understanding of the network densification without emphasis on reviewing the research status of this paradigm shift. On the other hand, Liu *et al.* [8] consider reviewing the state-of-the-art of user association in different scopes, specifically Heterogeneous Networks (HetNets), massive multiple-input multiple-output (massive-MIMO) networks, millimeter waves (mmWaves) networks, and energy harvesting networks [9]. Finally, Gotsis *et al.* [10] give a general overview of UDN without explicit definition of ultra-dense networks or the evolution of cellular networks towards UDN. Generally, they provide some background without discussing of the research status of different disciplines in the UDN context.

Different from [7]–[10], in this survey, we present the state-of-the-art in different research directions in the context of ultra-dense networks. We review the conducted research in many relevant active research disciplines. Also, we discuss the challenges facing the research progress as well as the open problems that require serious investigations in order to answer the raised questions and to give insights. Consequently, this shed lights on the way to the successful deployment of UDNs.

In this survey, we review the recent works in the UDN literature. The research work in network densification is still in its infancy, and hence there is much work to be done in different research directions. In order to identify the research gaps and the unanswered questions, we review the published research in different disciplines assuming a UDN environment as defined in Section II. Henceforth, we use the terms dense network, hyper-dense network, extremely-dense network, and ultra-dense network (abbr. UDN) interchangeably to refer to the same concept.

Modelling techniques and key performance metrics are discussed in Section III. Then the enabling technologies and the driving factors of network densification are discussed in Section IV. In Section V, a discussion of the recent work in user association considering a UDN network is presented. Different interference management schemes are discussed and compared in Section VI. The backhauling alternatives and challenges in UDN context are discussed in Section VII. The energy efficiency of UDN deployments is discussed in Section VIII. In Section IX, we consider another set of research disciplines which are relevant to the progress of UDN research status. This set includes small cell discovery, spectrum sharing; resource management; and scheduling, propagation modelling, and economics of UDN deployment. Finally, the challenges facing the development of UDN and the open problems are highlighted in Section X. The conclusions and summary of the survey are presented in Section XI. Table I lists the acronyms used throughout the survey and Figure 2 provides a summary of the organization of the survey.

## II. WHAT IS A UDN?

In this section, we provide a basic background to understand UDNs. We summarize the different definitions of UDN in literature, and we discuss the fundamental features of UDN as compared to traditional networks. Moreover, two different classification schemes are presented to distinguish various densification approaches.

### A. Definitions of UDN

Ultra-Dense Networks can be defined as those networks where there are more cells than active users [7], [11]–[14]. In other words, $\lambda_b \gg \lambda_u$, where $\lambda_b$ is the density of access points, and $\lambda_u$ is the density of users. Another definition of UDN was solely given in terms of the cell density, irrespective of the users density. Ding *et al.* [15] provided a quantitative measure of the density at which a network can be considered ultra-dense ($\geq 10^3$ cells/km$^2$). In fact, the first definition converges to the second given that the active users density considered in dense urban scenarios is upper bounded by about 600 active users/km$^2$ [16].

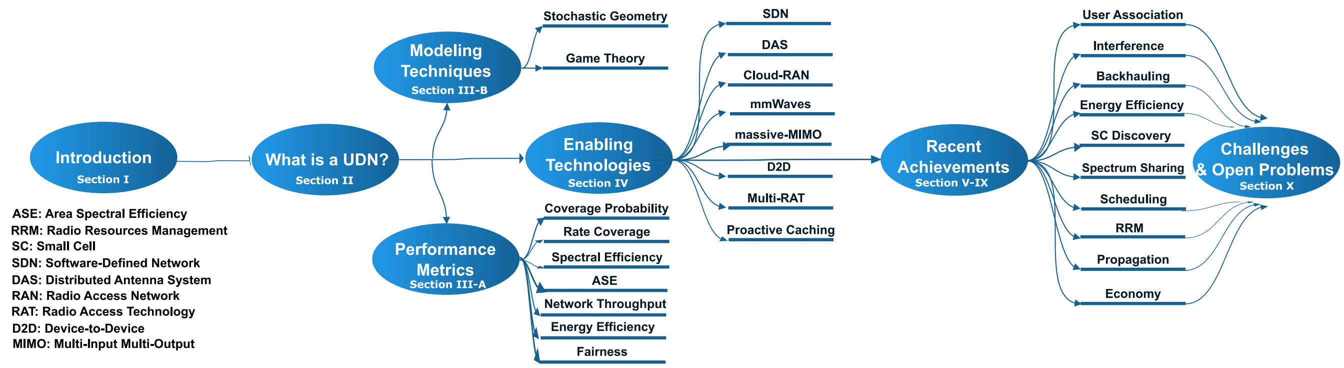


Fig. 2. The organization of the survey.

TABLE II
DIFFERENT TYPES OF SMALL CELLS

| Type of small cell | Deployment Scenario | Coverage | Power | Access Scenario | Backhaul |
|---|---|---|---|---|---|
| Picocells (fully-functioning) | indoor/outdoor (planned) | up to 100 meters | indoor ($\leq$ 100 mW)<br>outdoor (0.25 – 2 W) | Open Access | Ideal |
| Femtocells (fully-functioning) | indoor (unplanned) | 10 – 30 meters | $\leq$ 100 mW | Open/Closed/Hybrid Access | Non-Ideal |
| Relays (macro-extension) | indoor/outdoor (planned) | up to 100 meters | indoor ($\leq$ 100 mW)<br>outdoor (0.25 – 2 W) | Open Access | Wireless<br>(in-band/out-of-band) |
| RRHs (macro-extension) | outdoor (planned) | up to 100 meters | outdoor (0.25 – 2 W) | Open Access | Ideal |

Generally, the small cells in UDN can be classified into fully-functioning base stations (BSs) (picocells and femtocells) and macro-extension access points (relays and Remote Radio Heads (RRHs)). The fully-functioning BS is capable of performing all the functions of a macrocell with a lower power in a smaller coverage area. Specifically, the fully-function BS performs all the functions of the entire protocol stack [17]. On the other hand, a macro-extension access node is an extension for the macrocell to effectively extend the signal coverage, and it performs all or some of the PHY layer functions only. Moreover, the small cells feature different capabilities, transmission powers, coverage, and deployment scenarios [18], [19]. Table II summarizes the features of different small cell types. In what follows we explain the different types of small cells [20]:

- **Picocells** are small BSs which are installed by operators to cover a small coverage area in a range of one hundred meters. Usually picocells are deployed in hotspots (indoor or outdoor) to serve tens of active users by offloading their traffic from the macrocell. The transmission power of picocells is typically up to 33 dBm, and they are mainly deployed for capacity purposes. The backhauling of picocells is similar to that of the macrocells (fiber or microwave links) in order to provide ideal high-bandwidth low-latency links.
- **Femtocells** are user-deployed indoor BSs which are installed to cover indoor spots (homes, offices, and meeting rooms) in order to serve a small set of users. The transmission power of femtocells typically is less than 20 dBm and the coverage range is in the order of tens of meters. Thus, a femtocell provides a large indoor signal strength for the home users where most of the data traffic is generated. The femtocells can be connected to the network via any of the consumers' broadband connections such as Digital Subscriber Line (DSL), cable, or fiber.
- **Relays** are operator deployed access points which are usually deployed for coverage purposes to cover the dead zones and to improve the edge performance of the macrocells. They transmit the users data back and forth from and to the macrocell, featuring what is considered as wireless backhaul. Both relays and picocells have the same coverage and transmit power, but they mainly differ in three properties. First, a picocell is a fully-functioning BS while the relay is an extension for the macrocell. Second, picocells are deployed for capacity, but relays are deployed for coverage. Finally, the backhaul of the picocell is an ideal backhaul while the relay backhaul is a wireless in-band or out-of-band backhaul.
- **RRHs** are RF units which are deployed in order to extend the coverage of a central BS to a remote geographic location. RRHs are connected to the central BS via high speed fiber or microwave links [21]. They are deployed for coverage extension of the macrocell and can be used as a centralized densification alternative as compared to the distributed densification performed by the picocells or femtocells.

It is important to highlight that indoor small cells (femtocells) operate in three different access modes: open, closed, and hybrid. In open access mode, all subscribers of a given operator can access the node, while in closed access mode the access is restricted to a closed subscriber group (CSG). In hybrid mode, all subscribers can connect to the femtocell with the priority always given to the subscribers of the CSG. The deployment of small cells with regular macrocells is termed in the literature and standards as HetNet. HetNets in general represents a paradigm shift from homogeneous networks [22]. As depicted in Figure 3, UDN serves as another evolution from HetNets.

### B. Fundamental Features of UDN

In order to understand the current state of the research activities in UDN, the differences between dense networks and traditional networks need to be highlighted. These fundamental differences of UDN from traditional networks can be summarized as follows:

1) Many small cells are in the vicinity of a given user. The network access nodes in UDN environments are low-power small cells with a small footprint, or in other words, with a small coverage area. Accordingly, the inter-site distance would be in the range of meters or tens of meters. This defines a different wireless coverage environment where many small cells would be in a very close distance to the users.
2) Idle mode capabilities are of a great interest. Due to the high density of small cells, many small cells would be inactive. This motivates the idle mode concept, where inactive small cells are turned off to partially or fully mitigate their interference [23].
3) Drastic interference between neighboring cells is a limiting factor. Close proximity of the small cells to each other in UDN environments generates high interference. Hence, strict interference management schemes are unavoidable to mitigate the interference of neighboring cells [24]–[28].
4) Innovative frequency reuse techniques are required. In traditional cellular networks, the spectrum is reused at the level of a cluster of cells where a reuse pattern is repeated in each cluster. This reuse scheme touches its limit in code-division multiple access (CDMA) and orthogonal frequency-division multiple access (OFDMA) systems where the spectrum is reused in each cell, i.e., the frequency reuse factor is one. In UDN environments, there would be a need for a paradigm shift in the frequency reuse concept.
5) Backhauling in UDN environments is challenging. It might be difficult for operators to guarantee an ideal high-speed low-delay backhaul for each small cell. Also, the backhaul of a small cell might be the bottleneck of its capacity, where the backhaul capacity would limit the air-interface capacity [7], [29]–[33].
6) High probability of Line-of-Sight (LOS) transmissions. In UDN, the distance between BSs and users is small enough to have a high probability of LOS transmissions [15], [34], [35]. Accordingly, the need for a different propagation modelling becomes a necessity. Moreover, the propagation modelling in UDN should also consider a Rician channel model for multi-path fading due to the dominant LOS component in the received signal.

### C. Horizontal and Vertical Densification

The densification of wireless networks takes place mainly by the deployment of increasing number of small cells. Accordingly, the network densification comes in two different flavors, either horizontal densification or vertical densification. In horizontal densification, the access nodes are densified in the horizontal plane, e.g., in the streets or hotspots. On the other hand, the vertical densification evolves in the elevation plane where the customers deploy BSs in their apartments, offices, meeting rooms, and buildings interior. Figure 4 depicts vertical and horizontal network densification. The aforementioned classification highlights three major aspects of the densification schemes, specifically, the modelling of the densification scheme (vertical/horizontal) to consider appropriate propagation models, the backhauling alternatives for the different densification schemes, and the performance evaluation of the corresponding densification scheme.

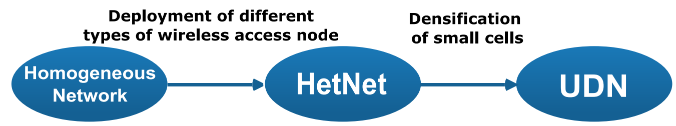


Fig. 3. The traditional homogeneous network is evolved to HetNet, and in turn the UDN is a densified HetNet.

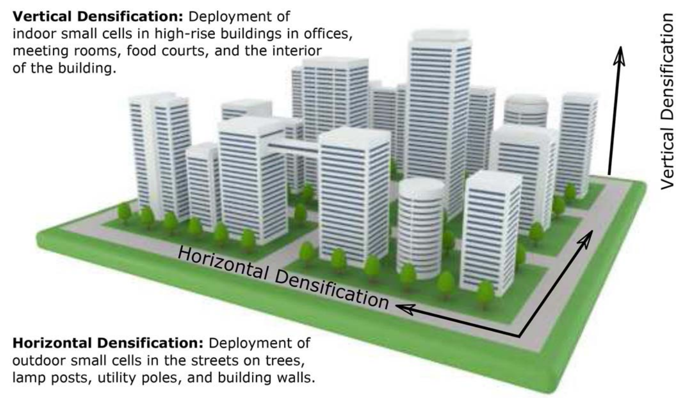


Fig. 4. Vertical densification versus horizontal densification in small cell networks.

Consequently, the investigation of UDNs requires different modelling for the two densification schemes, namely vertical and horizontal. In this manner, the three-dimensional (3D) modelling of the vertically densified networks is inescapable to reflect the reality of such networks. Only a few papers addressed the 3D modelling of cellular networks [36], [37] over the past decade. Recently, the modelling of wireless networks in 3D has been addressed in the work of Gupta *et al.* [34] considering a UDN context. Furthermore, the modelling and analysis of coverage in 3D cellular networks is conducted by Pan and Zhu [38]. Consequently, this gives rise to the consideration of 3D-MIMO [39] which might be used as a backhauling alternative in vertically densified networks. Also, this in turn motivates the modelling and analysis of 3D fading channels [40]. Moreover, the performance of network densification in the vertical plane is different from that of the horizontal plane. In vertical densification, the area spectral efficiency for the same area improves in high-rise buildings with more floors. This suggests incorporating the clutter of the buildings into the performance evaluation of such densification schemes.

### D. Centralized and Distributed Densification

In centralized densification, a central entity takes the coordination role between different elements in order to boost the network performance. This central entity can be a BS equipped with a massive-MIMO system [41], a BS extended with a Distributed Antenna System (DAS) [42], or a cloud of base band processing units in a Cloud- Radio Access Network (Cloud-RAN) [43]. On the other hand, the distributed densification of wireless nodes in small cell networks or the distributed densification of wireless links in Device-to-Device (D2D) requires scalable algorithms for the collaboration amongst different nodes.

Densification of wireless networks can be realized either by the deployment of increasing number of access nodes or by the densification of the number of links per unit area. In the first approach, the densification of access nodes can be achieved in a distributed manner by the deployment of small cells (picocells and femtocells) or via a centralized scheme using DAS or Cloud-RAN. Also, in the second theme, the increasing of the number of links per unit area is realized either in a distributed way in D2D communication, or by a centralized massive-MIMO deployment.

## III. Modeling Techniques and Performance Metrics

Different techniques and performance metrics are used in modelling of the problems in UDNs. In this section, we focus on two of the most commonly used modelling techniques, namely, stochastic geometry [44] and game theory [45]. Also, we define the key performance indicators (KPIs) that are usually used in quantifying the performance of the proposed techniques and solutions such as coverage and outage probability, rate coverage, spectral efficiency, area spectral efficiency (ASE), network throughput, energy efficiency, and fairness. Moreover, we present some use cases of the discussed techniques to model some problems in UDNs, these applications give a solid background to address similar problems while avoiding the pitfalls of modelling such problems.

### A. Performance Metrics

In this section, we explain the set of commonly used performance metrics in the modelling of UDN problems. These metrics are basically related to either the signal to interference-plus-noise ratio (SINR) (e.g., coverage (success) probability and outage probability) or the rate (e.g., rate coverage, average spectral efficiency, and ASE).

1) **Coverage/Success Probability and Outage Probability/SINR Distribution:** The coverage probability is defined as the probability that the SINR of a randomly selected user is above a certain threshold. In other words, the link quality is good enough to proceed to a successful connection. The coverage probability is also termed as the success probability. On the other hand, the outage probability or the SINR distribution is the probability that the SINR of an arbitrary user falls below a minimum threshold. A given user is considered in outage if the SINR of the link to the serving BS is not enough for a successful connection. The coverage probability, the success probability, the outage probability, and the SINR distribution quantify the quality of the link between the user and the serving BS.
2) **Rate Coverage and Rate Outage:** In small cell networks, a better coverage performance metric is the rate coverage, which is defined as the probability that the achievable rate of an arbitrary user is above a certain minimum. Conversely, the rate outage is the probability that the achievable rate of an arbitrary user falls below a certain threshold. It is known that the rate distribution and SINR distribution are strongly correlated in macrocell homogeneous networks [22]. Conversely, this is not the case in HetNets and then as well in UDN. In small cell networks, not only the SINR determines the achievable rate, but also the backhaul capabilities and the load of individual cells.
3) **Average Spectral Efficiency:** The average number of transmitted bits per second per unit bandwidth represents the efficiency of the spectrum. The efficiency of the spectrum is a crucial performance metric in 5G networks due to the scarcity of spectrum along with the high data rate requirements [68]. Also, the cell spectral efficiency is another form of this metric to measure the performance of a single cell.
4) **Area Spectral Efficiency:** Densification of cellular networks increases the reuse of spectrum per unit area. Thus, the ASE is an important metric to quantify the performance of UDN. ASE is defined as the average achievable data rate per unit bandwidth per unit area [69].
5) **Network Throughput:** The network throughput is another metric to quantify the performance of UDN and is defined as the average number of successfully transmitted bits per sec. per Hz. per unit area [55]. This metric considers the success probability in the evaluation of the ASE of a given network with a certain BS density and is defined as
$$R_n = \lambda_s p_a (1 - p_{out}) R_o, \tag{1}$$
where $\lambda_s$ is the BSs density, $p_a$ is the probability of active BSs, $p_{out}$ is the outage probability, and $R_o \triangleq \log_2(1 + \hat{\gamma})$ is the link capacity with a signal-to-interference ratio (SINR) threshold $\hat{\gamma}$.
6) **Energy Efficiency:** The ratio of the network throughput or the ASE to the power consumption per unit area is defined as the energy efficiency [55], [70]. The energy efficiency metric is a performance indicator that measures the benefit-cost ratio by comparing the achievable rate to the energy costs to achieve this rate [70].
7) **Fairness:** A crucial performance indicator to the evaluation of a given cell association, scheduling, or resource management scheme is the fairness between different users. The fairness index measures how likely a given resource allocation scheme is fair. Jain's [71] fairness

TABLE III
MODELING TECHNIQUES AND PERFORMANCE METRICS

| **Research Direction** | **References** | **Modeling Technique** | **Performance Metrics** |
|---|---|---|---|
| User Association | **[46]** | Stochastic Geometry | Spectral Efficiency, ASE |
| | **[47]** | | Coverage Probability |
| Interference Management | **[24], [25]** | Stochastic Geometry | Success Probability |
| | **[26]** | Simulation-based | Throughput, SINR Distribution |
| | **[27]** | Simulation-based | Throughput |
| | **[28]** | Simulation-based | Spectral Efficiency, Throughput |
| | **[48]** | Simulation-based | Average Cell Throughput |
| | **[49]** | Game Theory | Spectral Efficiency, Energy Efficiency, ASE |
| | **[50]** | Game Theory | Throughput, SINR Distribution |
| | **[51]** | Game Theory | Throughput, Coverage Probability |
| | **[52]** | Game Theory | Throughput |
| | **[53]** | Simulation-based | Achievable Rate per Cell |
| Backhauling | **[29]** | Stochastic Geometry | Backhaul Delay, Expected Network Delay, Backhaul Cost |
| | **[30]** | Simulation-based | Spectral Efficiency |
| | **[31]** | Simulation-based | Sum Capacity |
| | **[32]** | Simulation-based | Backhaul Throughput, Energy Efficiency |
| | **[33]** | Simulation-based | Throughput, Fairness |
| Energy Efficiency | **[54]** | Stochastic Geometry | Energy Efficiency |
| | **[55]** | Stochastic Geometry | Network Throughput, Energy Efficiency |
| | **[56]** | Simulation-based | ASE, Energy Efficiency, Cell Spectral Efficiency |
| | **[57]** | Stochastic Geometry | Cell Average Spectral Efficiency, Area Throughput, Energy Efficiency |
| | **[58], [59]** | Game Theory | Energy Efficiency, Outage Probability |
| | **[60], [61]** | Game Theory | Energy Efficiency, Spectral Efficiency |
| Small Cell Discovery | **[62]** | Simulation-based | Detection Probability |
| | **[63]** | Simulation-based | Scan Power, Small Cell Connected Time |
| Spectrum Sharing, RRM, and Scheduling | **[12]** | Stochastic Geometry | Rate Outage Probability |
| | **[64]** | Simulation-based | Minimum Separation Distance |
| | **[65]** | Simulation-based | Throughput |
| | **[66]** | Simulation-based | Throughput |
| | **[67]** | Game Theory | Throughput |
| Propagation Modeling | **[15]** | Stochastic Geometry | Coverage Probability, ASE |
| | **[34]** | Stochastic Geometry | Coverage Probability, Throughput |
| | **[35]** | Stochastic Geometry | Outage Probability, ASE, Energy Efficiency |
| Economics of UDN | **[13]** | Stochastic Geometry | Outage Probability |
| | **[14]** | Stochastic Geometry | Spectral Efficiency, Profit |

index is a widely-adopted index that computes the fairness of a set of user rates or resource allocations [8] and is given by

$$\mathcal{J}(r_1, \ldots, r_N) \triangleq \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N \sum_{n=1}^{N} r_n^2} \tag{2}$$

where $N$ is the number of users, and $r_n$ is the rate of the $n$-th user.

The aforementioned modelling techniques and performance metrics are widely used in the literature of UDN. Table III summarizes the corresponding modelling technique and metrics used in each considered discipline in this survey.

It is however important to note that the context of dense networks to a large extent is different from traditional networks. Thus, the need for other metrics to quantify the performance of UDN is a significant requirement. Andrews *et al.* [68] introduced a new metric, the BS densification gain $\rho$, which is defined as the ratio between the ratio of the rates corresponding to two different BS densities and the ratio of the corresponding BS densities, i.e.,

$$\rho = \frac{R_2/R_1}{\lambda_2/\lambda_1} = \frac{R_2\lambda_1}{R_1\lambda_2} \tag{3}$$

where $R_1$ is the rate corresponding to a BS density of $\lambda_1$, while $R_2$ is the rate if the density is increased to $\lambda_2$. In other words, this measure quantifies the payoff ratio in terms of rate relative to the cost ratio in terms of BS density.

### *B. Modelling Techniques*

1) **Stochastic Geometry:** The stochastic modelling of the spatial distribution of small cells has achieved significant results in the literature (see [44], [72]). The unplanned deployment of the access nodes reflects the randomness in their placement. Hence, the positions of the small cells can be modelled as points in two or three-dimensional Euclidean space, which is termed as a point process (PP). Stochastic geometry stems as a best-fit tool to study such random network environments [44], [72], [73]. Many results have been reported using stochastic geometry in the literature of traditional networks and HetNets [74]–[81]. Additionally, the application of stochastic geometry is expected to meet substantial success in dense environments (see [12]–[14], [24], [25], [29], [46], [47], [54], [55], [57] and the references therein).

The Poisson point process (PPP), is a point process model where the number of BSs in a given area $A$ in two-dimensional space or in a given volume $V$ in three-dimensional space has a Poisson distribution with mean $\lambda_b A$ or $\lambda_b V$, respectively, where the parameter $\lambda_b$ represents the density of the BSs per unit area or unit volume.

In Figure 5, we illustrate an example of the Voronoi tessellation of a PPP realization of a dense small cell network. We consider an area of 20m $\times$ 20m, where

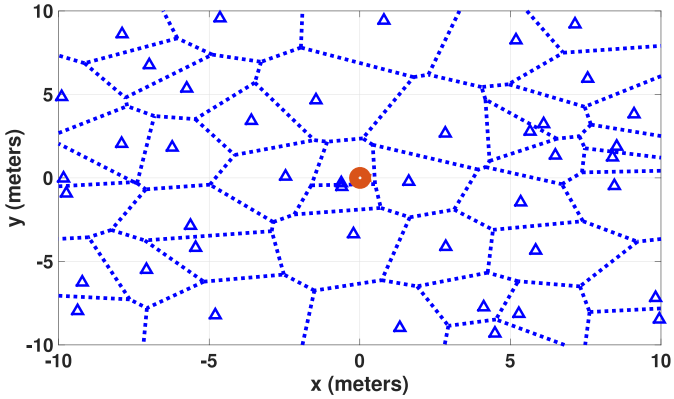


Fig. 5. The Voronoi tessellation of a PPP realization of a dense small cell network with density $\lambda_b = 0.1$ cells/m$^2$ in an area of 20m × 20m, the small cells are marked with a triangle, and a typical user at the origin is marked with a circle. A Voronoi cell is the area enclosed by dotted lines around a given small cell.

the small cells are marked with triangles, and the typical user is located at the origin and is marked by a circle. The Poisson Voronoi (PV) cell is defined by the edges marking the random coverage area of a given cell. The probability density function of the size of a typical PV cell is derived via Monte Carlo method [82], and is given by:

$$f_X^d(x) = \frac{\left(\frac{3d+1}{2}\right)^{\frac{3d+1}{2}}}{\Gamma\left(\frac{3d+1}{2}\right)} x^{\frac{3d-1}{2}} e^{-\left(\frac{3d+1}{2}x\right)} \tag{4}$$

where $X$ is a random variable that denotes the size of a typical PV cell normalized by the reciprocal of the density of the small cells $\lambda_s$, and $d$ is the dimensionality of the problem, i.e., $d = 1, 2, 3$ indicates 1D, 2D, and 3D respectively. $\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dt$ is the gamma function. Considering the 2D case in 2D network models, Equation (4) is reduced to:

$$f_X(x) = \frac{(3.5)^{3.5}}{\Gamma(3.5)} x^{2.5} e^{-(3.5x)} \tag{5}$$

The concept of a typical user in stochastic geometry refers to a user residing at the origin where the properties of the point process (PP) can be computed. In other words, the typical user is assumed to be a representative of all users. Most of the properties of a wireless network can be expressed as a function of the distance between the network nodes and the typical user. Hence, the distance from the typical user to the $n$th nearest BS is of a special importance in stochastic modelling of wireless networks. Let $f_n(r)$ denote the probability density function of the distance $r$ to the $n$th nearest small cell from the typical user that resides at the origin. Then, $f_n(r)$ is given by [44]:

$$f_n(r) = \frac{2}{\Gamma(n)} (\lambda_s \pi)^n r^{2n-1} e^{\left(-\lambda_s \pi r^2\right)} \tag{6}$$

The close proximity of access nodes in a dense network requires researchers to propose and investigate a class of distributed clustering techniques to exploit the cooperation of cells in the cluster. The investigation of such structures requires more advanced techniques from stochastic geometry. Besides Poisson point process (PPP), there exist many other point processes that match different applications. Binomial point process (BPP), Hard core point process (HCPP), and Poisson cluster process (PCP) are a few examples of the stochastic geometry toolbox [44]

2) **Game Theory:** Game theory is an applied mathematical discipline which consists of a set of tools and techniques to solve conflict of interest problems among a set of rational entities [83]. Game-theoretic approaches are originally developed to solve problems in economics. However, the applications of game theory have found a significant success in many other disciplines such as biology, political science, computer science and engineering.

A game is characterized in terms of three main elements, namely, players, actions, and payoffs (preferences) [84]. Players are the rational decision makers, they usually have a conflict of interest, and a decision of one player may harm other players. A decision of a player is an action which is chosen by the player from a set of actions to maximize his/her payoff or benefit. The set of actions might be finite, countable, or infinite. The preference of an action to a given player is an ordering for the actions in terms of payoffs.

Two different categories of games are widely studied and used to model problems in the literature; non-cooperative games [84] and cooperative games [85]. The players in non-cooperative games have no communication means so that they cannot agree on how to play the game to achieve a common benefit. Conversely, in cooperative games the players can bargain or form coalitions to improve their respective positions in playing the game and to achieve a better payoff. In this way, we can identify two different subcategories of cooperative games, namely, bargaining games [86] and coalition formation games [85].

In UDN, there exist many research areas where game theory is a potential tool to design effective algorithms. Interference management, discovery of small cells, association of users, and handover of mobile subscribers are amongst the areas where tools from game theory might find successful applications. The conflicting interests amongst the large number of nodes in a dense network encourages the development of distributed solutions to maximize a network-wide utility, and in this situation game theoretic approaches stem as a toolbox where many existing or new models can fit the problem in hand. Further specific examples for the use of game theory to model problems in UDN will be explained in Sections V–IX.

Needless to say that the scalability of game theoretic approaches with a large number of players is debatable [87]. This is an interesting issue to consider in UDNs where the number of small cells involved in a game might be large. Mean-Field Games (MFGs) represent a candidate modelling technique in such scenario where a player takes an action based on the average of the effect of other players' actions rather than the individual effects [58], [59], [88].

It is equally important to mention that many problems in UDN can be modelled as optimization problems, where various optimization techniques can be exploited to find an optimal solution. The utility maximization under practical constraints are widely used in different network densification contexts and for various objectives. In this survey, we discuss many proposals and investigations where an optimization technique is employed to understand the role of the considered parameters and optimization variables. Considering UDN scenarios, many problems in interference management [49], backhauling [29], [31]–[33], energy efficiency [70], spectrum sharing [89], and the economics of UDN deployment [14] are formulated as binary linear problems [90], [91], mixed binary nonlinear problems [92], or convex problems [93].

In UDN, the scalability of the optimization algorithms is important in terms of overhead, complexity, and convergence. The decoupling of the investigated problems via clustering into a family of localized optimization problems might result in reducing the complexity. To this end, various distributed and centralized optimization techniques can be exploited. The joint optimization of multiple objectives in UDN deployments is another important issue for further investigation. The joint optimization of energy efficiency, spectrum efficiency, and BS density while considering QoS requirements significantly impacts the design decisions in UDN deployments.

## IV. Enabling Technologies and Driving Factors

To cope with the strict requirements and expected immense amounts of traffic, 5G networks are likely to be a mixture of different technologies. There is a common understanding that the orchestration of a number of different technologies would govern the road to a successful next generation [68]. In this section, we discuss the most relevant technologies to network densification in order to give essential background for the understanding of the current research efforts and the challenges that need to be addressed.

### *A. Software-Defined Network*

In 5G networks, one expects a network that is dynamic, manageable, cost-effective, and adaptable. These requirements cannot be all in one network unless it is programmable. Software-Defined Networking (SDN) [94] emerges as a perfect solution in this regard, where the network control functions are decoupled from the packet forwarding functions. SDN is a paradigm shift in networking that offers several groundbreaking aspects for the next generation networks, flow-based forwarding decisions, centralized control of the network operation, reconfigurability and programmability through software applications, to name a few [94]. One more interesting aspect of SDN is the vendor neutrality; the specifications of SDN is open and standard-based. OpenFlow is a standard interface first introduced by Stanford University [95] then developed by Open Networking Foundation (ONF) to realize the functionality of SDN [96].

The extreme densification of small cells in UDNs requires an agile network architecture in order to overcome the limitations of UDNs. Densification of wireless networks has many limitations such as the bottlenecked backhaul, the drastic interference, the increasing signaling overhead due to mobility, and the high operational costs due to energy consumption [97], [98]. These limitations, amongst others, promote the employment of SDN architecture. The SDN architecture can significantly improve the performance of dense networks, and make it possible to overcome their limitations with elegant solutions. The flexibility and adaptability of SDN satisfy the requirements of a successful dense network, where the resources, both wireless and backhaul resources, are provisioned based on the traffic volumes. In other words, the dense wireless network would adapt itself via dynamic reconfiguration to the actual instantaneous loads of the users.

CROWD (Connectivity management for eneRgy Optimised Wireless Dense networks) [97] is a two-tier architecture that is introduced to address the limitations of UDN, specifically, the backhaul, the mobility management, and the energy consumption. CROWD aims at the design of protocols and algorithms for ultra-dense networks. The CROWD architecture proposes local controllers to take fast decisions on a fine granularity basis, and regional controllers to optimize the network operation globally. The local controllers oversee a district of BSs either cellular or ad hoc access points. They have functions such as monitoring and filtering, network discovery, power control setting, access selection setting, scheduling policy control, and WiFi parameter setting. The regional controllers on the other side have global functions in a large region comprised of many districts such as long-term clustering, long-term adaptation of radio parameters, and traffic-proportional backhaul reconfiguration [98].

WiSEED (Wireless Software-basEd architecture for Extremely Dense networks) [99] is another management architecture proposed to exploit the benefits of SDN in extremely dense networks. The architecture jointly manages a set of operational services, namely, routing, mobility, and spectrum usage. To explain, these operational services can be seen as a software that runs on an SDN controller. The management provided by WiSEED aims at satisfying key requirements for the future dense networks, scalability, resilience, and energy efficiency. The authors in [100] introduce another architecture to serve the machine-type communication (MTC) traffic generated by indoor devices in homes, offices, hospitals, and markets. The architecture suggests the use of indoor small cells to handle this traffic, which significantly reduces congestion and overloading of both the radio access network and the core network. SDWN (Software-Defined Wireless Network) [101] is another architecture which is proposed to extend and generalize the concept of SDN to the wireless networks. Niephaus *et al.* [101] discussed the unique challenges of the SDN concepts when it is implemented in wireless networks.

### B. Distributed Antenna Systems

A DAS is an architecture where many antenna elements (AEs) are geographically distributed and connect to a central BS in order to shorten the distance to the end users [42]. The distributed AEs provide coverage to the nearby users and they are connected to the central BS via high-speed low-latency links, fiber or microwave. The reduced distance between the user and the AE creates a more uniform coverage, which in turn reduces the required transmission power in both the uplink and the downlink. Consequently, a uniform high capacity can be offered to the users in the downlink [102] or the uplink [103]. However, DASs in general aim at improving the coverage first and then the capacity.

Relays, small cells (picocells and femtocells), and DAS are competing technologies in terms of network densification [42], [104]. DAS offers a cheap centralized densification solution where the deployment is performed by the operator, and hence a full coordination is achievable. In small cell networks, femtocells are usually installed by the subscribers to improve the coverage and capacity in residential areas, and the picocells are installed by the operators in hotspots. Thus, in small cell networks the coordination is likely to be distributed. Compared to relays, DAS transmit the user signals to the BS via fiber links, while relays use the wireless spectrum either in-band or out-of-band.

### C. Cloud-RAN

Cloud-RAN, as the name suggests, stems as an application for the cloud computing in the wireless area [105]. Cloud-RAN can be seen as a network where the base band resources of many BSs are pooled while the RF processing is left in the remote coverage area [43]. The RF unit of a BS is deployed to provide the coverage via what is called remote radio heads (RRHs) where the antenna units are installed. The base band resources of a collection of BSs are then pooled in a centralized base band unit (BBU) to be shared amongst the BSs [106]. The RRH stands as an interface between the radio and the BBU to perform the main tasks of the RF such as filtering, power amplification, digital to analog conversion (DAC), and analog to digital conversion (ADC). Cloud-RAN can be considered as a dynamic DAS [56], where traditional DASs are static in nature as they cannot be reconfigured to adapt to the traffic fluctuations in hotspots. The densification of cellular networks via Cloud-RAN can be realized by the deployment of as many RRHs as required to carry the generated traffic by the users [107].

In Cloud-RAN, the pooling of base band processing resources comes with many advantages [108] such as the low deployment costs of radio access network via sharing of resources, the low operation costs via energy saving, the improvement of the system performance by facilitating coordinated processing of signals, the adaptation of the signal processing resources to the actual traffic loads, the optimization of resource utilization by the dynamic allocation of resources, and the coexistence of multiple standards that can be simply implemented in the central entity. However, these advantages do not come for free, the RRHs need fast fiber or microwave links in order to connect to the central BBU which might not be easy to achieve. In other words, Cloud-RAN is an appealing solution for the operator with free or cheap already available fiber resources [106]. This suggests that Cloud-RAN can be used in special scenarios where fiber resources can be provisioned in a cost effective manner.

Unlike dense small cell networks, which are distributed in nature, Cloud-RAN can be considered as a centralized dense network where the densification is performed via the dense deployment of RRHs. Although Cloud-RAN and dense small networks can be seen as competitors, the coexistence of small cell dense networks and Cloud-RAN is more likely to occur. Specifically, in some scenarios densification via small cells would be better as in the case of homes or office buildings where fiber resources are not available. In other cases, the densification using cloud-RAN can provide better experience to the end users in crowded areas such as shopping malls, concerts, and stadiums [106].

### D. mmWaves Networks

The spectrum crunch has emerged as a serious problem in this decade. The underutilized spectrum in the millimeter band stems as a potential candidate to avoid the consequences [109], [110]. The spectrum at the $3 - 300$ GHz band has a vast amount of unused or lightly used spectrum which attracts the research interests to investigate the propagation properties and the device manufacturing technology challenges in this band [111]–[118]. The propagation characteristics in this spectrum differentiate the mmWaves cellular communication from traditional cellular communication. mmWaves signals suffer high penetration losses. Accordingly, it is sensitive to blockage effects than signals in lower spectrum. This promotes the use of mmWaves BSs for outdoor coverage which leaves the indoor coverage for other means such as mmWaves femtocells or mmWaves WiFi solutions [119]. Due to the short wavelengths, a high antenna gain can be obtained by the use of antenna arrays at the transmitter and the receiver [116]. This gives rise to the implementation of beamforming with high gains to compensate for the propagation losses. Consequently, the inter-cell interference is reduced which significantly improves the network performance [111].

Moreover, mmWaves networks consist of BSs that transmit and receive in the mmWaves band and cover a certain geographical area. To ensure adequate coverage, a dense deployment of the mmWaves BSs is required [117]. However, the backhauling of the dense mmWaves networks is costly due to the large number of BSs. This suggests that some of the mmWaves BSs can connect to the backhaul via other BSs [110].

### E. Massive-MIMO

The deployment of a large number of antennas in the BS is usually referred to in the literature as Massive-MIMO [120]. Other terminology for the same technology includes large-scale antenna systems [121], very large MIMO [122], and full-dimension MIMO [123]. The excess number of antennas deployed in a two-dimensional grid [41] helps to focus the transmitted power towards the end users by the accurate beamforming in both horizontal and vertical planes. In massive-MIMO systems, hundreds of antennas are deployed to serve many users at the same time in the same frequency resource [124]. In UDNs, massive-MIMO emerges as a wireless backhauling alternative [30] where many small cells can connect to a macrocell to transmit the traffic back to the network via wireless backhaul links.

Many challenges are facing the realization of the theoretical concepts behind massive-MIMO, the most prominent is the channel knowledge [125]. Since the number of the channel measurements and the resources needed to feedback these measurements both are functions of the number of antennas, the feasibility of perfect channel knowledge in large antenna grids is questionable. A deployment alternative to overcome this situation is to exploit the channel reciprocity in time division duplex (TDD) systems [126]. Thus, the uplink measurements performed by the cell would provide information about the downlink channel status. The deployment of massive-MIMO allows for the use of inexpensive hardware components in the BSs and mobile equipments replacing the high-cost hardware. The orchestration of such massive number of antenna elements is challenging in terms of the computational complexity, the development of distributed algorithms, and the synchronization of such large number of antenna elements. However, the energy efficiency of massive-MIMO systems and the throughput scaling makes them a potential competitor to small cell networks [127], [128].

### *F. Device-to-Device Communication (D2D)*

D2D communication is a new paradigm in cellular communication where a direct connection between two nearby devices can be established with a minimal intervention of the network [129], [130]. The direct flow of data between devices in close proximity significantly improves the efficient use of resources through densified local reuse of spectrum [2], [131]. D2D communication falls into two different categories, standalone D2D and network assisted D2D [130]. In standalone D2D communication, the connected devices organize the intercommunication in ad hoc manner without the intervention of the network. In the network assisted D2D communication, the signaling required to establish a data flow between two devices is initiated in the underlying cell, while the data transmission flows directly from one device to the other. In D2D, the network densification can be achieved by increasing the number of links per unit area where each D2D connection reuses the available spectrum.

D2D communications are challenging in many aspects. The complex process of discovering optimal peers for pairing in a data flow must be efficient [132]. Also, a given device might use a D2D link or a cellular link to accomplish certain data transmission. This kind of decisions is challenging and requires further investigations [133]. Additionally, the allocation of radio resources to the D2D users is an interesting research topic. This allocation might occur in centralized, distributed, or hybrid manners [134]. Other challenges to the proliferation of D2D communication include power control, interference management, and security.

### *G. Multi-RAT*

Considerable attention has been given by the operators to the offloading of the cellular traffic to WiFi access points in the unlicensed bands or to the small cells in the licensed bands [135]. The competition over the last decade between different Radio Access Technologies (RAT), namely the cellular technology and WiFi, has came to an end and the cooperation stems as a vital solution [136]. Multi-RAT refers to the coordination between different RATs to provide a high quality service to the end users. The associated strict performance requirements of the 5G [137] necessitate the exploitation of every single resource. Correspondingly, the abundance of WiFi nodes with comparable rates to the current cellular technology inspires many collaboration techniques where the delay intolerance traffic can be offloaded to the WiFi layer [138].

The RAT selection algorithms and the offloading mechanisms are of a key importance to the fruition of this paradigm [139], [140]. Also, the mobility of the flows across cellular and WiFi access points is challenging, however active investigations are in progress [136], [141], [142]. Moreover, the splitting of data across multiple flows in Multi-RAT has emerged as another challenge. Furthermore, the simultaneous connection to access nodes of different RAT stems as a viable offloading alternative, while different flows with different Quality of Service (QoS) requirements are carried by the cellular cells or the WiFi access nodes [143].

### *H. Proactive Caching*

Proactive caching is the predictive storing of popular content in the BSs or the user equipment (UE) to serve the user demand to this content in peak traffic loads [144]. The storing of such content occurs in off-peak periods to alleviate the load on the wireless and backhaul resources [145]. Advances in context-awareness, social networks, storage, secure communications, and D2D communications have a great influence on the potential gain of content caching, and the efficient use of resources in general [146]–[150].

The design of caching schemes to be implemented in dense networks requires the understanding of the spatial and social structure of such networks [144]. Successful prediction of the popular content has a two-fold gain, efficient use of storage resources at the network-edge, and achieving the potential gains of caching. However, the fundamental limits of the predictive caching need to be investigated to assess the role of different parameters and to promote effective design techniques [147], [151]. Moreover, the secure transmission of such content is an important aspect to be considered, especially in case of caching at UE [149].

### *I. Internet of Things (IoT)*

IoT refers to a network of devices with Internet connectivity to communicate directly without human-intervention in order to provide smart services to users [152]. The connectivity of such devices eases the collaborative decision making through processing of real-time data and the improved access to information. The achievements in smart sensors, wireless communication technologies [153], context-aware computing, cloud technologies, and Internet protocols can be considered as the building blocks of IoT architecture [154]. Also, the research and standardization efforts in machine-to-machine (M2M) communication plays a significant role in the development of the state-of-the-art of IoT [155].

Applications in health [156], smart security, and smart cities found their way to the market and realizes the potential benefits of this technology [157]. In addition, many other applications of IoT can be enumerated such as agriculture, industry, natural resources (water, forests, etc.) monitoring, transport system design, and military applications [158].

Many challenges are facing the fruition of IoT technology, namely, addressing and identification of the connected devices, the standardization of the technology for optimal interoperability, the privacy of the information, the security of the sensors or actuators, the provisioning of wireless backhaul and storage resources for billions of connected devices, and the energy efficient deployment of edge-devices and communication nodes [158].

Network densification is considered as an enabler for the successful diffusion of IoT services and application in the society. The availability of nearby communication links alleviates the strict requirements on the wireless network infrastructure. The deployment of indoor small cells (picocells and femtocells) stems as an excellent solution for providing connectivity to home smart devices and offloads a great portion of the traffic from the macro-cellular network.

## V. User Association in UDN

The association of users to cells is crucial to the optimal operation of cellular networks. The user association (or cell association) is the selection of a BS amongst several BSs to serve a given user. In traditional cellular networks, the user association is initiated by the user based on the measurement of received signal strength (RSS) of neighbouring cells. A user always connects to the cell with the maximum RSS (max-RSS association). Correspondingly, another association rule, based on the signal quality rather than the signal strength, is used to associate users to cells. In the signal quality association, a user is connected to the cell with the largest SINR, which is termed as max-SINR association.

### A. Range Expansion

In HetNets, where there are different types of access nodes with different transmission power and coverage, the association based on the signal strength or the signal quality is far from the optimal operation of the network. The deployment of small cells in HetNets is intended to offload the traffic from macrocells to small cells. However, with the large gap in the transmission power (macrocells: 46 dBm, picocells: 33 dBm, and femtocells: 20 dBm), this offload will not happen, yielding to the inefficiency of small cells deployment. A user finds the signal received from a macrocell stronger than that of a small cell and thus associates to the macrocell [159].

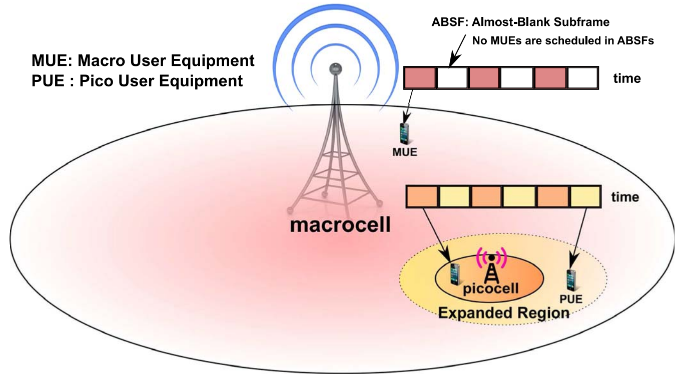


Fig. 6. More users are biased to connect to the small cells via the range expansion, the users in the expanded area suffer from high interference from the macrocell which requires coordination between the macrocell and the small cell to mitigate this interference. ABSF is one of the time-domain techniques for such coordination.

Recall that a UDN is a densified HetNet, and hence, the same situation applies in UDN. Consequently, the user association in HetNets follows a load-based association rule, where the users are biased to connect to the nearest small cell to offload their traffic. The small cells are usually lightly-loaded due to the limited coverage area, and hence, the association of a given user to the nearest small cell gives the user a higher data rate privilege. The biasing of users to small cells is performed via the virtual expansion of their coverage area, which is termed as range expansion (RE) [160]. A small cell received signal strength or quality is weighted by a range expansion bias to attract more users. Consequently, the users associate to the small cell with maximum biased signal strength or quality.

The biased association of a user located at $y$ to a cell in a multi-tier network via range expansion can be determined by the downlink received power from BSs measured at the user side. A user is associated to a tier-$k$ BS if it provides the maximum biased received power, this can be formulated as [80]:

$$P_k B_k \left( \min_i \left| x_{k,i} - y \right| \right)^{-\alpha} \geq P_j B_j \left( \min_l \left| x_{k,l} - y \right| \right)^{-\alpha}, \quad \forall j \qquad (7)$$

where $B_k$ is the bias indicating the RE bias towards tier-$k$, $P_k$ is the transmit power of BSs in tier-$k$, and $x_{k,i}$ is the position of cell $i$ in tier-$k$. Figure 6 illustrates the range expansion concept and the biasing of users to connect to small cells rather than macrocells. It is also noteworthy to mention that the use of the range expansion to offload traffic to small cells might not work in dense networks. The range expansion is mainly used in co-channel deployment where the macrocells and the small cells share the same spectrum. However, the densification of small cells requires orthogonal deployment to the macrocells to mitigate the cross-tier interference.

### B. Dual Connectivity

Another emerging association alternative is the Dual Connectivity (DC) [161]–[163]. In DC mode, the user connects to a macrocell and a set of small cells simultaneously as depicted in Figure 7. DC mode ensures robustness of the

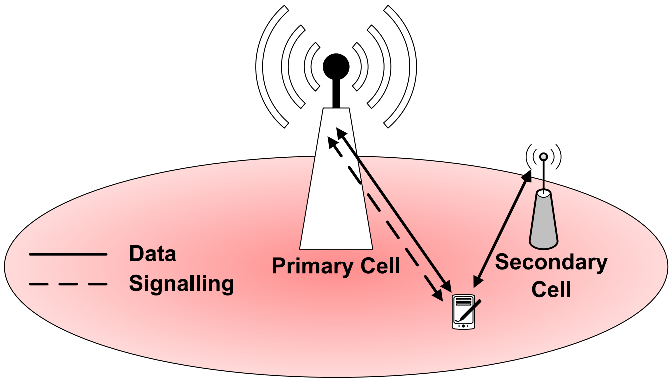


Fig. 7. In dual connectivity, a user connects to a (primary) macrocell and one or more (secondary) small cells. The connection to the primary cell is either signaling or data connection, while the connection to the secondary cell is data connection only.

TABLE IV
SIMULATION PARAMETERS OF MULTIPLE ASSOCIATION IN UDNs [46]

| Parameter | Value |
|---|---|
| Network Model | The downlink of a dense small cell network environment where the small cell density $\lambda_s$ is much larger than the users density $\lambda_u$ |
| Idle Mode Capabilities | A BS in the idle mode is turned off to fully mitigate its interference. |
| Antenna System | SISO |
| Pathloss Exponent | 4 |
| Fading Channel Model | Rayleigh |
| Multicell Size | 1, 5, and 10 |
| Small cells Power | 100 mwatts |
| User Density $\lambda_u$ | $100 - 1000$ users / Km$^2$ |
| Small cells Density $\lambda_s$ | $10^3 - 10^6$ cells / Km$^2$ |

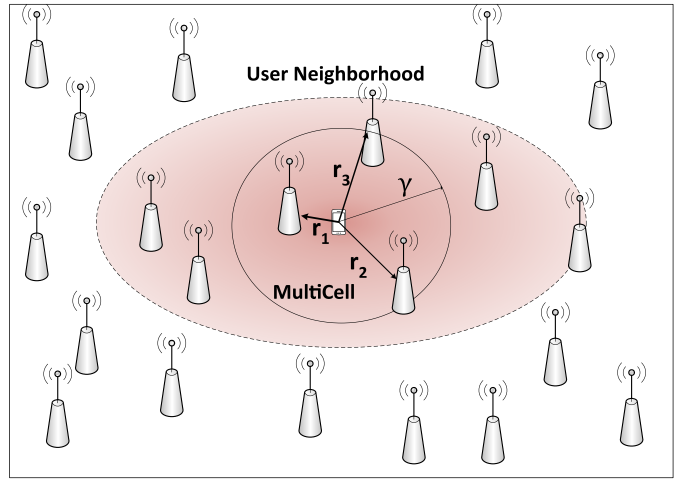


Fig. 8. The user neighborhood can be defined as the set of cells which are in close proximity to a given user, where this proximity is characterized by the average received signal strength threshold. Accordingly, the *MultiCell* is a subset of the user neighborhood, thus the user connects to the nearest *M* cells to form its *MultiCell*.

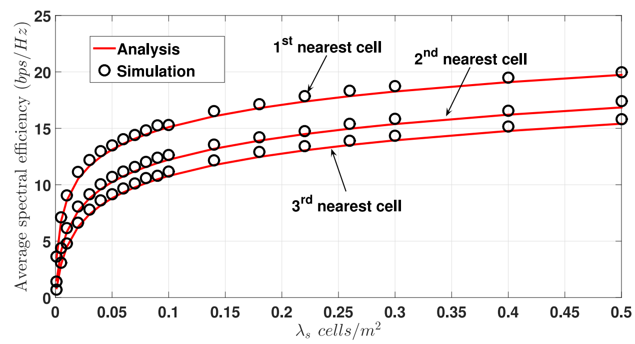


Fig. 9. Average spectral efficiency for different small cell density of the connections of the typical user with the first, second, and third nearest cells ($P_s = 20$ dBm, $\lambda_u = 300$ users/km$^2$) [46].

mobility management of UEs since they are connected to two cell tier, macrocells tier and small cells tier. The main usage of DC is the splitting of the user traffic flows to satisfy the user data rate requirements and to distribute the load of users amongst a set of small cells in its neighborhood. More interestingly, the signalling plane and the data plane might be split in the DC mode. The user signalling is transmitted to the macrocell, while the traffic is offloaded to one or more small cells.

### *C. Multiple Association*

The case might be different in UDN where a given user is in the vicinity of many small cells. Hence, the cell selection mechanism involves a more complicated decision making process. In [46], we proposed a multiple association mechanism where a user connects to more than one cell to form what we termed a *Multicell*. The user connects to the nearest *M* cells and distributes the traffic amongst them to overcome the backhaul and the maximum achievable rate of individual cells, thus aggregating higher data rate. Figure 8 illustrates the *Multicell* concept.

In the aforementioned investigation [46], we simulate the proposed model to assess the accuracy of the analytical results. The simulation parameters of the system model are listed in Table IV. Figure 9 depicts the average spectral efficiency versus the small cell density ($\lambda_s$) for the connection of a typical user to the first, second, and third nearest small cells. The results show that the average spectral efficiency monotonically increases with higher small cell density, however the gains are diminishing. The difference between the spectral efficiency of the link to the first and second nearest small cell, or the second and third nearest small cell is independent of the cell density. Also, the loss in the spectral efficiency due to connecting to farther cells is decreasing with the index of the small cell (first, second, third, etc.).

We use the ASE as the performance metric to account for the network capacity. Recall that the ASE is defined as the number of transmitted bits per second per Hz. per unit area. In the context of multiple association, ASE is interpreted as the sum of the average ergodic rate (i.e., $\bar{R}_j$) in a *MultiCell* multiplied by the number of Multicells per unit area. Since each user forms a *MultiCell* by multiple association to many cells in its vicinity, the *MultiCell* density is the same as the users density (i.e., $\lambda_u$). Hence, the ASE is defined as

$$ASE \triangleq \lambda_u \sum_{j=1}^{M} \bar{R}_j. \tag{8}$$

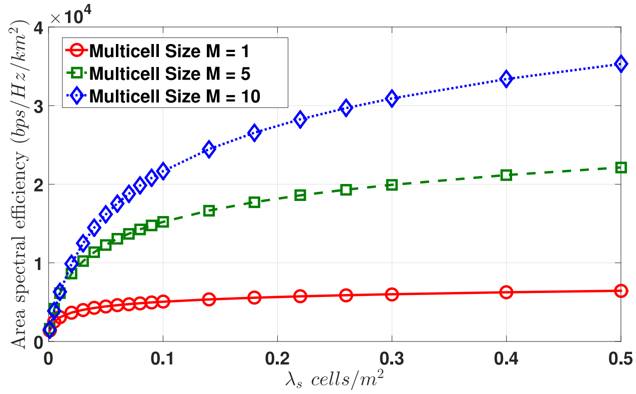


Fig. 10. Area spectral efficiency versus small cell density for different *MultiCell* size ($P_s = 20$ dBm, $\lambda_u = 300$ users/km$^2$) [46].

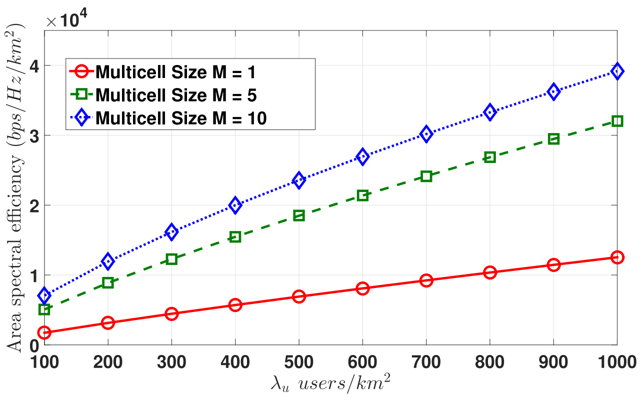


Fig. 11. Area spectral efficiency versus user density for different *MultiCell* size ($P_s = 20$ dBm, $\lambda_s = 0.05$ cells/m$^2$) [46].

Figure 10 illustrates the area spectral efficiency versus small cells density for different *MultiCell* size. The results show a higher ASE for higher *MultiCell* sizes. This is due to the increase of the number of connections per unit area which significantly improves the area spectral efficiency. Moreover, the ASE in case of single association ($M = 1$) is invariant for higher small cells density. This is intuitive since the number of connections does not change with higher small cells density, and the gain in spectral efficiency is diminishing. However, in multiple association, the ASE is increasing with the small cells density. This can be explained by recalling that higher small cells density brings the cells closer to the user. Accordingly, the link quality to the nearest $M$ cells improves significantly with higher densities of the small cells.

The effect of higher user density on the ASE is shown in Figure 11 where the area spectral efficiency increases with the user density. In multiple association, the number of connections increases linearly with the user density. As a result, the ASE improves significantly with higher user density for larger *MultiCell* sizes.

Liu *et al.* [8] comprehensively surveyed the user association schemes in 5G networks. They considered the state-of-the-art association mechanisms in three paradigms of the 5G networks: HetNets, massive MIMO networks, and mmWaves networks. Liu *et al.* [8] delved into the aspects of user association

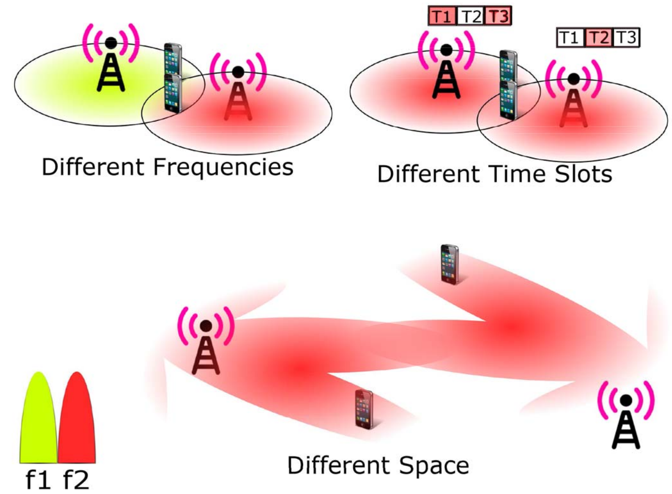


Fig. 12. Alternatives of inter-cell interference coordination.

in 5G networks where they discussed different modelling techniques, performance metrics, and network topology models. Liu and Wang [47] investigated a general random cell association scheme to study the fundamental correlation between cell association and void cell probability (AKA idle mode probability). The findings in [47] reveal accurate bounds for the idle mode probability in a PPP modelled cellular network where they claim that the existing result [11] is not accurate in a general setting, or in other words its accuracy is conditioned on the considered association scheme (e.g., nearest cell association).

## VI. Interference Management in UDN

The interference management is challenging in densified networks. Various types of small cells are deployed with large densities to provide the users with very high rate connections. The use of inter-cell coordination to mitigate the interference requires increasing signalling overhead due to the large number of deployed small cells. Thus, distributed control is preferred to mitigate the interference in UDN.

### A. Interference Coordination Domains

The interference coordination amongst interfering cells takes place in the frequency domain, time domain, space domain, power domain, or a mix of them. In the frequency domain, interference mitigation is done through the use of orthogonal frequency channels, either by the static allocation of these orthogonal channels to different cells or by dynamic allocation [164]. The interference coordination in time domain exploits the blanking of sub-frames. Almost Blank Sub-Frame (ABSF) is a successful proposal that is studied extensively and standardized in LTE Rel10 [165]. In a different front, the advances in MIMO systems give rise to the wide use of spatial interference coordination [166]. Also, the power control is another method to coordinate the inter-cell interference especially in the uplink direction [167]. Figure 12 provides a summary of the different interference mitigation techniques.

TABLE V
COMPARISON OF DIFFERENT INTERFERENCE MANAGEMENT STUDIES

| Ref. | Direction | Model | Coordination Domain | Control | Clustering | Involved Interferers | Signalling Overhead | Antenna System |
|---|---|---|---|---|---|---|---|---|
| [25] | Downlink | Stochastic Geometry | Space | Distributed | *N/A* | BSs within the *Nulling Range* | Low | MISO $(M \times 1)$ |
| [26] | Downlink | Simulation | Frequency | Static Planning | *N/A* | All BSs | - | MIMO $(2 \times 2)$ |
| [27] | Downlink | Simulation | Frequency and Time | Distributed | Non-overlapped | Dominant Interferer | Low | SISO |
| [28] | Downlink | Simulation | Frequency | Centralized | *N/A* | First and second dominant interferers | Moderate | MIMO $(2 \times 2)$ |
| [48] | Downlink | Simulation | Space | Distributed | *N/A* | Strongest interferers | - | MIMO $(M \times M)$ |
| [49] | Downlink | Game Theory | Frequency | Distributed | *N/A* | All interferers | Low | SISO |
| [50] | Downlink | Game Theory | Frequency | Distributed | Overlapped | All interferers | Low | SISO |
| [51] | Downlink | Game Theory | Power | Distributed | Non-overlapped | All interferers in a cluster | - | SISO |
| [52] | Downlink | Game Theory | Frequency | Distributed and Centralized | Non-overlapped | All interferers in a cluster | Low | SISO |
| [53] | Uplink | Simulation | Power | Distributed | *N/A* | All interferers | Low | SIMO $(1 \times M)$ |

### B. Idle Mode Capabilities

In UDN, the interference mitigation stems as a challenging issue [26], [27]. That is many BSs become dominant interferers to each other, and the coordination between them requires sophisticated mechanisms. On the positive side, in the dense deployment of small cells, it is more likely to find idle cells, i.e., without connected users. Thus, it is desirable to turn off such cells to partially or completely mitigate their interference to the neighbouring cell. This is so called idle mode capabilities of small cells [23]. The activation of smart idle mode capabilities in dense small cell networks is another interference mitigation alternative. In that, a small cell supported with idle mode functionality can reduce its power consumption to the minimum (device power consumption) while no users is connected to it.

Ashraf *et al.* [168] discussed three different techniques to control the idle (sleep) mode of small cells, namely, small cell driven, core network driven, and UE driven. In the first approach, the small cells are equipped with a low-power sniffer capability in order to allow for the detection of active users in its coverage area. In this event, the small cell is activated or deactivated depending on the presence of active users. In the core network driven technique, turning the small cell on or off is controlled by wake-up control messages which are sent from the core network via the backhaul. Finally, in the UE driven approach the UE can broadcast wake-up signals in order to activate the small cells in its vicinity.

### C. Research Status and Findings

Various downlink interference mitigation techniques are investigated by Soret *et al.* [27] where two algorithms are proposed, a time domain and a frequency domain small cell interference coordination. They considered four interference scenarios, and they highlighted the role of the dominant interferer (DI). On the other hand, Polignano *et al.* [26] addressed the inter-cell interference dilemma in dense outdoor small cell networks. The impairment to the user experience due to inter-cell interference is investigated to evaluate the conditions that make the interference coordination preferred to the universal frequency reuse. In a different direction, an enhanced dynamic cell muting scheme (eDCM) is proposed by Wang *et al.* [28] where the authors exploit the Coordinated MultiPoint (CoMP) framework of LTE Rel-11 to develop a dynamic muting mechanism to mute some resources at certain small cells for the benefit of other small cells. In their work, the inter-cell coordination function to generate the muting patterns considers a benefit metric for individual users and a proportional fairness scheduling amongst all users. Moreover, the enhanced muting technique considered not only the first dominant interferer, but also the second dominant interference source.

In a MIMO setting, Tavares *et al.* [48] utilized MIMO spatial multiplexing to mitigate the inter-cell interference in small cell networks. Rather than the traditional frequency reuse planning (FRP), they proposed maximum rank planning (MRP). In their proposal, the reduction of spatial multiplexing streams increases the probability of higher degree-of-freedom for the interference rejection receivers to reject the dominant interference. In a different setting, Li *et al.* [24], [25] investigated a user-centric inter-cell interference nulling (ucICIN) scheme. In their work, the authors derived an approximate expression for the success probability of a typical user. In this model, a user requests the suppression of the interference of some neighbouring BSs based on their relative distance to the serving BS. Moreover, the simulation results confirmed the accuracy of the approximation to some extent. Furthermore, the authors studied the effect of limited channel state information (CSI) on the performance of the interference nulling technique.

Using game theory concepts, Al-Zahrani *et al.* [49] exploited game-theoretic approaches to investigate the cross-tier and co-tier interference management. To overcome the curse of dimensionality in case of dense networks, the authors modelled their problem using mean-field game theory. In mean-field game theory [87], a player takes an action based on the average of the effect of other players' actions rather than the individual effects. In another setting, Liu *et al.* [50] exploited game theoretic approaches combined with graph-coloring algorithms to model a joint CoMP clustering and inter-cell resource allocation for interference mitigation. A scalable algorithm is proposed to account for the large number of cells in a dense network. The distributed two-step algorithm is evaluated and potential performance improvements are concluded. A power allocation algorithm is proposed by Yuehong *et al.* [51] to coordinate the interference especially for the benefit of edge users. Non-cooperative game theory is applied to find the Nash Equilibrium for the power allocations in the downlink of a dense network. A non-cooperative game is formulated by Sun *et al.* [52] to investigate the role of cluster-based spectrum allocation and CoMP transmission to mitigate the sever interference in UDNs. In this investigation, the authors consider the load condition of the cells to associate the users to the best cell in order to optimize the network performance.

In the uplink direction, Cho *et al.* [53] considered a power control scheme designed for interference management in a time-division duplex (TDD) setting where the individual users tune their transmission power to keep a preset interference threshold to other BSs. Consequently, each BS schedules the users having the best normalized channel gains according to the corresponding transmission power.

It is important to note however, that the investigation of effective clustering techniques is crucial to the implementation of efficient interference management schemes in the scenario of UDN. A learned lesson from the above studies is that the scalability of a solution depends greatly on the clustering technique such that the signalling overhead between collaborating nodes remains within practical limits. A comparison for the above-surveyed interference management techniques is provided in Table V.

## VII. Backhauling in UDN

The backhauling is the transmission of data from a BS back to the core network, either by a direct link to the core network or via Internet connections. The backhauling of dense small cell networks has emerged as a bottleneck of their successful deployment. The increasing number of deployed small cells and the lack of ideal backhaul links would be limiting factors of the network densification gains.

### A. Backhauling Alternatives

Different backhaul technologies with different capabilities are available to small cell networks [30]. The backhauling technology is either wired or wireless. Moreover, the wired backhaul can be categorized as ideal with very high throughput and very low latency, or non-ideal with moderate throughput and latency. Different from the wired backhaul, the wireless backhaul is always non-ideal. However, it might be the feasible solution in hyper-dense networks. Figure 13 depicts the various backhauling alternatives in small cell deployment scenarios. For the ease of comparison, the technical details of different backhauling technologies are summarized in Table VI.

One of the main challenges for the dense deployment of small cells is backhauling [7]. The promised radio interface capacity of the small cells might be bottlenecked by the wired or wireless backhaul capacity. To explain, the association of a user to a single small cell limits its maximum achievable data rate to the backhaul capacity of this cell. Moreover, the cloud-computing trend and the bandwidth-hungry applications accelerate the need to even higher data rates than what could be offered by a single cell. This motivates us to propose the multiple association scheme as a solution to distribute the traffic load of the user to multiple small cells in the user's neighborhood [46].

TABLE VI
ALTERNATIVES OF SMALL CELLS BACKHAUL [169]

| Backhaul Category | Backhaul Technology | Latency (one way) | Throughput |
|---|---|---|---|
| Non-Ideal | Fiber Access 1 | 10-30ms | 10 Mbps-10 Gbps |
| Non-Ideal | Fiber Access 2 | 5-10ms | 100-1000 Mbps |
| Non-Ideal | Fiber Access 3 | 2-5ms | 50 Mbps-10 Gbps |
| Non-Ideal | DSL Access | 15-60ms | 10-100 Mbps |
| Non-Ideal | Cable | 25-35ms | 10-100 Mbps |
| Non-Ideal | Wireless Backhaul | 5-35ms | 10-100 Mbps typical, maybe up to Gbps range |
| Ideal | Fiber Access 4 | less than 2.5 us | Up to 10Gbps |

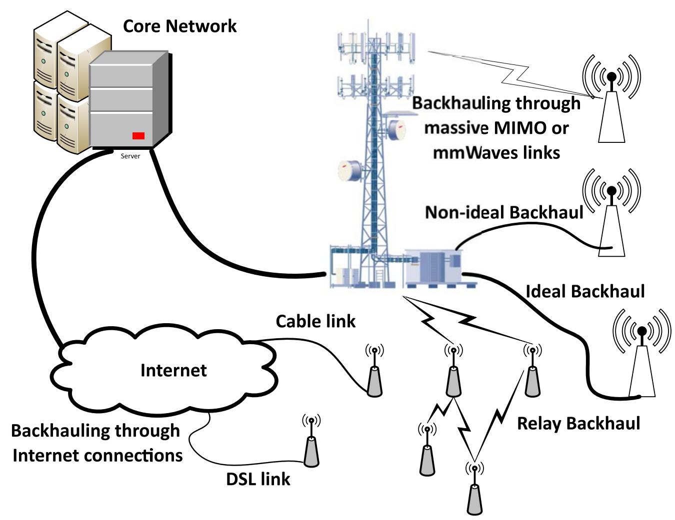


Fig. 13. Alternatives of backhauling in UDN.

### B. Research Status and Findings

Wang *et al.* [170] surveyed the backhauling solutions for 5G small cells from the perspective of radio resource management. They discussed the relation between the emergent backhauling solutions and some radio resource management (RRM) issues including, but not limited to, cell association, interference management, scheduling, and inter-cell coordination.

Ge *et al.* [32] studied the throughput and energy efficiency of 5G wireless backhaul networks. Specifically, they adopted two traffic models, namely centralized backhauling model and distributed backhauling model. In the centralized model, a given macrocell aggregates the traffic of the small cells in its coverage area assuming an ideal backhaul link between the macrocell and each small cell. This assumption is rather ideal in UDN environments since the large number of small cells in the coverage area of a macrocell makes it almost impossible to provide the small cell tier with ideal backhaul links. In the distributed model, a small cell which is connected to the core network via fiber-to-the-cell (FTTC) link collects the traffic of the small cells in its vicinity through mmWaves communication links.

The wireless backhauling, although non-ideal, emerged as a viable solution for the backhauling in dense small cell networks. Amin *et al.* [33] studied the performance of self-backhauled small cells. In their model, a Long Term Evolution (LTE) macrocell backhauls High Speed Packet Access (HSPA) small cells. A massive MIMO backhauling solutions were investigated in [30] and [31]. Also Chen *et al.* [29] proposed a hierarchical network model to investigate the backhauling in small cell networks, where they considered both wired and wireless backhaul. They derived analytical expressions for the backhaul delay and the average delay seen by a typical user considering two scenarios, namely, static (i.e., no mobility case), and extreme mobility case.

## VIII. Energy Efficiency in UDN

In this section, we consider the energy efficiency of network densification. In that, the global warming phenomenon attracts significant attention to the efficient use of energy in communication networks, especially wireless networks [171], [172]. That is the power consumption by a BS falls in two categories, the first is the node power consumption and the second is the communication power consumption. In particular, the node power consumption is due to signal processing, cooling, and battery backups as well. On the other hand, the communication power consumption is the transmitted power to achieve a certain coverage. Consequently, the ratio between the total network throughput and the total network power consumption defines the energy efficiency of the network. Hence, the energy efficiency of the network with the units of *bits/joule* signifies to what extent a given procedure, algorithm, or technique is more efficient in the sense of energy consumption than others. This energy efficiency $\eta_{EE}$ is defined as [173]

$$\eta_{EE} = \frac{T}{P} \tag{9}$$

where $T$ is the effective throughput of the network measured in bits per second, and $P$ is the total power consumption of the network measured in watts.

In dense small cell networks, the energy efficiency is a vital consideration. The immense number of small cells, despite the small transmit power of each, would consume a massive energy. The environmental impact of this energy consumption is an interesting factor to consider in the deployment of dense networks [174]. On the positive side, most of the consumed power in small cells is used to provide coverage to the subscribers. Thus, there is no need for cooling which consumes a large portion of the power budget of a given macrocell.

### A. Research Status and Findings

Björnson *et al.* [54], [70], by the aid of a stochastic geometry model, studied the energy efficient deployment of dense small cell networks. In their work, they considered the uplink of a multi-cell multi-user MIMO network. The closed-form expressions obtained via solving the energy efficiency maximization problems shed lights on the role of all the considered parameters and optimization variables. In a different setting, Li *et al.* [55] modelled the downlink of a dense multi-transmission antennae small cell network to quantify the performance in terms of ASE and energy efficiency.

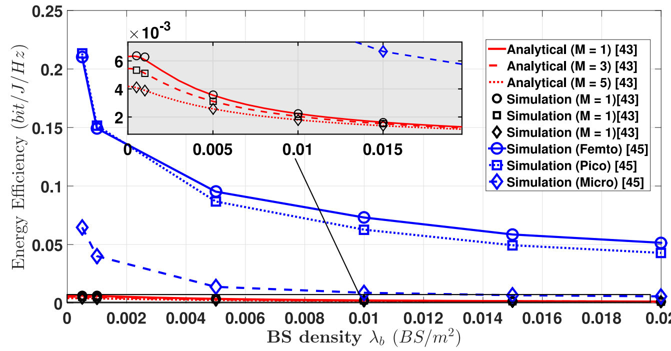


Fig. 14. Comparison between different energy efficiency studies.

A tractable expression for the outage probability is derived via stochastic geometry approach and then exploited in the computation of the ASE and the energy efficiency. In this, Liu *et al.* [8] assessed the effect of deploying more BSs and more transmit antennas per BS on the aforementioned performance metrics. Moreover, the optimal BS density and the optimal number of antennas per BS to optimize the energy efficiency is computed.

A comparison between three network densification scenarios is conducted by Yunas *et al.* [56]. These scenarios are the densification of the outdoor macrocell tier, the densification of the indoor femtocell tier, and the densification of DASs. The results of the study confirmed that the resources efficiency in terms of spectrum and energy is much higher in the second and third densification strategies, compared to the first scenario. Consequently, the rule of thumb in network densification is to densify the small cells, not the macrocells. Moreover, they found out that the densification of indoor femtocells not only improves the indoor network capacity, but also improves the outdoor network capacity in case of open access mode (i.e., the indoor femtocells are open to serve outdoor users in their vicinity). Finally, the results obtained verified the efficacy of the dense deployment of dynamic DAS in terms of resource efficiency.

Another stochastic geometry analytical study considered the performance of UDN in terms of energy efficiency along with cell average spectral efficiency and area throughput [57]. Ren *et al.* [57] concluded that the three performance indicators cannot be optimized simultaneously, and a tradeoff is unavoidable to meet the required network performance.

Using game-theoretic approach, Samarakoon *et al.* [58], [59] investigated a joint power control and user scheduling in dense scenario to optimize the energy efficiency. They formulated a dynamic stochastic game and analyzed the mean-field equilibrium. In another venue, Yang [60] studied three important performance metrics in a dense network setting: spectrum, energy, and cost efficiencies. The author formulated a Nash-product form of the corresponding utility function, and analyzed the tradeoff equilibrium amongst the considered metrics

In order to compare the findings for different studies, we generated the results in Figure 14 based on a normalized simulation setup for the investigations in [55] and [57]. In this simulation setup, we consider a path loss exponent of 4, a SINR threshold of 1, and UE density of 1000 UE/km$^2$. Both studies consider downlink dense network models, the first study [55] investigates the effect of multiple transmit antenna in a multi-input single-output (MISO) system along with the BS density on the energy efficiency of the network. On the other hand, the second study [57] considers the energy efficiency of the densification of three different BS types namely, microcells, picocells, and femtocells in a single-in single-out (SISO) setting where each BS and each UE is equipped with a single antenna.

Figure 14 shows the network energy efficiency with different BS density. Two important conclusions can be drawn from theses results. Firstly, the densification of small cells is more energy-efficient than the densification of macrocells. Evidently, the densification of macrocells is not efficient from neither the cost nor the operation point of view. Secondly, the densification of the indoor femtocells or the outdoor picocells is highly efficient in terms of energy efficiency, and there would be a tradeoff between the maximization of EE and the optimization of other parameters particularly, the cell throughput, the ASE, and the coverage probability.

## IX. Other Advancements in UDN

In the previous sections, we reviewed the state-of-the-art research in four other directions, specifically, user association, backhauling, interference management, and energy efficiency. These research directions are of a great importance to the proliferation of UDNs, thus a serious and extensive research has to be conducted to complement the existing results with more findings and insights of the corresponding problems. In this section we discuss other research directions which also are considered very relevant to the advancement of UDNs. In the following subsections, a discussion is presented for these research directions particularly, small cell discovery, spectrum sharing, RRM, and scheduling, propagation modeling, and the economy of UDN deployment.

### A. Small Cell Discovery

The fast discovery of small cells in dense networks is another emerging research direction. Due to the large number of small cells in the vicinity of a user, there is a need for optimized cell discovery mechanisms. Many features in UDN, such as idle mode capabilities [23], CoMP [175], load balancing [176], and enhanced Inter-cell Interference Cancellation (eICIC) [20], require fast and efficient discovery of small cells. In that direction, Prasad *et al.* [62] evaluated disparate cell discovery mechanisms especially designed for energy-efficient detection of small cells. A graph coloring based scheme for small cell discovery is proposed and evaluated by Shuai *et al.* [63]. In this scheme, the small cells in the same vicinity are clustered into disjoint groups and each cluster takes a turn to transmit the synchronization sequence. Only minimal changes to the conventional synchronization scheme are required, and thus guaranteeing backward compatibility. The scheme improves the detection probability of small cells.

### B. Spectrum Sharing, Resource Management, and Scheduling

The dense deployment of indoor and outdoor small cells requires the provisioning of a new spectrum to alleviate the interference. The spectrum sharing thus stems as a viable solution. In spectrum sharing, the UDN cells are allocated a spectrum as secondary users in a cognitive network regime. Another alternative, is the inter-network spectrum sharing where the spectrum is shared amongst multiple operators [177]. Another key aspect is the multiple access and resource management in dense small cells. In spite of the small probability of having multiple users in the coverage area of a small cell in a dense network, still there would be a chance that many users are served by a small cell in a given hotspot.

The authors in [64] studied the spectrum sharing for UDN in the radar bands. They modelled a primary/secondary spectrum sharing scenario, where the primary system is the radar system and the secondary system is the dense small cell network. They developed deployment regulations, namely, area power regulation and deployment location regulation, and studied its effectiveness in different environments. Different from the former cognitive radio regime, Teng *et al.* [65] considered the inter-network spectrum sharing, in particular the co-primary spectrum sharing. In co-primary spectrum sharing, two or more operators pool their licenses to achieve flexible spectrum sharing amongst their network nodes which is co-located but with only relative displacement.

Stefanatos and Alexiou [12] studied the effect of multiple access and the density of BSs on the performance of a dense network scenario. They also derived a lower bound for the optimal number of bandwidth partitions and a closed-form upper bound for the BS density to guarantee an asymptotically small rate outage probability.

In terms of resources management, Jafari *et al.* [66] studied the performance of different scheduling techniques. In particular, they compared the performance of proportional fair (PF) scheduler and round robin (RR) scheduler. The key aspect of their model is to consider the LOS transmission which is more probable in dense networks. Furthermore, Chen *et al.* [67] investigated a distributed spectrum resource allocation and proposed a learning algorithm. The algorithm is proven to converge to Nash equilibrium and the performance results asserts that co-tier and cross-tier interference is mitigated. The throughput performance of the proposed system model is investigated and potential performance improvements verified by simulations.

### C. Propagation Modelling

The propagation modelling is a vital part of the investigation of wireless communication problems. Since the network densification brings the access point closer to the users, the LOS transmission components become most probable. Hence, the study of dense networks requires a different propagation model where the LOS transmission is considered. Also, in dense indoor networks, the cells are deployed in buildings with many floors, thus a three-dimensional propagation environment should be considered. This suggests two major modifications to the traditional propagation modelling in macrocellular networks; the consideration of dual-slope or multi-slope path loss model while the path loss exponent becomes a function of the distance to the user, and employing Rician fading channel instead of the simple Rayleigh fading model [66].

In order to acquire accurate modelling for the propagation environment in dense networks, the consideration of dual-slope or multi-slope becomes inevitable. In dual-slope propagation model, the propagation path loss $l(r)$ is expressed using two different path loss exponents, and is given by [34]

$$l(r) = \begin{cases} r^{-\alpha_0}, & \text{for } r \leq R_c \\ \eta r^{-\alpha_1}, & \text{for } r \geq R_c \end{cases} \tag{10}$$

where $R_c$ is the critical distance, $\alpha_0$ and $\alpha_1$ are the close-in path loss exponent and the long-range path loss exponent, respectively. Also, it is assumed that $0 \leq \alpha_0 \leq \alpha_1$, and $\eta = R_c^{\alpha_1 - \alpha_0}$ is a constant to provide continuity. In the same way, multi-slope path loss model can be expressed in terms of many path loss exponents indexed with $n \in \{1, 2, \ldots, N\}$ [15]:

$$l_n(r) = \begin{cases} l_n^L(r) = A_n^L r^{-\alpha_n^L}, & \text{for LOS} \\ l_n^{NL}(r) = A_n^{NL} r^{-\alpha_n^{NL}}, & \text{for NLOS} \end{cases} \tag{11}$$

where $l_n^L(r)$ and $l_n^{NL}(r)$ are the $n$-th piece of the path loss function for LOS transmission and NLOS transmissions, respectively. $A_n^L$ and $A_n^{NL}$ are the path losses at a reference distance $r = 1$, $\alpha_n^L$ and $\alpha_n^{NL}$ are the path loss exponents for the LOS and the NLOS cases, respectively.

Ding *et al.* [15] investigated a dense small cell network considering LOS transmission. Despite their assumption of a fully-loaded network $\lambda_u \geq \lambda_b$, the study reveals the impact of network densification on the coverage probability which consequently affects the ASE. Furthermore, they presented a clear definition for what is a UDN in terms of the access point density and suggested a minimum density for dense networks to provide a linear ASE with the increasing BS density. In another study, Galiotto *et al.* [35] further studied the effect of LOS and Non-Line of Sight (NLOS) transmissions on the performance of UDN. Different from [15], the authors in [35] considered both fully-loaded and partially-loaded network setups. Furthermore, they suggested a frequency reuse mechanism to reduce the impact of network densification in both the coverage probability and the area spectral efficiency. Also, they studied the energy efficiency in the provided UDN setup under the assumption of LOS transmission.

Progressively, Gupta *et al.* [34] focused on the modelling of three-dimensional dense networks. In their work, the authors considered a vertically stacked horizontally infinite dense network and studied the performance in terms of coverage probability and throughput.

### D. Economy of UDN Deployment

The densification of access nodes is shown to have a significant impact on the performance of cellular networks. However, the network cost is an important factor to consider. The cost of network densification can be categorized to capital expenditures (CAPEX) and operating expenses (OPEX) [14]. The CAPEX includes all deployment costs, e.g., access nodes hardware, backhauling, and core network equipments. The OPEX costs include energy, backhaul transmission, site rentals, and operation and maintenance (OAM). The sharing of these costs between the operators and users is one of the main advantage of UDN since the deployment of small cell BSs in homes, offices, and markets is usually done by the users while the deployment in the hotspots and outdoors is done by operators.

In small cell networks, the CAPEX and OPEX are much less than the corresponding ones in traditional networks. The access points are much cheaper, and the backhauling is made easier by the customer's DSL or cable modem [19]. Also, the transmission power of each node is small and the OAM functions are automated via self organizing network functionality (SON) [178]. However, the densification of small cell networks increases the energy consumption costs and the backhaul cabling costs in case of outdoor deployments. Thus, the network density should be optimized to make the best of this paradigm.

Lee and Huang [13] are the first to address the economy aspects of deploying many BSs in a cellular network. Using a stochastic model for the downlink of a dense cellular network, they quantified the outage probability and found its relation to the BS density. More importantly, they derived the optimal BS density to minimize a multi-objective cost function that accounts for the network deployment economy. The cost function considers the hardware costs, backhaul cabling, and energy consumption, i.e., a mix of OPEX and CAPEX. The derived result shows a tradeoff between the performance gain in terms of the outage probability and the network cost.

Park *et al.* [14] modelled a problem to investigate the relation between the downlink average spectral efficiency and the BS density in a dense network setting. Furthermore, they derived a closed-form for the optimal BS density and utilized spectrum to maximize the operator profits. Park *et al.* [14] also considered a profit function that takes into account the user demand along with the access points and spectrum operating costs. Additionally, they provided guidelines for the operator to make the best profit by investing either in network densification or acquiring more spectrum based on user demands.

## X. Challenges and Open Problems

The significant impact of network densification on wireless network performance in terms of coverage, throughput, and area spectral efficiency has attracted the attention of researchers and practitioners. Network densification amongst other proposed techniques such as mmWaves and massive MIMO are the main players in shaping the 5G wireless networks. In this survey, we considered the dense deployment of small cell BSs and studied the state-of-the-art of the research work conducted in this area.

In this section, we consider the challenges facing the successful deployment of dense networks, and hence the open problems for extensive research. In [7], the authors listed the main challenges facing UDN, and they explained the relevance of each challenge to the practical deployment of dense small cell BSs. Different from this, we delve into the research challenges that have not been addressed and we discuss the open problems that require further investigations.

- **User Association** The user association has been studied extensively in traditional networks and HetNets. However, in the scenario of dense networks, there are unique challenges that need to be considered and accurately investigated. The drastic interference between the nearby cells due to the LOS components requires proposing of novel association rules to exploit the idle mode capabilities of the small cell BSs. The backhauling is another interesting factor that must be considered while associating a user to a cell. Another challenge to the association of users to cells in a dense network is the mobility management, where fast users would generate many handover events if they are associated to cells with small coverage area. Effective collaborative-based solutions are required to account for these unique challenges.
  Another important open problem is the applicability of range expansion in dense scenarios where the interference would be a limiting factor. The common understanding is that 5G networks would be a mix of many radio access technologies (RATs) such as cellular networks, WiFi, and mmWaves networks. This introduces another research venue which is the multiple association of a user to many cells in individual or in different RATs. To explain, a user might connect to many small cells in a cellular network, or to a cell in a cellular network, to a WiFi access point, and to a mmWaves cell simultaneously. In [46], we investigated a multiple association setting to lay out a basic mathematical model and to understand the insights of such user association advancement. The backhaul-aware association of users are considered in HetNets [179], but in UDN, the study of backhaul-aware association is still an open problem. Moreover, the consideration of Quality-of-Service (QoS), and Quality-of-Experience (QoE) in dense networks is missing in the current published work, although it is very relevant to the admission of a given user to a given cell.
- **Backhauling** The backhauling is identified as the bottleneck for the wide deployment of dense networks. The provisioning of ideal backhaul to all small cells in a dense network is challenging. Accordingly, the wireless backhauling emerges as a viable alternative. There are many wireless backhauling techniques including mmWaves links, relays links, and massive-MIMO backhaul links. Certainly, one of the open problems is the study of the effect of the wireless backhauling on the user experience in a dense network environment. Another open problem is the consideration of realistic traffic distributions and user distributions to evaluate the performance of wireless backhauling networks in UDN.
- **Interference Management** Interference management is of a predominant influence on the operation of a dense network. Imagine a wireless network with immense number of cells that operate in co-channel scenario. Undoubtedly, the interference could be the limiting factor on the fruition of such dense network dispelling the densification gains. The coordinated interference management is challenging with such a large number of neighboring cells. The curse of dimensionality arose uniquely in dense networks while considering collaborative interference management. The consideration of idle mode capabilities in modelling interference problems in UDN would be another interesting problem. The performance evaluation of proactive turning off of lightly-loaded dominant interferers could yield interesting results. The reduced distance between the cells in the vicinity of the same user makes the interferes as strong as the servers due to the LOS components, and this uniquely challenges the interference management in dense networks. A multi-domain interference management is another interesting problem, where the interference management is performed in frequency, time, space domains simultaneously. Also, the consideration of realistic user and traffic distributions although beneficial, but still an open problem to consider in dense networks.
- **Energy Efficiency** The power consumption plays a main role in specifying the OPEX of a dense network. In spite of the small footprint of a small cell, the aggregate consumed power of a large number of such cells is immense. Energy efficiency refers to the number of transmitted bits per unit energy. Thus, increasing the energy efficiency conflicts with the link quality, and hence the QoS. The maximization of energy efficiency considering the user experience is an interesting model to be investigated in UDN. Another setting which has a great impact on the successful deployment of dense networks is the energy efficient wireless backhauling. Thus considering a joint backhaul-aware energy efficient association of users to cells in a dense network would yield interesting results.
- **Small Cell Discovery** The detection of cells in close proximity of a given user in a cellular network is crucial to the optimal operation of the network. However, this becomes more important and much harder in a densified network. Many small cells are in the vicinity of a user and the efficient detection of them is not an easy task. The main challenge in this context is how to manage the reuse of synchronization signals in neighbouring small cells, which are in the interference range of each other, in order to ease the cell discovery task. Optimization of cell discovery in terms of time and energy-efficiency is an open problem in UDN scenarios. Moreover, the exploitation of location data and fingerprints in optimizing small cell discovery [62] is an interesting direction to investigate.
- **Propagation Modelling** Another open research direction in the study of dense networks is the consideration of 3D channel modelling. Also, the consideration of multi-slope path loss models requires further investigation in different densification contexts. The modelling of channel fading to account for the propagation characteristics in UDN suggests the use of Rician fading model which requires further rigorous investigation.

## XI. Conclusion

The race towards 5G networks is fueled by the forecasts of the imminent traffic. Network densification is a prospective winner in this race and is expected to provide the required capacity and performance for the 2020 networks. In this survey, we presented an introduction to ultra-dense networks. Also, we reviewed the recent achievement in different research directions to develop an understanding of the state-of-the-art. More research activities are required to account for the fundamental differences of the UDN from traditional and HetNet cellular networks.

Moreover, further in-depth investigations are required to layout a concrete understanding of the control parameters to optimize the operation of a dense network. The trade-offs between different performance metrics such as the area spectral efficiency, the energy efficiency, the coverage/outage probability, and the network throughput require the understanding of the individual effect of the controlling parameters specifically the density of BSs, the number of antennae per BS, the transmission power, and the idle mode capabilities.

The fundamental differences in UDNs encourage the consideration of relevant and more appropriate propagation modelling techniques. The decreasing distance between adjacent cells increases the probability of LOS transmissions, and thus the need for multi-slope propagation model (e.g., different path loss exponent at different distances). Accordingly, and as a consequence for the same reason, the commonly used fading channel model in traditional networks (Rayleigh model) is no more accurate in the context of UDN. The consideration of Rician and Nakagami-m fading models become a necessity in dense networks and densified cells equipped with MIMO, respectively.

Another challenge in the accurate modelling of UDNs is the consideration of vertical densification where the small cell BSs are densified in the elevation plane. In this context, the 3D modelling of the dense cellular network is crucial to the performance evaluation of such densification alternative. Numerous challenges and open problems are presented and discussed in this survey in different disciplines to identify the research gaps for researchers and practitioners in this active area.

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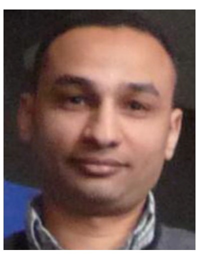

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