User Association in 5G Networks: A Survey and an Outlook

Dantong Liu, *Student Member, IEEE*, Lifeng Wang, *Member, IEEE*, Yue Chen, *Senior Member, IEEE*,
Maged Elkashlan, *Member, IEEE*, Kai-Kit Wong, *Fellow, IEEE*, Robert Schober, *Fellow, IEEE*,
and Lajos Hanzo, *Fellow, IEEE*

Abstract—The fifth generation (5G) mobile networks are envisioned to support the deluge of data traffic with reduced energy consumption and improved quality of service (QoS) provision. To this end, key enabling technologies, such as heterogeneous networks (HetNets), massive multiple-input multiple-output (MIMO), and millimeter wave (mmWave) techniques, have been identified to bring 5G to fruition. Regardless of the technology adopted, a user association mechanism is needed to determine whether a user is associated with a particular base station (BS) before data transmission commences. User association plays a pivotal role in enhancing the load balancing, the spectrum efficiency, and the energy efficiency of networks. The emerging 5G networks introduce numerous challenges and opportunities for the design of sophisticated user association mechanisms. Hence, substantial research efforts are dedicated to the issues of user association in HetNets, massive MIMO networks, mmWave networks, and energy harvesting networks. We introduce a taxonomy as a framework for systematically studying the existing user association algorithms. Based on the proposed taxonomy, we then proceed to present an extensive overview of the state-of-the-art in user association algorithms conceived for HetNets, massive MIMO, mmWave, and energy harvesting networks. Finally, we summarize the challenges as well as opportunities of user association in 5G and provide design guidelines and potential solutions for sophisticated user association mechanisms.

Index Terms—5G, user association, HetNets, massive MIMO, mmWave, energy harvesting.

I. INTRODUCTION

THE proliferation of multimedia infotainment applications and high-end devices (e.g., smartphones, tablets, wearable devices, laptops, machine-to-machine communication devices) exacerbates the demand for high data rate services. According to the latest visual network index (VNI) report from

Cisco [1], the global mobile data traffic will increase nearly tenfold between 2014 and 2019, reaching 24.3 exabytes per month by 2019, wherein three-fourths will be video. Researchers in the field of communications have reached a consensus that incremental improvements fail to meet the escalating data demands of the foreseeable future. A paradigm shift is required for the emerging fifth generation (5G) mobile networks [2].

The intensifying 5G debate fuels a worldwide competition. To secure Europe's global competitiveness, in the seventh framework programme (FP7), the European commission has launched more than 10 European Union (EU) projects, such as METIS [3], 5GNOW [4], iJOIN [5], TROPIC [6], MCN [7], COMBO [8], MOTO [9], and PHYLAWS [10] to address the architectural and functionality needs of 5G networks. Over the period from 2007 to 2013, the EU's investment into research on future networks amounted to more than €700 million, half of which was allocated to wireless technologies, contributing to the development of fourth generation (4G) and 5G systems. From 2014 to 2020, Horizon 2020 [11], which is the most extensive EU research and innovation programme, provides funding for the 5G-Public Private Partnership (5G-PPP) [12]. To elaborate, 5G-PPP focuses on improving the communications infrastructure with an EU budget in excess of €700 million for research, development, and innovation over the next seven years. On the other hand, the governments of China and South Korea have been particularly devoted to pursuing 5G development efforts. In China, three ministries—the Ministry of Industry and Information Technology (MIIT), the National Development and Reform Commission (NDRC) as well as the Ministry of Science and Technology (MOST)— set up an IMT-2020 (5G) Promotion Group in February 2013 to promote 5G technology research in China and to facilitate international communication and cooperation [13]. Meanwhile, South Korea has established a 5G forum [14], which is similar to the EU's 5G-PPP, and committed $1.5 billion for 5G development. Japan and the United States (US) have been less aggressive than the EU, China, and South Korea in setting national 5G research and development (R&D) initiatives; nevertheless, the Japanese and US companies have also been proactive, with both academic institutions and enterprises taking up the 5G mantle. In May 2014, NTT DoCoMo announced plans to conduct "experimental trials" of emerging 5G technologies together with six vendors: Alcatel-Lucent, Ericsson, Fujitsu, NEC, Nokia, and Samsung. The NYU wireless program [15], launched in August 2012 by New York University's
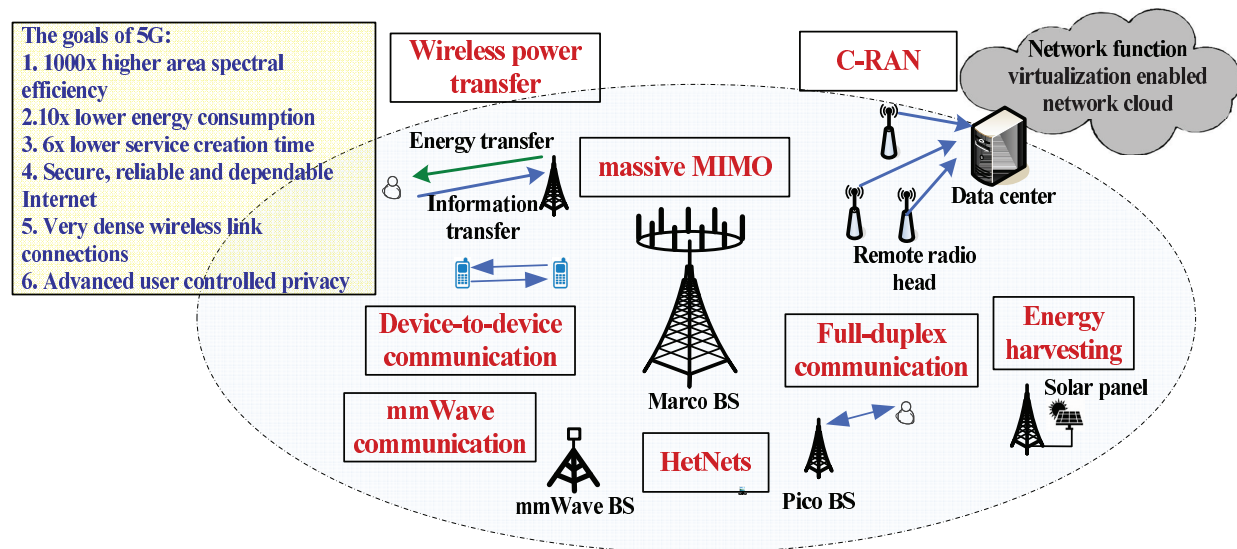
Fig. 1. Enabling technologies and expected goals of 5G networks.

Polytechnic School of Engineering, is working on millimeter wave (mmWave) technologies and other research deemed crucial for 5G.

The goals of 5G are broad, but are presumed to include the provision of at least 1,000 times higher wireless area spectral efficiency than current mobile networks. Other high-level key performance indicators (KPIs) envisioned by 5G-PPP include 10 times lower energy consumption per service, reduction of the average service creation time cycle from 90 hours to 90 minutes, creation of a secure, reliable, and dependable Internet with a "zero perceived" downtime for service provision, facilitation of very dense deployment of wireless communication links to connect over 7 trillion wireless devices serving over 7 billion people and enabling advanced user controlled privacy [12]. To achieve these KPIs, the primary technologies and approaches identified by Hossain *et al.* [16] for 5G networks are dense heterogeneous networks (HetNets), device-to-device (D2D) communication, full-duplex communication, massive multiple-input multiple-output (MIMO) as well as mmWave communication technologies, energy-aware communication and energy harvesting, cloud-based radio access networks (C-RANs), and the virtualization of wireless resources. More specifically, Andrews *et al.* [2] spotlight dense HetNets, mmWave, and massive MIMO as the "big three" of 5G technologies. Fig. 1 illustrates the enabling technologies and expected goals of 5G networks.

User association, namely associating a user with a particular serving base station (BS), substantially affects the network performance. In the existing Long Term Evolution (LTE)/LTE-Advanced (LTE-A) systems, the radio admission control entity is located in the radio resource control layer of the protocol stack, which decides whether a new radio-bearer admission request is admitted or rejected. The decision is made according to the quality of service (QoS) requirements of the requesting radio bearer, to the priority level of the request and to the availability of radio resources, with the goal of maximizing the radio resource exploitation [17]. In existing systems, the received power based user association rule is the most prevalent one [18], where a user will choose to associate with the specific BS, which provides the maximum received signal strength (max-RSS). The aforementioned new technologies and targets of 5G networks inevitably render such a rudimentary user association rule ineffective, and more sophisticated user association algorithms are needed for addressing the unique features of the emerging 5G networks.

Numerous excellent contributions have surveyed the radio resource allocation issues in wireless networks. Explicit insights for understanding HetNets have been provided in [19]–[21]. A range of theoretical models, practical constraints, and challenges of HetNets were discussed in [19]. Seven key factors of the cellular paradigm shift to HetNets were identified in [20]. An overview of load balancing in HetNets was given in [21]. Additionally, the authors of [22] presented recent advances in interference control, resource allocation, and self-organization in underlay based HetNets. Lee *et al.* [23] provided a comprehensive survey of radio resource allocation schemes for LTE/LTE-A HetNets. With the emphasis on green communication, Peng *et al.* [24] reviewed the emerging technologies conceived for improving the energy efficiency of wireless communications. The recent findings in energy efficient resource management designed for multicell cellular networks were surveyed in [25], while those designed for wireless local area networks (WLANs) and cellular networks were summarized in [26]. The benefits of BS sleep mode were considered in the same context in [27]. In terms of network selection and network modeling, [28] studied the mathematical modeling of network selection in heterogeneous wireless networks relying on different radio access technologies. A suite of game-theoretic approaches developed for network selection were investigated in [29]. In [30], stochastic geometry based models were surveyed in the context of both single-tier as well as multi-tier and cognitive cellular wireless networks.

While the aforementioned significant contributions have laid a solid foundation for the understanding of the diverse aspects

of radio resource allocation in wireless networks, the resource allocation philosophy of 5G networks is far from being well understood. The following treatises have surveyed the recent advances in 5G networks, such as the key enabling technologies and potential challenges [16], [31], the architecture visions [32], [33], the interference management [34], and the energy efficient resource allocation [35]. Nevertheless, user association in 5G networks was not highlighted in these works. To highlight the significance of user association in 5G networks, this paper commences with a survey of user association in the context of the "big three" 5G technologies, defined in [2]: HetNets, mmWave, and massive MIMO. We then address the important issues surrounding user association in energy harvesting networks. The challenges regarding user association in networks employing other 5G candidate technologies are also briefly elaborated on. Thereby, the contributions of this survey are fourfold, as summarized below.

1) We present a comprehensive survey on the recent advances in user association algorithms designed for HetNets. The challenges imposed by the inherent nature of HetNets are identified. Many of those were largely ignored by most of the existing user association algorithms, although they have a great impact on the network performance.

2) We investigate user association in the context of massive MIMO networks. The effects of massive MIMO on the received power, throughput, and energy efficiency are examined, and the existing solutions are reviewed. We highlight that the specific implementation of massive MIMO has a strong impact on user association and point out the fundamental aspects that should be carefully considered, when designing user association algorithms for massive MIMO networks.

3) We study user association in mmWave networks. We highlight that the mmWave channel characteristics play a key role in the user association design. A range of important factors are illustrated in order to underline opportunities and challenges of this new field.

4) We treat user association in energy harvesting networks, where we consider two specific energy harvesting mechanisms: energy harvesting from renewable energy sources and radio frequency (RF) energy harvesting. We also identify practical open challenges of user association in energy harvesting networks.

In a dynamic scenario, a problem closely related to user association is the *re-association/handover* problem. Deciding on when to trigger a re-association/handover is an equally important problem, and understandably has gained significant attention [36]–[38]. In this survey, we focus our attention on the extensive review of user association in 5G networks, but disperse with the survey of re-association/handover.

The rest of this paper is organized as follows. Section II presents a taxonomy which serves as a framework for systematically surveying the existing user association algorithms conceived for 5G networks. Section III elaborates on the existing user association algorithms for HetNets. The recent advances and open challenges of user association in massive MIMO and mmWave networks are discussed in Sections IV
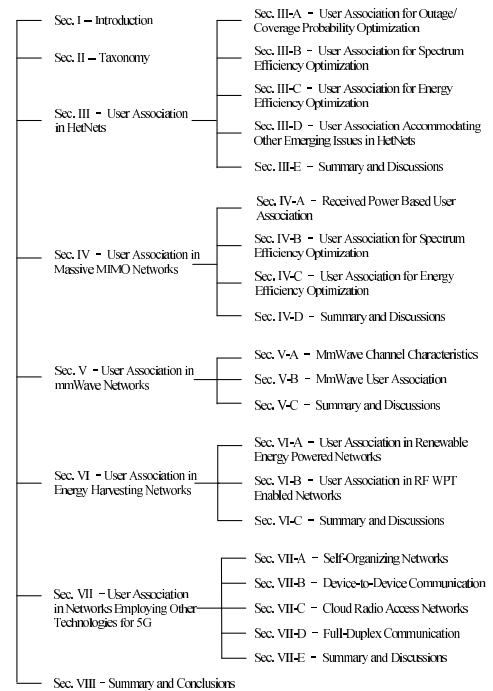

Fig. 2. The organization of this paper.

and V, respectively. In Section VI, user association algorithms designed for networks, which harvest energy from renewable energy sources and employ wireless power transfer (WPT) are surveyed. Section VII investigates the user association in networks employing other potential 5G technologies. Finally, the paper is concluded with design guidelines and conclusions in Section VIII and Section IX, respectively. For the sake of clarity, The summary of abbreviation is shown in Table I, the organization of this paper is shown in Fig. 2

II. TAXONOMY

To systematically survey the existing user association algorithms for 5G networks, we develop a taxonomy, which could serve as a framework that accounts for all design aspects and may be used for evaluating the advantages and disadvantages of the proposed algorithms. Fig. 3 illustrates the advocated taxonomy, which consists of five non-overlapping branches: (1) Scope, (2) Metrics, (3) Topology, (4) Control, (5) Model. Each branch is further subdivided into different categories, as detailed below.

A. Scope

- **HetNets**
  Cell densification constitutes a straightforward and effective approach of increasing the network capacity, which relies on densely reusing the spectrum across a geographical area and hence brings BSs closer to users. Specifically, the LTE-A standardization has already envisaged a multi-tier HetNets roll-out, which involved small cells underlaying macro-cellular networks. Small cells, such as picocells, femtocells and relays, transmit at a low power and serve as the fundamental element for the traffic offloading
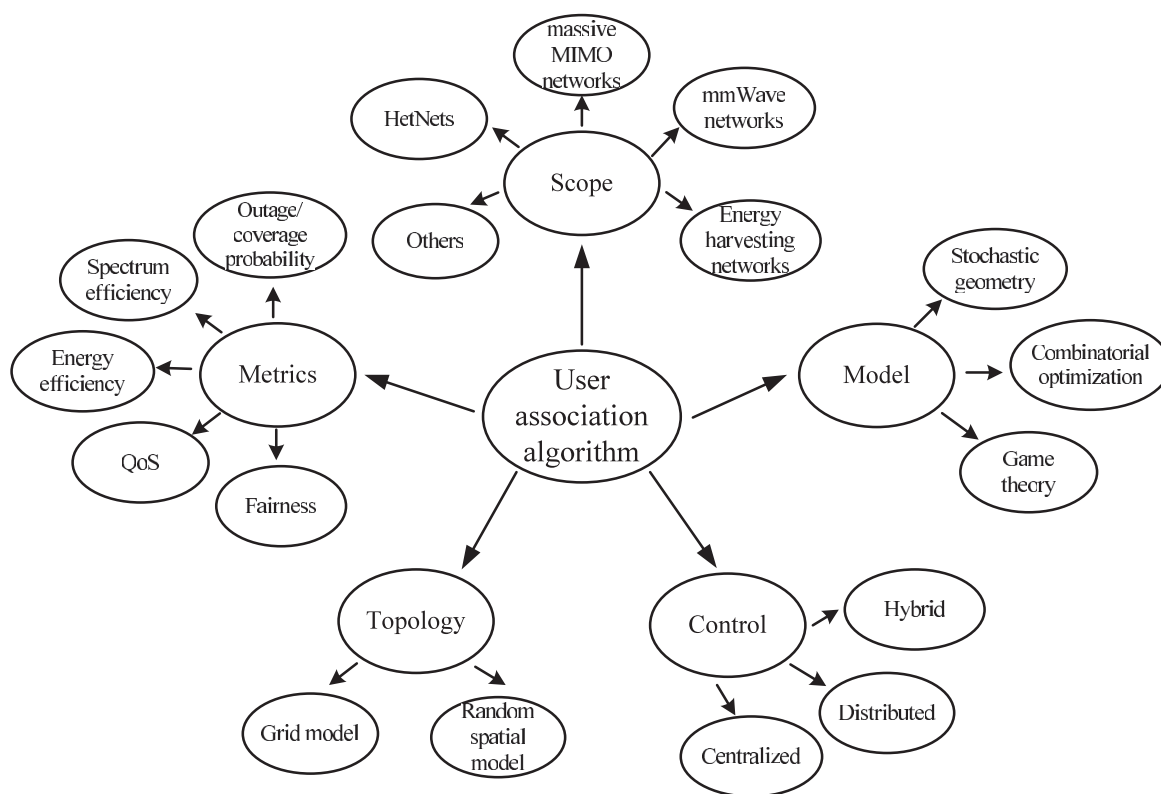
Fig. 3. The advocated taxonomy structure.

from macrocells, thereby improving the coverage quality and enhancing the cell-edge users' performance, whilst boosting both the area spectral efficiency and the energy efficiency [39]. As another benefit, this new palette of low power "miniature" BSs in small cells requires less upfront planning and lease costs, consequently reducing both the network's operational and capital expenditures (OPEX, CAPEX) [40]. The following details the features of small cells in HetNets.

– Picocells are covered by low-power operator-installed BSs relying on the same backhaul and access features as macrocells. They are usually deployed in a centralized manner, serving a few tens of users within a radio range of say 300 m or less, and have a typical transmit power ranging from 23 to 30 dBm [39]. Picocells do not require an air conditioning unit for the power amplifier, and incur much lower cost than traditional macro BSs [41].

– Femtocells, also known as home BSs or home eNBs, are low-cost, low-power, and user-deployed access points. Typically, a femtocell's coverage range is less than 50 m and its transmit power is less than 23 dBm. Femtocells operate in open or restricted (closed subscriber group) access [39].

– Relays are usually operator-deployed access points that route data from the macro BS to users and vice versa [39]. Relays are typically connected to the rest of the network via a wireless backhaul. They can be deployed both indoors and outdoors, with

the transmit power ranging from 23 to 33 dBm for outdoor deployment, and 20 dBm or less for indoor deployment [41].

- **Massive MIMO Networks**
Conventional MIMO is unable to achieve the high multiplexing gains required to meet the 5G KPIs, due to the limited number of antennas. By contrast, massive MIMO BSs with large antenna arrays are potentially capable of serving dozens of single-antenna users over the same time and frequency range [42]. The main features of massive MIMO are as follows.

– Massive MIMO achieves a high power-gain, hence significantly increasing the received signal power. Therefore, it necessitates a reduced transmit power to achieve a required QoS [43].

– Massive MIMO exhibits a high spectrum efficiency, which substantially improves the throughput. This is attributed to the fact that BSs having large antenna arrays are capable of serving more users [44].

– Channel estimation errors, hardware impairments, and small-scale fading effects are averaged out when the number of BS antennas is sufficiently high [45]. However, the so-called pilot contamination becomes the main performance limitation, which is due to reusing the same pilot signals in adjacent cells [45].

- **MmWave Networks**
Due to its large bandwidth, mmWave supports Gigabit wireless services. As mentioned in [46], mmWave can be a scalable solution for future wireless backhaul

networks. MmWave transmission has been adopted in several standards such as IEEE 802.15.3c [47] for indoor wireless personal networks (WPANs) and IEEE 802.11ad [48] for WLANs. As one of the key 5G techniques, mmWave systems exhibit the following features.

– Compared to the traditional low frequency communication systems, the path-loss experienced by high-frequency mmWave signals is increased by several orders of magnitude [49]. Hence, mmWave transmission is only suitable for short-range systems.

– In mmWave systems, highly directional communication relying on narrow beams is employed for achieving a high beamforming gain and for suppressing the interference arriving from neighboring cells [50].

– For a fixed array aperture, mmWave BSs pack more antennas into a given space and hence attain an increased array gain. They also adopt low-complexity analog beamforming/precoding schemes due to hardware constraints experienced at these high frequencies [51].

- **Energy Harvesting Networks**
  Recent developments in energy harvesting technologies have made the dream of self-sustaining devices and BSs potentially possible. As such, energy harvesting is highly desirable both for prolonging the battery life and for improving the energy efficiency of networks [16], [52]. According to the specific sources of the harvested energy, energy harvesting networks may be categorized as follows.

  – BSs and users may harvest renewable energy from the environment, such as solar energy or wind energy [16], [53]. However, the renewable energy is volatile, e.g., the daily solar energy generation peaks around noon, and decays during the later part of the day. This inherent intermittent nature of renewable energy challenges the reliable QoS provision in wireless networks [54]–[56].

  – Alternatively, BSs and users can harvest energy from ambient radio signals, relying on RF energy harvesting [57]–[62]. In this context, simultaneous wireless information and power transfer is envisaged as a promising technology for 5G wireless networks [16].

- **Other 5G Candidate Technologies**
  Apart from the aforementioned network types, networks employing other candidate technologies may also constitute imperative part of the wireless evolution to 5G. They are elaborated as follows.

  – Self-Organizing Networks (SONs) have the ability of self-configuration, self-optimization, and self-healing, which minimize the level of manual work. For these networks, multiple use cases are identified for network optimization [63].

  – Device-to-Device (D2D) communication allows direct transmission between devices for improving

the spectrum efficiency and energy efficiency. One of the key features in D2D communication is that it is controlled by BSs [64].

– Cloud Radio Access Networks (C-RAN) move the baseband units to the cloud for centralized processing, which significantly reduces CAPEX and OPEX. In the C-RAN, the backhaul between remote radio heads (RRHs) and base band units (BBUs) forms a key component [65].

– Full-duplex communication supports the downlink and uplink transmission at the same time and frequency resource, which enhances the spectrum efficiency. However, self-interference suppression plays a key role in full-duplex communication [66].

B. Metrics

For user association in 5G networks, different metrics have been adopted for determining which specific BS should serve which user. Five metrics are commonly used in this context: Outage/coverage probability, spectrum efficiency, energy efficiency, QoS, and fairness. In the related research literature, either one of the specified metrics or a combination of several of them is used.

- **Outage/coverage probability:** A crucial aspect in the evaluation and planning of a wireless network is the effect of co-channel interference imposed on radio links. The probabilities that the signal-to-interference-plus-noise ratio (SINR) drops below and rises above a certain threshold are defined as outage probability and coverage probability, respectively. The outage/coverage probability is crucial in terms of benchmarking the average throughput of a randomly chosen user in the network, and serves as a fundamental metric for network performance analysis and optimization [30], [67], [68].

- **Spectrum efficiency:** Spectrum efficiency refers to the maximum information rate that can be transmitted over a given bandwidth in a specific communication system. With the surge of data traffic and limited spectrum resources, a high spectrum efficiency is a mandatory requirement of 5G networks [69].

- **Energy efficiency:** Driven by environmental concerns, green communication has drawn tremendous attention from both industry and academia [26], [69]. Various energy efficiency metrics have been adopted in the literature to provide a quantitative analysis of the power saving potential of a certain algorithm. There are two main types of energy efficiency metrics:
  1) The ratio between the total data rate of all users and the total energy consumption (bits/Joule) [70]–[72].
  2) The direct presentation of the power/energy saving achieved by means of a certain algorithm (e.g., the difference in power/energy consumption before and after the adoption of a certain algorithm, the percentage of power saving, etc.) [71], [73], [74].

- **QoS:** As the salient performance metric experienced by users of the network, the QoS is of primary concern for network operators, whilst maintaining profitability. The

QoS provision can be quantitatively measured in terms of the traffic delay [54], the user throughput [70], [75], [76], the SINR [77], [78], etc., in order to cater for the heterogeneous requirements of today's and tomorrow's diverse multimedia infotainment applications and broadband-hungry mobile devices.

- **Fairness:** Facilitating fairness amongst users constitutes another important issue in the radio resource allocation of wireless networks. The traditional fairness problem is related to packet scheduling among users, where each user should receive a fair amount of radio resources for his/her wireless access. In HetNets, the fairness problem arises not only in scheduling within a traditional cell but also in the user association decision among cells in different tiers. Specifically, if radio resources are allocated on the basis that the lowest achievable rate among users is maximized, the allocation is said to be max-min fair [79], [80]. In other words, users with a poor channel quality will receive more radio resources and those having a good channel quality will receive a smaller proportion of radio resources. To evaluate fairness, the Jain's fairness index [81] has been widely adopted [75], [76], which is defined as

$$\mathcal{J}(r_1, \cdots r_n, \cdots r_N) = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N \sum_{n=1}^{N} r_n^2}. \qquad (1)$$

Jain's fairness index rates the fairness of a set of values where N is the number of users and r_n is the throughput of the n-th user.

C. Topology

Currently, there are two distinct approaches in modeling the topology of networks.

- **Grid model:** The grid model is widely used in the research of radio resource allocation in wireless networks, where all BSs are assumed to be located on a regular grid, (e.g., the traditional hexagonal grid model). For such a model, time-consuming Monte Carlo simulations are required for performance evaluation, and their mathematical analysis is often intractable.
- **Random spatial model:** The random spatial model is an emerging approach of modeling the topology of wireless networks. This model is capable of capturing the topological randomness in the network geometry. Employing tools from stochastic geometry, simple closed-form expressions can be derived for key performance metrics, which leads to tractable analytical results [30]. However, the accuracy of the results largely depends on whether the adoption of point processes routinely used in stochastic geometry is capable of appropriately capturing the characteristics of real network conditions.

Fig. 4 and Fig. 5 show a 3-tier HetNet topology for the grid model and the random spatial model, respectively.
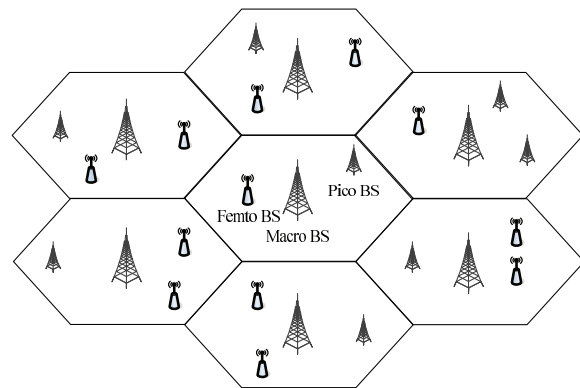

Fig. 4. A 3-tier HetNet topology for the grid model, where the macro BSs are located in the center of the hexagonal cell with the pico and femto BSs located along the macro BSs.
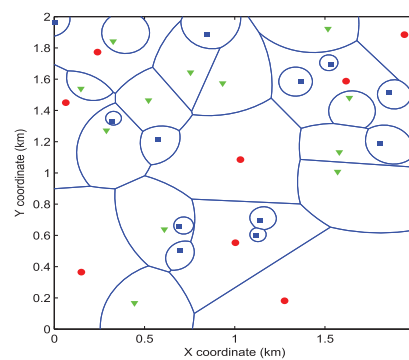

Fig. 5. A 3-tier HetNet following the random spatial model from stochastic geometry, where the macro BSs (red circle) are overlaid with pico BSs (green triangle) and femto BSs (blue square).

D. Control

The adopted control mechanisms heavily affect the computational complexity, the signaling overhead, and the optimality of user association algorithms. Broadly speaking, there are three different control mechanisms.

- **Centralized control:** In the centralized approach, the network contains a single central entity that performs resource allocation. This central entity collects information, such as the channel quality and the resource demand from all users. Based on the information obtained, the central entity decides which particular BS is to serve which user [82]–[84]. Centralized control is capable of providing optimal resource allocation for the entire network and exhibits a fast convergence, but the required amount of signaling may be excessive for medium to large-sized networks.
- **Distributed control:** By definition, distributed control does not require a central entity and allows BSs and users to make autonomous user association decisions by themselves through the interaction between BSs and users. Hence, distributed control is attractive owing to its low implementational complexity and low signaling overhead. It is particularly suitable for large networks, especially for HetNets associated with many autonomous femtocells [85], [86]. However, for distributed control,

users or BSs make autonomous decisions in a distributed manner, which may lead to the "Tragedy of the Commons" [87]. Explicitly, this describes a dilemma in which multiple individuals acting independently in their own self-interest, ultimately jam the limited shared resources even when it is clear that it is not in anyone's long term interest for this to happen.

- **Hybrid control:** Hybrid control relies on a compromise approach, which combines the advantages of both centralized and distributed control. For instance, the power control at the BS may rely on using a distributed method, whereas load balancing across the entire network could be implemented in a centralized manner [73].

E. Model

Utility is widely employed for modeling the user association problem. For making a decision, utility quantifies the satisfaction that a specific service provides for the decision maker [88]. Depending on the metric adopted, the utility relied upon in user association may be constituted of spectrum efficiency, energy efficiency, QoS, etc. In some recent studies, logarithmic [72], [85], exponential [76], [89], and sigmoidal [90] utility functions are utilized to model these attributes. By contrast, for studies which do not specifically discuss the choice of utility functions, we may safely assume that they use linear utility functions, namely that the utility is the spectrum efficiency, energy efficiency, or QoS itself. Combined with the utility based design, game theory, combinatorial optimization, and stochastic geometry are the prevalent tools popularly adopted for solving the user association problem.

- **Game theory:** Game theory is a mathematical modeling tool, which has distinct advantages in investigating the interaction of multiple players. The combination of strategies incorporating the best strategy for every player is known as *equilibrium* [28]. In particular, the solution of the game achieves *Nash Equilibrium*, if none of the players can increase its utility by changing his or her strategy without degrading the utility of the others [29]. Hence, game theory is a powerful tool which is also capable of solving user association problems. In this context, the players can be the BSs as in [72], [75], [76] or the users as in [91] or both as in [92]–[96], and the strategies are constituted of the corresponding user association decisions. In non-cooperative game theory modeling as in [91]–[93], [96], [97], the players seek to maximize their own utility and compete against each other by adopting different strategies, such as adjusting their transmit powers [91] or placing bids representing the willingness to pay [96]. By contrast, cooperative game theory models a bargaining game as in [72], [75], [76], where the players bargain with each other for the sake of attaining mutual advantages. Game theory is suitable for designing distributed algorithms endowed with flexible self-configuration features, despite only imposing a low communication overhead [29]. However, it is important to note that game theory operates under the assumption of rationality, that is, all players are rational individuals acting in their own best interest. However, in 5G networks, players — BSs or users — can not be guaranteed to act in a rational manner all the time [98]. For example, BSs involved in the game may have different optimization objectives, the one maximizing its energy efficiency will perhaps be perceived as non-rational by the other one maximizing its transmission rate and vice versa.

- **Combinatorial optimization:** Utility maximization under resource constraints constitutes a general modeling approach for user association in 5G networks, which is formulated as:

$$\max_{\mathbf{x}} \ \mathcal{U} = \sum_{m=1}^{M} \sum_{n=1}^{N} x_{mn} \mu_{mn},$$
$$\text{s.t.} \quad f_i(\mathbf{x}) \leq c_i, \ i = 1, \cdots, p, \tag{2}$$

where $\mathbf{x} = [x_{mn}]$ is the user association matrix, in which $x_{mn} = 1$, if user n is associated with BS m, otherwise $x_{mn} = 0$; $\mathcal{U}$ is the total network utility; μ_{mn} is the utility of user n, when associated with BS m; $f_i(\mathbf{x}) \leq c_i$ represents the resource constraints, such as spectrum constraints, power constraints, QoS requirements, etc. Since we normally assume that a specific user can only be associated with a single BS at any time, that is $x_{mn} = \{0, 1\}$, the resultant problem is a combinatorial optimization problem, which is in general NP-hard. In other words, performing an exhaustive search for solving the problem optimally is computationally prohibitive even for medium-sized networks. A popular method of overcoming this issue is to make the problem convex by relaxing the user association matrix from $x_{mn} = \{0, 1\}$ to $x_{mn} = [0, 1]$. Then, the classic Lagrangian dual analysis [99] can be invoked, followed by recovering the primal user association matrix $\mathbf{x}$ from the optimal dual problem. However, due to the discrete nature of primal combinatorial optimization, the relaxation of the user association matrix $\mathbf{x}$ may lead to a duality gap between the primal and dual problems [85], [86], [100].

- **Stochastic geometry**: Stochastic geometry constitutes an emerging modeling approach, which not only captures the topological randomness of the network geometry, but serendipitously leads to tractable analytical results. Stochastic geometry is a powerful mathematical and statistical tool conceived for the modeling, analysis, and design of wireless networks relying on random topologies [30]. In stochastic geometry based analysis, the network is assumed to obey a certain point process, which captures the network properties. More explicitly, depending on the particular network type as well as on the MAC layer behavior, a closely matching point process is selected for modeling the positions of the network entities. Examples of particular point processes include the Poisson point process (PPP), the Binomial point process (BPP), the Hard core point process (HCPP), and the Poisson cluster process (PCP), whose detailed definition can be found in [30], [101]. Based on the specific properties of the selected point process, analytical expressions can be derived for the interference, for the coverage probability, for the outage probability, etc. [67], [68], [78].

However, the performance metrics considered in most of the recent treatises are mainly based on Shannon's capacity formula. Despite the rich literature, the adoption of point processes that accurately capture the characteristics of 5G networks is still an open research challenge.

III. User Association in HetNets

Dense HetNets are likely to become the dominant theme during the wireless evolution towards 5G [102]. However, the conventional max-RSS user association rule is unsuitable for HetNets, since the transmit power disparity of marcocells and small cells will lead to the association of most of the users with the macro BS [103], hence potentially resulting in inefficient small cell deployment.

To cope with this problem, the concept of biased user association has been proposed by 3GPP in Release 10 [104], where the users' power received from the small cell BSs is artificially increased by adding a bias to it to ensure that more users will be associated with small cells. In [105], the macro-to-small cell off-loading benefits of biased user association were demonstrated in terms of the attainable capacity improvement. However, the drawback of biased user association is that the group of users, who are forced to be associated with small cells owing to the added bias, experience strong interference from the nearby macrocell [106]. In this context, the improvement achieved by offloading traffic to small cells might be offset by the strong interference. Therefore, the trade-off between network load balancing and network throughput strictly depends on the value of the selected bias, which has to be carefully optimized in order to maximize the network utility [34]. In [107], Q-learning was used for determining the bias value of each user, where each user independently learns from past experience the bias value that minimizes the number of users in outage. Moreover, several interference mitigation schemes based on resource partitioning have been proposed for solving the above problem in biased user association, including the inter-cell interference coordination (ICIC) technique proposed in 3GPP Release 8 and the enhanced inter-cell interference coordination (eICIC) solution advocated in 3GPP Release 10 [108]. The authors of [109] optimized both the bias value and the resource partitioning in eICIC enabled HetNets.

In this section, the existing research results on user association in HetNets are surveyed and categorized according to a diverse range of different performance metrics, as summarized in Table II, which provides a qualitative comparison of all user association algorithms conceived for HetNets and discussed in this section. In Table II, "-" means that the corresponding algorithm did not consider this metric, "UA" stands for user association, "DL" and "UL" represent downlink and uplink, respectively. Additionally, a range of open challenges in user association for HetNets are highlighted.

A. User Association for Outage/Coverage Probability Optimization

The outage/coverage probability is used for evaluating the performance of the desired user in wireless networks. In fact,

TABLE I
Summary of Abbreviation

5G	Fifth Generation
5G-PPP	5G-Public Private Partnership
AP	Access Point
BBU	Base Band Unit
BPP	Binomial Point Process
BS	Base Station
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CCO	Capacity and Coverage Optimization
CDF	Cumulative Distribution Function
CIR	Channel Impulse Response
CoMP	Coordinated Multipoint
C-RAN	Cloud Radio Access Network
D2D	Device-to-Device
DL	Downlink
eICIC	enhanced Inter-Cell Interference Coordination
EU	European Union
FDD	Frequency-Division Duplex
HetNets	Heterogeneous Networks
ICIC	Inter-Cell Interference Coordination
LOS	Line-Of-Sight
LTE	Long Term Evolution
LTE-A	LTE-Advanced
LZFBF	Linear ZF Beamforming
M2M	Machine-to-Machine
MIMO	Multiple-Input Mutiple-Output
MLB	Mobility Load Balancing
MRT	Maximum Ratio Transmission
NLOS	Non-Line-Of-Sight
mmWave	millimeter Wave
OFDMA	Orthogonal Frequency-Division Multiple Access
OPEX	Operational Expenditure
PCP	Poisson Cluster Process
PPP	Poisson Point Process
QoS	Quality of Service
RF	Radio Frequency
RRH	Remote Radio Head
RSS	Received Signal Strength
SIR	Signal-to-Interference Ratio
SI	Self-Interference
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-noise Ratio
SON	Self-Organizing Network
TDD	Time-Division Duplex
TPC	Transmit Pre-Coding
UA	User Association
UL	Uplink
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Network
WPT	Wireless Power Transfer
ZF	Zero-Forcing

the outage/coverage probability is the primary performance metric employed for user association analysis in conjunction with stochastic geometry. In particular, the authors of [67], [68] modeled and analyzed the performance of max-RSS user association in K-tier downlink HetNets with the aid of stochastic geometry. The coverage probability of interference limited underlay HetNets was presented, and the nature of cell loads experienced in K-tier HetNets was demonstrated in [67]. The authors showed that due to the high load difference amongst the coexisting network elements, some network elements might be idle and hence would not contribute to the aggregate interference level. Therefore, the SINR model of [67] was improved in [68] in order to account for the activity factor of the coexisting heterogeneous BSs. It was shown that adding lightly-loaded femtocells and picocells to the network increases the overall coverage probability. However, due to the random deployment of small cells coupled with the high transmit power difference with regard to the macro BSs, there might be some overloaded network elements (i.e., marcocell) and a large number of under-utilized small cells. By relying on an approach

TABLE II
QUALITATIVE COMPARISON OF USER ASSOCIATION ALGORITHMS FOR HETNETS

Ref.	Algorithm	Topology	Model	Direction	Control	Spectrum efficiency	Energy efficiency	QoS provision	Fairness	Coverage probability
[67]	max-RSS UA			DL	Distributed	Low	-	Moderate	-	Low
[68]	max-RSS UA			DL	Distributed	Moderate	-	Moderate	-	Moderate
[78]	max-RSS UA+ spectrum partitioning	Random spatial	Stochastic geometry	DL	Distributed	High	-	High	-	High
[110]	biased UA			DL	Distributed	Moderate	-	Moderate	-	Moderate
[111]	biased UA			DL	Distributed	Moderate	-	High	-	High
[112]	biased UA+spectrum partitioning			DL	Distributed	High	-	Moderate	-	Moderate
[113, 114]	biased UA+spectrum partitioning			DL	Distributed	High	-	Moderate	-	High
[115]	biased UA+spectrum partitioning			DL/UL	Distributed	High	-	Moderate	-	High
[77]	biased UA+BS sleeping			DL	Distributed	-	High	High	-	High
[116]	UA			DL	Centralized	High	-	Moderate	Low	-
[85]	UA			DL	Distributed	Moderate	-	Moderate	High	-
[117]	UA			DL	Centralized	High	-	-	-	-
[70]	UA			DL	Distributed	-	High	High	Low	-
[82]	UA			DL	Centralized	High	High	High	-	-
[83, 84]	UA+spectrum partitioning	Grid	Combinatorial optimization	DL	Centralized	Moderate	-	Moderate	High	-
[118]	UA+spectrum partitioning			DL	Centralized	High	-	Moderate	Moderate	-
[86]	UA+power control			DL	Distributed	High	-	Moderate	High	-
[119, 120]	UA+power control			DL	Distributed	High	-	High	High	-
[121]	UA+power control			UL	Centralized	-	High	High	Low	-
[73]	UA+power control			DL	Hybrid	-	High	High	Moderate	-
[122]	UA+power control			DL	Centralized	Moderate	High	-	-	-
[71]	UA+BS sleeping			DL	Centralized	-	High	Moderate	High	-
[74]	UA+BS sleeping			DL	Distributed	-	High	High	-	-
[75]	UA			DL	Distributed	Moderate	-	Moderate	High	-
[76]	UA			DL	Distributed	Moderate	-	High	High	-
[92]	UA			DL	Distributed	High	-	Moderate	High	-
[93, 97]	UA	Grid	Game theory	DL	Distributed	Moderate	-	High	Moderate	-
[95]	UA			UL	Distributed	Moderate	-	High	Moderate	-
[91]	UA+power control			UL	Distributed	High	-	High	High	-
[96]	UA+power control			UL	Distributed	High	-	Moderate	High	-

similar to the one used in [67], [68], the authors of [78] first derived the coverage probability for each tier under different spectrum allocation and femtocell access policies, and then formulated the throughput maximization problem subject to specific QoS constraints expressed in terms of both coverage probabilities and per-tier minimum rates. The results provided beneficial insights into the optimal spectrum allocation.

The effect of biased user association was investigated in the context of multi-tier downlink HetNets in [110] and [111] with the aid of stochastic geometry, where the optimal bias resulting in the highest signal-to-interference ratio (SIR) and the highest rate coverage were determined using numerical evaluation techniques. Biased user association and spectrum partitioning between the macrocell and small cells were considered in [112]–[114]. The authors of [112] analyzed the coverage guaranteeing a certain throughput for a two-tier topology and provided insights concerning the most appropriate spectrum partitioning ratio based on numerical investigations. For a general multi-tier network, spectrum partitioning and user association were optimized in the downlink analytically in terms of the attainable coverage probability in [113] and the coverage guaranteeing a certain throughput in [114]. In contrast to the aforementioned works on downlink HetNets, in [115] the optimal user association bias and spectrum partitioning ratios were derived analytically for the maximization of the proportionally fair utility of the network based on the coverage probability both in the downlink and uplink of HetNets. The results revealed that the optimal uplink and downlink user association biases are not identical, thereby reflecting the tradeoff between uplink and downlink performance in HetNets, when the users are constrained to associate with the same BS in both uplink and downlink.

A qualitative comparison of the above-mentioned user association algorithms for coverage probability optimization in HetNets is provided in Table II.

B. User Association for Spectrum Efficiency Optimization

Spectrum efficiency is a widely accepted network performance metric. In [116], dynamic user association was proposed for the downlink of HetNets in order to maximize the sum rate of all users. The authors derived an upper bound on the downlink sum rate using convex optimization and then proposed a heuristic user association rule having a low complexity and approaching the performance upper bound. Their simulation results verified the superiority of the proposed heuristic user association rule over the classic max-RSS and biased user association in terms of the average user data rate. However, it is widely recognized that maximizing the sum data rate of all users may result in an unfair data rate allocation, which was also reflected by the results of [116, Fig. 3]. Based on [116, Fig. 3], we can observe that the load of small cells is much heavier than that of macrocells, hence resulting in small cells that are congested. Consequently, only the privileged users in the macrocell center achieve high data rates, while the other users are starved. To cope with this problem, in [85] a low-complexity distributed user association algorithm was proposed for maximizing the user data rate related utility, which was defined as a logarithmic function of the user data rate. Since the logarithm is a concave function and has diminishing returns, allocating more resources to an already well-served user has low priority, whereas providing more resources to users having low rates is desirable, thereby encouraging both load balancing

and user fairness. In [85], by relaxing the primal deterministic user association to a fractional association, the intractable primal combinatorial optimization problem was converted into a convex optimization scenario. By exploiting the convexity of the problem, a distributed user association algorithm was developed with the assistance of dual decomposition and the gradient descent method, which converged to the optimum solution under the guarantee of not exceeding a certain maximum discrepancy from optimality. We note that the convergence speed of the gradient descent method heavily depends on the particular choice of the step size. For the same problem formulation as in [85], a coordinate descent method was proposed in [86] for providing a rigorous performance guarantee and faster convergence compared to the algorithm in [85]. In [117], the user association in femtocell networks was formulated as a combinatorial problem for minimization of the latency of service requested by the users, which was solved with the aid of approximation algorithms achieving a proven performance bound.

Game theory is also widely applied in the context of user association for spectrum efficiency optimization. The downlink user association for HetNets was formulated as a bargaining problem in [75], [76], where the BSs acted as players competing for serving users. In [75], a bargaining problem was formulated for the maximization of the data rate based utility, while guaranteeing a certain minimal rate for the users, and simultaneously maintaining fairness for all users as well as balancing the traffic load of the cells in different tiers. By extending the contribution of [75], the QoS was maintained for multi-service traffic in [76], where an opportunistic user association algorithm was developed for classifying human-to-human traffic as the primary service and machine-to-machine traffic as the secondary service. The proposed opportunistic user association aimed for providing fair resource allocation for the secondary service without jeopardizing the QoS of the primary service. Furthermore, the authors of [92], [93], [97] formulated the downlink user association in HetNets as a many-to-one matching game, where users and BSs evaluated each other based on well defined utilities. In [92], users and BSs ranked one another based on specific utility functions that accounted for both the data rate and the fairness to cell edge users, which was captured in terms of carefully coordinated priorities. In contrast to [92], which relied on differentiating user priorities, in [93] the delivery time, handover failure probability, and heterogeneous QoS requirements of users were taken into consideration when designing utility based user association. With the aid of a problem formulation similar to the one in [93], the authors of [97] specifically focused their attention on multimedia data services and characterized the user's quality of experience in terms of mean opinion scores that accurately reflected the specific characteristics of the wireless application considered. Another interesting study was disseminated in [95], where the uplink user association of HetNets was formulated as a college admission game combined with transfers, where a number of colleges, i.e., the BSs in macrocells and small cells, sought to recruit a number of students, i.e., users. The college admission game formulated carefully captures the users' need to optimize their packet success rates and delays, as well as the

small cell's incentive to offload traffic from the macrocell and thereby to extend its coverage.

The densely deployed small cells further exacerbate the demand for interference management in HetNets. The joint optimization of user association and of other aspects of radio resource allocation understandably has prompted significant research efforts. In [83], joint optimization of user association and channel allocation decisions between macrocells and small cells was investigated with the objective of maximizing the minimum data rate. Extending the advance proposed in [83], in [84] joint user association, transmission coordination, and channel allocation between macrocells and small cells was proposed for the sake of maximizing the data rate based utility. Joint user association and power control was investigated in the context of the downlink of HetNets in [86], [119], [120], and for the uplink of HetNets in [91], [96]. The algorithms proposed in [86], [91], [119], [120] iteratively updated both the user association solution and the transmit power until convergence was attained. The authors of [96] formulated the sum throughput maximization problem as a non-cooperative game, with both users and BSs acting as players. In [118], a cooperative small cell network architecture was proposed, where both user association as well as spectrum allocation and interference coordination were implemented through the cooperation of neighbouring cells, so as to enhance the capacity of hotspots. We note that the aforementioned joint optimization of user association and channel allocation/power control turns out to be NP-hard, hence finding the optimal solution is not trivial. The solution may be approached for example by updating the user association and the power level sequentially in an iterative manner until convergence is reached as in [86], [91], [119], [120]. Alternatively, the user association may first be optimized with the aid of fixed channel allocation/transmission coordination and then followed by optimizing the channel allocation/transmission coordination accordingly and vice versa, as in [83], [84], [96], [118]. As a result, we may conclude that careful user association optimization is crucial for the holistic optimization of HetNets, indisputably underlining the significance of a survey on user association.

The qualitative comparison of the above-mentioned user association algorithms for spectrum efficiency optimization in HetNets is detailed in Table II.

C. User Association for Energy Efficiency Optimization

The escalating data traffic volume and the dramatic expansion of the network infrastructure will inevitably trigger an increased energy consumption in wireless networks. This will directly increase the greenhouse gas emissions and mandate an ever increasing attention to the protection of the environment. Consequently, both industry and academia are engaged in working towards enhancing the network energy efficiency.

Maximizing the network energy efficiency may be supported by maximizing the amount of successfully sent data, while minimizing the total energy consumption. As far as the problem formulation is concerned, maximizing the network energy efficiency can be either expressed as minimizing the total energy consumption while satisfying the associated traffic demands or

maximizing the ratio between the total data rate of all users and the total energy consumption of the network, which is defined as the overall energy efficiency (bits/Joule). Note that macrocells have a significantly higher transmit power than small cells, thus the access network energy consumption is typically higher when a user is associated with a macrocell. Hence, the network energy efficiency is crucially dependent on the user association decisions [123].

Numerous valuable contributions have been published on energy efficient user association in HetNets [70], [73], [82], [121], [122]. In [121], a user association algorithm was developed for the uplink of HetNets in order to maximize the system energy efficiency subject to users' maximum transmit power and minimum rate constraints. In [70], user association for the downlink of HetNets was optimized by maximizing the ratio between the total data rate of all users and the total energy consumption. In contrast to the problem formulation in [70], in [73] the authors investigated energy efficient user association by minimizing the total power consumption, while satisfying the users' traffic demand. The authors of [82] considered the association problem for users involving video applications, where a video content aware energy efficient user association algorithm was proposed for the downlink of HetNets, with the goal of maximizing the ratio of the peak-signal-to-noise-ratio and the system energy consumption. Thereby, both nonlinear fractional programming and dual decomposition techniques were adopted for solving the problem. In [122], a Benders' decomposition [124] based algorithm was developed for joint user association and power control with the goal of maximizing the downlink throughput. This was achieved by associating every user with the specific BS, which resulted in the minimization of the total transmit power consumption.

Statistical studies of mobile communication systems have shown that 57% of the total energy consumption of wireless networks can be attributed to the radio access nodes [125]. Furthermore, about 60% of the power dissipated at each BS is consumed by the signal processing circuits and air conditioning [126]. As a result, shutting down BSs which support no active users is believed to be an efficient way of reducing the network power consumption [24], [25].

In [71], joint optimization of the long-term BS sleep-mode operation, user association, and subcarrier allocation was considered for maximizing the energy efficiency or minimizing the total power consumption under the constraints of maintaining an average sum rate target and rate fairness. The performance of these two formulations (namely, energy efficiency maximization and total power minimization) was investigated using simulations. In [74], an energy efficient algorithm was introduced for minimizing the energy consumption by beneficially adjusting both the user association and the BS sleep-mode operations, where the dependence of the energy consumption both on the spatio-temporal variations of traffic demands and on the internal hardware components of BSs were considered. Additionally, in [77] the coverage probability and the energy efficiency of K-tier heterogeneous wireless networks were derived under different sleep-mode operations using a stochastic geometry based model. The authors formulated both power consumption minimization as well as energy efficiency

maximization problems and determined the optimal operating regimes of the macrocell.

The qualitative comparison of the above-mentioned user association algorithms for energy efficiency optimization in HetNets is detailed in Table II.

D. User Association Accommodating Other Emerging Issues in HetNets

Apart from the transmit power disparity between small cells and macrocells in HetNets, the inherent nature of HetNets manifests itself in terms of the uplink-downlink asymmetry, the backhaul bottleneck, diverse footprints and so on. This imposes substantial challenges for the user association design. However, these issues have only briefly been alluded to in the majority of the existing research. In the following, we highlight three crucial issues, as summarized in Table III.

1) Uplink-Downlink Asymmetry: Most of the research on user association in HetNets investigated the problem from either a downlink or an uplink perspective. However, HetNets typically introduce an asymmetry between uplink and downlink in terms of the channel quality, the amount of traffic, coverage, and the hardware limitations. Amongst them, the uplink and downlink coverage asymmetry is the more severe in HetNets. In the downlink, due to the large power disparities between the different BS types in a HetNet, macrocells have much larger coverage areas than small cells. By contrast, the users' devices may transmit at the same power level in the uplink, regardless of the BS type. Although some promising results related to decoupling of the uplink and downlink user association have been reported in [143]–[145], this decoupling inevitably requires a tight synchronization as well as a high-speed and low-delay data connectivity between BSs. Ever since the inception of mobile telephony, users have been constrained to associate with the same BS in both the downlink and uplink directions, since this coupling makes it easier to design and operate the logical, transport, and physical channels [146]. Hence, a coupling of uplink and downlink may also be expected for 5G networks. Due to the uplink-downlink coverage asymmetry of HetNets, a user association that is optimal for either the downlink or the uplink may become less effective for the opposite direction. Specifically, the max downlink RSS based user association rule may associate a user with the far-away marcocell, rather than with the nearby small cell. As a result, the user has to transmit at a potentially excessive power for guaranteeing the target received signal strength in the uplink, thereby inflicting a high uplink interference on the small cell users, hence degrading both the spectrum and energy efficiencies as well as shortening the battery recharge period. We note that the uplink-downlink asymmetry exists, regardless of whether time-division duplex (TDD) or frequency-division duplex (FDD) is adopted for separating the uplink and downlink transmissions in HetNets.

Consequently, in HetNets using sophisticated joint uplink and downlink user association optimization is imperative. Hence, the authors of [127] proposed a user association algorithm, which jointly maximized the number of users admitted and minimized the weighted total uplink power consumption.

Issues	Example	Key point	Ref.
Uplink-downlink asymmetry	HetNets introduce a major asymmetry between the uplink and the downlink. The optimal user association for downlink or uplink will be less effective for the opposite direction.	Optimize downlink and uplink performance jointly in the user association design.	[72, 127–129]
Backhaul bottleneck	Densely deployed small BSs may introduce overwhelming traffic augments for the backhaul link and current small cell backhaul solutions cannot provide sufficiently large data rate.	Design backhaul-aware user association for HetNets.	[79, 123, 130–135]
Mobility support	User association without considering user mobility may result in frequent handovers among the cells in HetNets.	Account for the user mobility when making the user association decision in HetNets to enhance the long-term system-level performance and avoid excessive handovers.	[136–142]

However, the performance of the algorithm highly depended on the specific weight, which was heuristically obtained in [127]. The objective function used in [127] was further improved in [128] so as to maximize the network utility, which was based on the ratio between the downlink data rate and the uplink power consumption. In [72], the user association optimization problem was formulated as a bargaining problem configured for maximizing the sum of uplink and downlink energy efficiency related utilities. In [129], a user association and beamforming algorithm was developed for minimizing the total uplink and downlink energy consumption, under specific QoS constraints for the users.

2) Backhaul Bottleneck: HetNets are expected to constitute a cellular paradigm shift, which raises new research challenges. Among these challenges, the importance of the backhaul bottleneck has not been fully recognized in the context of the 4G LTE network [20]. Specifically, most of the research assumed a perfect backhaul between the BS and the network controller, and focused on the achievable performance gains of the wireless front-end without taking into account the specific details of the backhaul implementation and any possible backhaul bottleneck. This assumption is generally correct for well-planned classical macrocells. However, in HetNets the potentially densely deployed small BSs may impose an overwhelming backhaul traffic. On the other hand, the current small cell backhaul solutions, such as xDSL and non-line-of-sight (NLOS) microwave, are far from an ideal backhaul solution owing to their limited data rate [147]. As already observed in [102], the full benefits of dense HetNets can be realized only if they are supported by the careful consideration of the backhaul. Hence, the backhaul capacity constraint is of considerable importance in HetNets.

Therefore, for HetNets, backhaul-aware user association mechanisms, which fully take the backhaul capacity constraint into account, are needed. A distributed user association algorithm was developed for maximizing the network-wide spectrum efficiency in [130] involving relaxed combinatorial optimization. Similarly, a sum of the user rate based utility was investigated in [131] under backhaul constraints. In [132], a waterfilling-like user association algorithm was devised for maximizing the weighted sum rate of all users in conjunction with carrier aggregation (CA), while enforcing a particular backhaul constraint for small cell BSs. Furthermore, the authors of [133] conceived a heuristic user association algorithm for maximizing the overall network capacity under both backhaul

capacity and cell load constraints. In [134], cache-aware user association was designed using the power of game theory in backhaul-constrained HetNets, which was modeled as a one-to-many matching game. Specifically, the users' and BSs' association were characterized based on the capacity and by giving cognizance to the utility that accounted for both the BSs' data storage capabilities and the users' mobility patterns. The authors of [135] presented an intriguing model, where third parties provided the BSs with backhaul connections and leased out the excessive capacity of their networks to cellular providers, when available, presumably at a significantly lower cost than that of QoS guaranteed connections. The authors provided a general user association optimization algorithm that enabled the cellular provider to dynamically determine which specific users should be assigned to third-party femtocells based on the prevalent traffic demands, interference levels as well as channel conditions and third-party access pricing. With user fairness in mind, the authors of [79] considered the joint resource allocation across wireless links and the flow control within the backhaul network for maximizing the minimum rate among all users. Turning our attention to energy efficiency, Mesodiakaki *et al.* [123] studied energy efficient user association issues of HetNets by taking both the access network's and the backhaul's energy consumption into account.

3) Mobility Support: The increased cell densification encountered in HetNets continuously poses challenges for mobility support. The reduced transmit powers of small cells lead to reduced footprints. As a result, for a user having moderate or high mobility, a user association algorithm that does not consider the mobility issues may result in more frequent handovers among the cells in HetNets compared to conventional homogeneous cellular networks. However, it is well understood that handovers trigger a whole host of complex procedures, impose costly overheads as well as undesirable handover delays and possibly dropped calls. Moreover, as shown in a 3GPP technical report [148], the handover performance experienced in HetNets is typically not as good as that in systems with pure macrocell deployment. Hence, it is imperative to account for user mobility, when making user association decisions in HetNets in order to enhance the long-term system-level performance and to avoid excessive handovers.

Taking advantage of stochastic geometry, the authors of [136] first derived the downlink coverage probability considering the users' speed, under the biased user association rule. Then, the optimal bias maximizing the coverage was obtained,

where both the optimal bias and the coverage probability were related to the users' speed. Not surprisingly, the results in [136] revealed that a speed-dependent bias factor was capable of effectively improving both the coverage probability and the overall network performance. In [137], the authors modeled the user mobility by a Markov modulated Poisson process [149] and jointly considered it with the user association problem with the goal of optimizing the system performance in terms of the average traffic delay and the blocking probability. Moharir *et al.* [138] studied user association in conjunction with the effect of mobility in two-tier downlink HetNets and showed that traditional algorithms that only forwarded each packet at most once either to a BS or to a mobile user had a poor delay performance. This unexpected trend prevailed, because the rapidly fluctuating association dynamics between BSs and users necessitated a multi-point relaying strategy, where multiple BSs stored redundant copies of the data and coordinated for reliably delivering the data to mobile users. The authors of [139], [140] provided an interesting framework, where Q-learning was adopted for finding the best user association in a non-stationary femtocell network by exploring the past cellular behavior and predicting the potential future states, so as to minimize the frequency of handovers.

Recently, dual connectivity has been standardized in 3GPP release 12 [150]–[152] as a remedy for mobility support in HetNets. Dual connectivity can significantly improve the mobility resilience and increase the attainable user throughput due to its potential of extending the CA and coordinated multi-point (CoMP) to multiple BSs, which allows users to be simultaneously associated with both macro BSs and small cell BSs. More specifically, dual connectivity enables a user to maintain the connection to the macro BS and receive signalling messages as long as it is in its coverage area. This user does not have to initiate handover procedures unless moving to the coverage of another macro BS, thereby indisputably handling the handover more efficiently. User association, which determines the specific BSs the user should associate with, pre-determines the relative performance gain achievable with dual connectivity. In [141], the impact of different user association criteria on the attainable performance of dual connectivity was evaluated via simulations. In [142], the user association problem for maximization of the sum rate of all users was formulated, and a low-complexity sub-optimal user association algorithm was proposed for solving the problem. It is noted that despite the potential benefits of dual connectivity in enhancing the resilience to user mobility and increasing the user throughput, dual connectivity also imposes several technical challenges in terms of buffer status report calculation and reporting, transmission power management, etc. [153]. As such, more efforts have to be devoted to tackling these issues before fully deploying dual connectivity for enhanced mobility support in HetNets.

E. Summary and Discussions

Supporting QoS, spectrum efficiency, energy efficiency and fairness in 5G networks is an essential requirement for real-time applications. How to address these performance metrics at the user association stage is becoming increasingly important [69]. From Table II, we observe that most existing research contributions do not take all of these metrics into account.

A theoretical analysis of the tradeoffs between the energy efficiency and spectrum efficiency under the additional consideration of the user QoS and fairness was carried out for downlink orthogonal frequency-division multiple access (OFDMA) scenarios in [154] and for homogeneous cellular networks in [155]. A similar tradeoff is expected for HetNets. However, how to characterize this tradeoff with closed-form expressions remains an open challenge, since HetNets are much more complex than conventional homogeneous networks. As such, more research is required for theoretically analyzing the tradeoff amongst the attainable spectrum efficiency, energy efficiency, QoS, and fairness in HetNets, which can provide deep engineering insights regarding the interplay of these performance metrics. This could provide guidelines for conceiving user association strategies that simultaneously cater to all of these performance metrics.

Apart from the above-mentioned interplay of the performance metrics, the inherent nature of HetNets has imposed a plethora of challenging issues, such as the uplink and downlink asymmetry, the backhaul bottleneck, and the need for efficient mobility support. All these issues have been set aside for future research by the majority of the existing works. Although there is some initial research addressing each one of the above issues in the context of user association algorithm design as shown in Table III, these topics are still in their infancy and more theoretical analysis as well as practical independent verification is required.

Finally, most of the existing contributions on user association conceived for HetNets focus on either optimisation or theoretical performance analysis. The application of theoretical results to realistic models and practical systems is still an open area. To make further progress, conceiving a holistic architecture, which employs the aforementioned advanced technologies to provide improved QoS, spectrum efficiency, energy efficiency, and fairness, as well as accounting for the issues imposed by the inherent nature of HetNets becomes highly desirable for 5G evolution.

IV. User Association in Massive MIMO Networks

Massive MIMO [156] constitutes a fundamental technology for achieving the ambitious goals of 5G systems and hence it has attracted substantial interests from both academia and industry. This new design paradigm may be viewed as a large-scale multi-user MIMO technology, where each BS is equipped with a large antenna array and communicates with multiple terminals over the same time and frequency band by distinguishing the users with the aid of their unique user-specific channel impulse response (CIR) [42]. Compared to current small scale MIMO networks, massive MIMO systems achieve high power and spectrum efficiencies, despite their low-complexity transceiver designs. Random impairments, such as small-scale fading and noise, are averaged out, when a sufficiently high number of antennas are deployed at the BS [43]. Moreover, the effects of interference, channel estimation errors, and hardware impairments [157] vanish, when the number of

Ref.	Algorithm	Topology	Model	Direction	Control	Spectrum efficiency	Energy efficiency	QoS provision	Fairness	Coverage probability
[159]	max-RSS UA	Random	Stochastic	DL	Distributed	Low	-	Moderate	-	Low
[160]	biased UA	spatial	geometry	DL	Distributed	High	High	-	-	Moderate
[80]	UA	Grid	Game	DL	Distributed	High	-	Moderate	High	-
[161]	UA		theory	DL	Centralized/Distributed	High	-	Moderate	High	-
[131]	UA	Grid	Combinatorial	DL	Centralized	High	-	High	High	-
[100]	UA		optimization	DL	Distributed	-	High	High	High	-

antennas becomes sufficiently high, leaving only the notorious pilot contamination problem as the performance-limiting factor [45]. The implementation of massive MIMO is also beneficial in other networks, such as cognitive radio networks. It was shown in [158] that when the number of primary users was proportional to the number of antennas at the primary BS, the number of antennas at the secondary BS should be larger than the logarithm of the number of primary users, in order to mitigate the effects of interference.

The distinct characteristics of massive MIMO inevitably necessitate the redesign of user association algorithms. On the one hand, BSs equipped with large antenna arrays provide high multiplexing gains and array gains. On the other hand, the power consumption increases due to the more complex digital signal processing. In the following, we investigate the effects of massive MIMO on user association in terms of the received power, throughput, and energy efficiency. Table IV illustrates the qualitative comparison of existing user association algorithms conceived for massive MIMO networks.

A. Received Power-Based User Association

In the massive MIMO downlink, the N-antenna BS typically uses linear transmit pre-coding (TPC) schemes to transmit data signals to S users relying on the knowledge of the downlink CIR, which facilitates the use of a low-complexity single-user receiver. There are two commonly used TPC schemes, i.e., maximum ratio transmission (MRT) and zero-forcing (ZF) TPC [44]. For MRT, the power received at the user is proportional to N. For ZF TPC, the intra-cell interference is cancelled at the cost of reducing the degrees of freedom and hence the diversity order to $(N - S + 1)$ [162]. For instance, by using ZF TPC with equal power allocation, the long-term average power received at the intended user can be expressed as

$$P_r = (N - S + 1) \cdot \frac{P_t}{S} \cdot L, \qquad (3)$$

where P_t is the BS's transmit power and L is the path-loss. Eq. (3) reveals that for user association based on the maximum received power, the cell coverage is expanded due to the large antenna array gain.

In HetNets, massive MIMO may be adopted in macrocells, since the physically large macro BSs can be readily equipped with large antenna arrays [163]. In [159], a stochastic geometry based approach is invoked for analyzing the impact of massive MIMO on the max-RSS user association. Considering a two-tier HetNet consisting of macrocells and picocells, Fig. 6 shows the probability that a user is associated with the macro BS relying on the max-RSS user association. We observe that
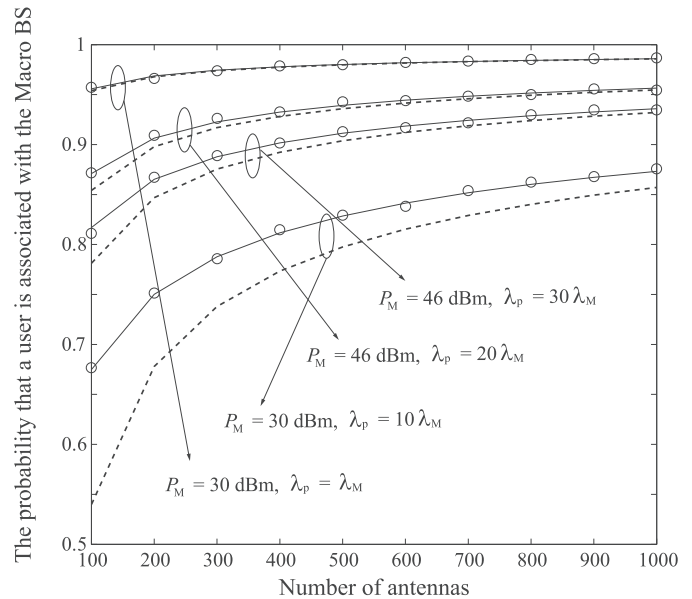

Fig. 6. The probability that a user is associated with the macro BS. The locations of the macro BSs and the pico BSs follow independent homogeneous Poisson point processes with densities λ_M and λ_p, respectively. The carrier frequency is 1 GHz, $S = 5$, P_M is the macro BS transmit power, and $P_p = 30$ dBm is the pico BS transmit power. The solid lines are validated by Monte Carlo simulations marked with 'o' and the dashed lines represent the asymptotic results as the number of antennas goes towards infinity.

even when the macro BS reduces its transmit power to the same level as the pico BS (i.e., $P_M = 30$ dBm), a user is still much more likely to be associated with the macro BS than with the pico BS, due to the large array gain brought by the massive MIMO macro BS. We also observe that increasing the number of transmit antennas at the macro BS improves the probability that a user is associated with the macro BS, which indicates that macro BSs having large antenna arrays are capable of carrying higher traffic loads, hence reducing the number of small cells required.

B. User Association for Spectrum Efficiency Optimization

Massive MIMO is capable of achieving a high spectrum efficiency by simultaneously transmitting/receiving multiple data streams in the same band. The low-complexity max-RSS user association may be incapable of balancing the load in multi-tier HetNets with the aid of massive MIMO [164], as indicated in Fig. 6. In [164], load balancing was investigated in multi-tier networks where the BSs of different tiers were equipped with different numbers of antennas and used linear ZF beamforming (LZFBF) for communicating with different numbers

of users. Bethanabhotla *et al.* [164] focused their attention on a pair of user-centric association algorithms, namely on the max-rate association and on the load based association. Under max-rate association, each user decided to associate with the specific BS which provided the maximum peak rate. In contrast, for load based association, each user aimed for selfishly maximizing its own throughput by also considering the traffic load of the BS. The performance of these user centric association schemes was also examined in [164]. In [80], a user-centric distributed probabilistic scheme was proposed for massive MIMO HetNets, which showed that the proposed scheme converged to a pure-strategy based Nash equilibrium with a probability of one for all the practically relevant cases of proportional fair and max-min fair utility functions. In [161], user association was investigated in two-tier HetNets with a massive MIMO aided macrocell and multiple conventional picocells. Both the centralized and distributed perspectives were considered. The goal of Gotsis *et al.* [165] was to identify the optimal user-to-access point association decision for maximizing the worst rate in the entire set of all users in massive MIMO empowered ultra-dense wireless networks. This contribution showed that at the network-level, optimal user association designed for densely and randomly deployed massive MIMO networks had to account for both the channel and traffic load conditions. In [131], joint downlink user association and wireless backhaul bandwidth allocation was considered for a two-tier HetNet, where small cells relied on in-band wireless links connecting them to the massive MIMO macro BS for backhauling. It was shown that under the specific wireless backhaul constraint considered, the joint scheduling problem for maximizing the sum of the logarithm of the rates for users constituted a nonlinear mixed-integer programming problem. The authors of [131] also considered the global and local backhaul bandwidth allocation.

C. User Association for Energy Efficiency Optimization

The energy efficiency of massive MIMO systems has been studied in [43], [157], [166]–[169]. In [43], the energy efficiency and spectrum efficiency tradeoff was analyzed. However, Ngo *et al.* [43] only took into account the transmit power consumption, but not the circuit-power dissipation. In practice, the internal non-RF power consumption scales with the number of antennas [166]. Compared to a typical LTE BS, it is implied in [166] that BSs with large scale antennas achieve much higher energy efficiencies. In [168], a more specific power consumption model was provided to show how the power scales with the number of antennas and the number of users. In this power consumption model, both the RF power consumption and the circuit power consumption including the digital signal processing and the analog filters used for RF and baseband processing were considered. An important insight obtained from [168] is that although using hundreds of antennas expends more circuit-power, the per-user energy efficiency still improves by serving an increased number of users with interference-suppressing regularized ZF TPC.

Energy-efficient user association in massive MIMO aided HetNets is still in its infancy. In [160], the impact of flexible user association on the energy efficiency in K-tier massive
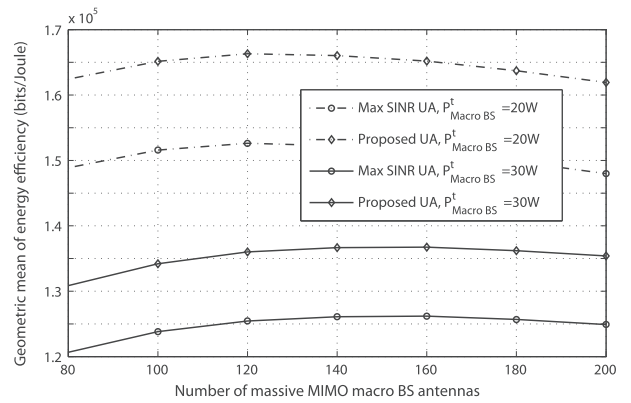

Fig. 7. Energy efficiency versus the number of antennas for different downlink transmit powers of the macro BS $P_{\text{Macro BS}}^{\text{t}}$.

MIMO enabled HetNets was evaluated. In [167], soft-cell coordination was investigated where each user could be served by a dedicated user-specific beam generated via non-coherent beamforming, and the total power consumption was minimized under a specific QoS constraint. In [169], the uplink energy efficiency of a massive MIMO assisted cellular network was analyzed, where stochastic geometry was applied for modeling the network and the user association was based on the minimum path-loss criterion. Distributed energy efficient and fair user association in massive MIMO assisted HetNets was first proposed in our recent work [100], where user association objective was to maximize the geometric mean of the energy efficiency, while considering QoS provision for users. Fig. 7 illustrates the geometric mean of the energy efficiency of different numbers of antennas and downlink transmit powers at the macro BS. We observe that regardless of both the number of antennas and the transmit power of the macro BS, our proposed algorithm achieves a better energy efficiency than the max SINR based user association algorithm. For a given macro BS's transmit power, the energy efficiency initially slightly increases and then gracefully decreases with increasing number of antennas. This is attributed to the fact that when the number of antennas exceeds a critical value (approximately 120 when the transmit power of macro BS is 20 W, $P_{\text{Macro BS}}^{\text{t}} = 20$ W), adding more antennas improves spectrum efficiency, but as usual, at the cost of degrading energy efficiency due to the increased power consumption. Fig. 7 also illustrates that given the same number of antennas, a lower macro BS transmit power facilitates a higher energy efficiency. This trend demonstrates the superiority of massive MIMO in fulfilling the QoS requirement at a reduced transmit power. To provide further insights, Fig. 8 shows the cumulative distribution function (CDF) of the energy efficiency experienced by users expressed in bits/Joule for different user association algorithms. We set the macro BS's downlink transmit power to 30W and the number of macro BS antennas to $N = 100$. We observe that the proposed algorithm improves the CDF in the low energy efficiency domain. The CDF of max SINR based user association approaches that of our proposed algorithm at an energy efficiency of 4×10^5 bits/Joule. This can be explained by the fact that, as the objective of the proposed
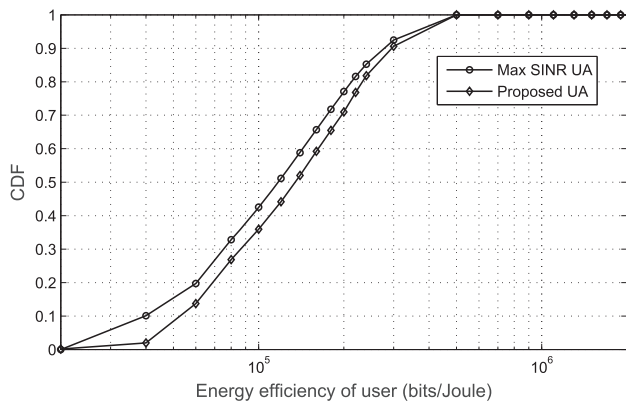
Fig. 8. Cumulative distribution function of user energy efficiency.

algorithm, maximizing the geometric mean of energy efficiency leads to proportional fairness, which provides a more uniform energy efficiency by reassigning resources from the users. As such, our proposed algorithm [100] improves the user fairness in terms of the energy efficiency compared to the max SINR based user association algorithm.

D. Summary and Discussions

The application of massive MIMO has a substantial effect on user association. The existing contributions summarized in Table IV have shown the importance of user association in massive MIMO aided networks. User association schemes designed for the already operational cellular systems may not be capable of fully exploiting the specific benefits provided by massive MIMO BSs. For the emerging 5G HetNets employing massive MIMO, the design of new user association schemes is required, and there are at least two aspects that should be taken into account: 1) The max-RSS based user association may force the massive MIMO BS to carry most of data traffic in HetNets, resulting in significant load imbalance between the macrocells and picocells. Therefore, throughput load balancing is important in massive MIMO assisted HetNets; and 2) Although massive MIMO uses large numbers of antennas and requires more power for complex signal processing, it can still remain energy efficient by serving more users since the power consumption per user is reduced and an increased spectrum efficiency is achieved. As such, energy efficient user association in massive MIMO HetNets should carefully balance the interplay between the number of antennas at the BS and the number of users served by the massive MIMO BS.

From the discussions above, we conclude that user association in massive MIMO HetNets is a promising research topic, and hence more research efforts are needed for facilitating its enhancement in practical 5G networks.

V. USER ASSOCIATION IN MMWAVE NETWORKS

Due to the rapid proliferation of bandwidth-hungry mobile applications, such as video streaming with up to high definition television (HDTV) resolution, more spectral resources are required for 5G mobile communications [170]. However, the existing cellular band is already heavily used and even using CA [171] relying on several parallel carries fails to meet the high spectrum demand of 5G networks. New spectrum has to be harnessed at higher carrier frequencies. Hence, mmWave communications with a large bandwidth have emerged as a potentially promising 5G technology [50], [51].

A. MmWave Channel Characteristics

The channel quality between the user and the BS plays a key role in user association. Hence, we first have to understand the mmWave channel. The mmWave channel characteristics can be highlighted as follows:

- **Increased path-losses**. According to the Friis transmission formula [172] of free-space propagation, the path-loss increases with the square of the carrier frequency, which indicates that mmWave transmissions suffer from high power losses.
- **Different propagation laws**. NLOS signals suffer from a higher attenuation than LOS signals [50]. This important feature of the propagation environment has to be incorporated into the design and analysis of mmWave networks [173].
- **Sensitivity to blockages**. MmWave signals are more sensitive to blockage effects than signals in lower frequency bands, and indoor users are unlikely to be adequately covered by outdoor mmWave BSs [173].

These channel characteristics have a significant effect on cell coverage, which indicates that the attainable throughput of mmWave networks is highly dependent on the user association [174]. In [46], [173], the users are assumed to be associated with the specific BS offering the minimum path-loss, where stochastic geometry based mmWave modeling incorporating blockage effects was considered. It was demonstrated in [46], [173] that mmWave networks tended to be noise-limited, because the high path-loss attenuated the interference, which was likely to be further attenuated by directional beamforming. Hence, user association metrics designed for interference-limited homogenous systems are not well suited to mmWave systems [38]. In contrast, user association should be designed to meet the dominant requirements of throughput and energy efficiency without considering interference coordination. Additionally, user orientation has a substantial impact on the performance of mmWave links due to the fact that directional transmission is required for combatting the high path-loss. As such, users may not be associated with the geographically closest BS, since a better directional link may exist for a farther away BS.

B. MmWave User Association

Current standards for mmWave communications, such as the IEEE 802.11ad and IEEE 802.15.3c, adopt RSS-based user association, which may lead to an inefficient use of resources [175]. Moreover, RSS-based user association may result in overly frequent handovers between the adjacent BSs and may increase the overhead/delay of re-association [38]. In [176], the optimal assignment of the BSs to the available access

TABLE V
QUALITATIVE COMPARISON OF USER ASSOCIATION ALGORITHMS FOR MMWAVE NETWORKS

Ref.	Algorithm	Topology	Model	Direction	Control	Spectrum efficiency	Energy efficiency	QoS provision	Fairness	Coverage probability
[46, 173]	max-RSS UA	Random spatial	Stochastic geometry	DL	Distributed	Low	-	Moderate	-	Low
[176]	UA	Grid	Game theory	DL	Distributed	High	-	-	-	-
[177]	UA	Grid	Combinatorial optimization	DL	Distributed	High	-	-	-	-
[178]	UA			DL	Distributed	High	-	-	High	-
[179]	UA			DL	Centralized	High	-	High	High	-
[180]	UA			DL	Distributed	High	High	-	-	-

points (APs) in 60 GHz mmWave wireless access networks was investigated, and a BS association method was proposed for maximizing the total requested throughput. Since the problem considered in [176] was a classical multi-assignment optimization problem where an AP was assigned to more than one BS, an auction-based solution was proposed. Xu *et al.* [177] extended the line of work in [176] by deploying relays in the network, which helped the clients associated with the AP. More explicitly, a combination of distributed auction algorithms was used for jointly optimizing the client association and relay selection processes. In [178], the optimization of user association was carried out by giving special cognizance to both load balancing and fairness in mmWave wireless networks. The study in [178] aimed for balancing the AP utilization in the network, in an effort to improve the throughput and fairness in resource sharing.

MmWave cells may be regarded as another tier in future 5G HetNets [51], [175], [179]. Unlike conventional HetNets, where all the tiers use the same frequency band, which necessitates interference management [17], the mmWave tier has no effect on the other tiers, since it operates at higher frequencies. Therefore, the deployment of mmWave cells not only offloads the data traffic of existing HetNets, but also reduces the interference by avoiding the deployment of cellular BSs in the cellular band. In [179], multi-band HetNets conceived for 5G were considered, where the different tiers operated at different frequencies. The 60 GHz band has a factor 100 more bandwidth than the current cellular bands. To allow small cell BSs to accommodate more data traffic and to maximize the system's data rate, a novel user association method using combinatorial optimization was introduced in [179], where the supported achievable rate and the number of users in each cell were considered. In [180], user association was considered in a hybrid HetNet, where macro cells adopt massive MIMO, and small cells adopt mmWave transmissions. The work of [180] showed that the proposed algorithm can well coordinate the capabilities of massive MIMO and mmWave in the 5G networks.

Table V qualitatively compares the existing user association algorithms proposed for mmWave networks.

C. Summary and Discussions

Although the aforementioned literature has shown the significant impact of user association on mmWave networks, user association in mmWave networks is far from being well understood and hence faces prominent challenges. RSS-based user association may not be feasible in future networks employing multiple frequency bands. The solution provided in [176]–[178]

ignored some important mmWave channel characteristics, such as the NLOS/LOS propagation laws and blockage. The velocity of mobility also has a substantial effect on mmWave user association/re-association, which suggests that mobility management has to be adopted in mmWave networks [38]. Considering the fact that mmWave links are sensitive to blockage and mobility, the channel conditions may vary significantly over time and it may be necessary to request re-association after each channel coherence time. In addition, since mmWave communication has been standardized in IEEE 802.11ad for supporting Gigabit WiFi services, mmWave cellular networks may coexist with IEEE 802.11ad systems in the unlicensed spectrum for 5G. In such a scenario, user association may have to be reconsidered in order to make best use of the unlicensed spectrum. To date, this problem has not been investigated yet, and current research efforts focus mainly on user association in integrated LTE-WiFi networks [181], [182]. Considering that mmWave networks will also coexist with the diverse HetNets, the following aspects have to be carefully addressed for effective user association design.

- **Large mmWave bandwidth**. Compared to the narrow cellular bandwidths, mmWave cells provide substantially wider bandwidths, which significantly improves the attainable throughput [183]. As such, new user association methods should account for the effect of system bandwidth.
- **Large array gains**. For a fixed array aperture, the shorter wavelengths of mmWave frequencies enable the mmWave BSs to pack more antennas in the same space, which provides large array gains and therefore increases the received signal power. The simple user association metric based on the minimum-distance rule [38] may become inefficient, particularly when massive MIMO is applied in macrocells [163]. The antenna array gains in the mmWave cells will be different from the antenna array gains in the macrocells. As such, new user association methods should also address the effect of large array gains, which is however coupled with very narrow pencil-beams that are hard to update at high velocities.
- **Energy efficiency**. Since mmWave systems use large bandwidths and large antenna arrays, the associated power consumption has to be carefully considered [184]. As such, new energy efficient user association methods are required.

So far, we have only discussed the coupled user association based on the downlink. The decoupling access techniques [144], [146], [185], which basically consider the downlink and uplink as separate network entities, may be difficult to

TABLE VI
QUALITATIVE COMPARISON OF USER ASSOCIATION ALGORITHMS FOR ENERGY HARVESTING NETWORKS

Ref.	Algorithm	Topology	Model	Direction	Control	Spectrum efficiency	Energy efficiency	QoS provision	Fairness	Coverage probability
[186]	max-RSS UA	Random spatial	Stochastic geometry	DL	Distributed	-	High	Moderate	-	Moderate
[187]	biased UA			DL	Distributed	High	High	-	-	Moderate
[188]	UA			DL	Distributed	High	High	High	High	-
[189]	UA	Grid	Combinatorial optimization	DL	Centralized	High	High	High	-	-
[190]	UA			DL	Distributed	Moderate	High	High	High	-
[191]	UA+power control+ resource block allocation			UL	Centralized	High	High	High	-	-
[54, 192, 193]	UA			DL	Distributed	Moderate	High	High	-	-
[194]	UA			DL	Centralized	-	High	High	-	-
[55]	UA+energy allocation	Grid	Combinatorial optimization	DL	Centralized	-	High	Moderate	-	-
[56]	UA+energy allocation			DL	Distributed	-	High	High	-	-
[195]	UA+bandwith allocation			DL	Distributed/ Centralized	-	High	High	-	-
[60]	UA	Random spatial	Stochastic geometry	UL	Distributed	-	High	High	-	Moderate
[196]	biased UA			UL	Distributed	-	High	High	-	High

be applied in mmWave cellular networks. As mentioned in [146], mmWave beamforming tends to rely on exploiting the uplink/downlink channel reciprocity. An interesting approach suggested in [146] is that a user is associated with the mmWave cell BS in the downlink and with a sub 6 GHz macro BS in the uplink.

Given the fact that mmWave solutions are expected to serve as an essential enabling technology in 5G networks, user association in mmWave 5G networks is a promising research field. In a nutshell, for the potential mmWave component of 5G networks, fundamental research facilitating efficient user association has numerous open facets.

VI. USER ASSOCIATION IN ENERGY HARVESTING NETWORKS

One of the main challenges in 5G networks is the improvement of the energy efficiency of radio access networks (RANs) and battery-constrained wireless devices. In the context of prolonging the battery recharge-time and improving the overall energy efficiency of the network, harvesting energy from external energy sources may be viewed as an attractive solution [16]. In this section, we survey user association in renewable energy powered networks and RF WPT enabled networks, respectively.

Table VI provides a qualitative comparison of the existing user association algorithms proposed for energy harvesting networks.

A. User Association in Renewable Energy Powered Networks

Motivated by environmental concerns and the regulatory pressure for finding "greener" solutions [197], network operators have considered the deployment of renewable energy sources, such as solar panels and wind turbines, in order to supplement the conventional power grid in powering BSs. In this scenario, BSs are capable of harvesting energy from the environment and do not require an *always-on* energy source [53]. This is of considerable interest in undeveloped areas, where the power grid is not readily available. Furthermore, it opens up entirely new categories of low cost *drop and play* small cell deployments for replacing the *plug and play* solutions.

1) User Association in Solely Renewable Energy Powered Networks: Due to the randomness of the energy availability in renewable energy sources, integrating energy harvesting capabilities in BSs entails many challenges in terms of the user association algorithm design. The user association decision should be adapted according to the energy and load variations across time and space. The authors of [186] developed a model for HetNets relying on stochastic geometry, where all BSs were assumed to be solely powered by renewable energy sources. They also provided a fundamental characterization of regimes under which HetNets relying on renewable energy powered BSs have the same performance as the ones benefiting from grid-powered BSs. By relaxing the primal deterministic user association to a fractional user association, the authors of [188] proposed a user association algorithm for the maximization of the aggregate downlink network utility based on the per-user throughput, where the BSs were solely powered by renewable energy and equipped with realistic finite-capacity batteries. In [189], adaptive user association was formulated as an optimization problem, which aimed at maximizing the number of supported users and at minimizing the radio resource consumption in HetNets with renewable energy powered BSs. Both optimal offline and online algorithms were developed. Authors of [190] proposed a distributed user association algorithm for energy consumption and traffic load balancing tradeoffs among heterogeneous base stations in HetNets with renewable energy supply. The deployment of relays having energy harvesting capabilities has also attracted significant attention, since they are able to improve the system capacity and coverage in remote areas which do not have access to the power grid. In this context, Song *et al.* [187] studied the user association problem targeting the downlink throughput optimization of energy harvesting relay-assisted cellular networks, where BSs were powered by the power grid and relays were powered by the renewable energy. The authors developed a dynamic biased user association algorithm, where the bias was optimized based on the renewable energy arrival rates. In [191], joint user association, resource block allocation, and power control was investigated with the goal of maximizing the uplink network throughput in cellular networks employing energy harvesting relays. The energy-harvesting process was characterized by a time-varying Poisson process. The authors proposed a new metric, referred

to as the survival probability, as selection criterion for an energy-harvesting relay.

2) User Association in Hybrid Energy Powered Networks: Although the amount of renewable energy is potentially unlimited, the intermittent nature of the energy from renewable energy sources results in a highly random energy availability at the BS. Thus, BSs powered by hybrid energy sources, which employ a combination of the power grid and renewable energy sources are preferable over those solely powered by renewable energy sources in order to support uninterrupted service [198]. The concept of hybrid energy sources has already been adopted by the industry. For instance, Huawei has deployed BSs which draw their energy from both constant energy supplies and renewable energy sources [199]. In the literature, power allocation [200], coordinated MIMO [201], and sophisticated network planning [202] have been studied in the context of cellular networks powered by hybrid energy sources. For the user association designed for such networks, the vital issue is the minimization of the grid energy consumption as well as guaranteeing the user QoS, as detailed in [54]–[56], [192]–[195] and in the references therein. Distributed delay-energy aware user association was proposed for the HetNets operating both with [192] and without the assistance of relays [54] in order to reduce the grid power consumption by maximizing the exploitation of "green" power harvested from renewable energy sources, as well as to enhance the QoS by minimizing the average traffic delay. Extending the solutions of [54], the authors of [193] addressed the backhaul constraint and the uplink-downlink asymmetry in the context of designing the user association algorithm for HetNets relying on hybrid energy sources. In [194], an intelligent cell breathing method was proposed for minimizing the maximal harvested energy depletion rate of BSs. In [195], a constrained total energy cost minimization problem was formulated, which was then solved with the aid of energy efficient user association and bandwidth allocation algorithms. Multi-stage harvested energy allocation and multi-BS traffic load balancing algorithms were designed for energy optimization in [55]. In [56], two-dimensional optimization of user association in the spatial dimension and harvested energy allocation in the time dimension was developed for minimizing both the total and the maximum grid energy consumption, while guaranteeing a certain QoS. Extending from [56], online algorithms for two-dimensional optimization were further developed in [203].

3) User Association in Energy Cooperation Enabled Networks: Because of the spatial and temporal dynamics of the renewable energy, BSs may suffer from geographical variability in terms of their harvested renewable energy. Fortunately, the recent development of the smart grid facilitates two-way information and energy flows between the grid and the BSs of cellular networks [204], which makes *energy cooperation* between BSs possible. Energy cooperation between BSs allows the BSs that have excessive harvested renewable energy to compensate for others that have a deficit due to either higher traffic load or lower generation rate of renewable energy, thereby substantially improving the renewable energy utilization and decreasing the grid energy consumption. The concept of *energy cooperation* has inspired significant research efforts
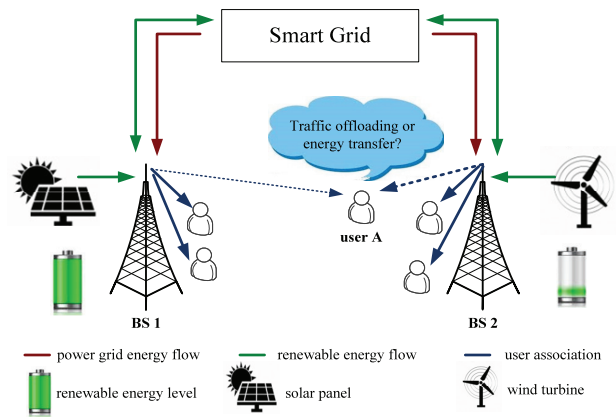

Fig. 9. The tradeoff between traffic offloading and energy transfer in energy cooperation enabled networks.

in recent years, see [205]–[207] and references therein. The optimal energy cooperation policy conceived for minimization of the system grid energy consumption was disseminated in [205]. Joint energy and spectrum cooperation invoked for the minimization of the energy cooperation cost was developed in [206]. In [207], the weighted sum rate of all users was maximized by joint power allocation and energy cooperation optimization in CoMP aided networks.

To the best of our knowledge, research results on user association in energy cooperation enabled networks are not available yet. User association in energy cooperation enabled networks introduces tradeoffs between traffic offloading and energy transfer, which is a challenging research topic. As shown in Fig. 9, the stored renewable energy level of BS 2 is much lower than that of BS 1, due to the low renewable energy generation of BS 2. Additionally, more users are located in the vicinity of BS 2. If both BS 1 and BS 2 use the same fixed transmit power, BS 2 will have to consume more renewable energy transferred from BS 1 or more energy from the power grid, in order to serve all the users in its vicinity. However, there will be some renewable energy loss during the energy transfer from BS 1 to BS 2. Alternatively, some users near BS 2 may choose to associate with the far-away BS 1 having more harvested renewable energy. For instance, user A in Fig. 9 may be associated with BS 1, which consequently avoids the renewable energy loss owing to energy transfer. Nonetheless, we observe that user A may suffer from more signal strength degradation, when it is offloaded to BS 1, since the distance between user A and BS 1 is larger than that between user A and BS 2. As such, it is crucial to strike a tradeoff between the signal strength degradation caused by traffic offloading and the renewable energy loss caused by energy transfer with the aid of user association optimization in energy cooperation enabled networks. Table VII summarizes the challenges of user association designed for renewable energy powered networks in different scenarios.

B. User Association in RF WPT Enabled Networks

Traditional energy harvesting sources, such as solar, wind, hydroelectric, etc., depend on locations and environments. RF WPT is an alternative approach conceived for prolonging the

TABLE VII
SUMMARY OF USER ASSOCIATION FOR RENEWABLE ENERGY POWERED NETWORKS

Classification	Scenario	Challenges	Ref.
User association in solely renewable energy powered networks	BSs in networks are solely powered by renewable energy from environment, such as solar energy, wind energy.	User association decision should be adapted according to the renewable energy and load variations across time and space. QoS provision may be deteriorated by insufficient renewable energy.	[186–191]
User association in hybrid energy powered networks	BSs in networks are powered by a combination of power grid and renewable energy sources.	User association decision should maximize the utilization of renewable energy, minimize the grid energy consumption and guarantee the QoS provision.	[54–56, 192–195]
User association in energy cooperation enabled networks	BSs with excess harvested renewable energy can aid other BSs with energy shortage via renewable energy transfer.	User association decision is crucial for the tradeoff between signal strength degradation caused by traffic offloading and energy loss in energy transfer.	–

lifetime of mobile devices [57]–[62]. The advantages of WPT are at least two-fold: 1) Unlike the traditional energy harvesting, it is independent of the environment's conditions, and can be applied anywhere; 2) It is flexible and can be scheduled at any time. Additionally, the potentially harmful interference received by the energy harvester actually becomes a precious energy source.

User association in cellular networks relying on ambient RF energy harvesting has been studied in [60], [196]. In [60], an analytical approach considering K-tier uplink cellular networks with RF energy harvesting was presented, where mobile users relied only on the energy harvested from ambient RF energy sources for powering up their devices for uplink transmissions. The "harvest-then-transmit" strategy was adopted by the users. This contribution performed uplink user association based on the best average channel gain, i.e., the lowest path-loss. The authors of [196] further examined RF energy harvesting in the context of HetNets in conjunction with flexible uplink user association. In the flexible user association, users were not necessarily associated with their nearest BS, because a different bias factor was added to each network tier.

As pointed out in [59], the RF energy scavenging considered in [60], [196] is only sufficient for powering small sensors, and dedicated power beacons have to be employed for powering larger devices. More particularly, in the HetNets associated with dense small cells, the distance between the users and the serving BSs is typically shorter, which suggests that the serving BS can act as a dedicated RF energy source to power its user, similar to power beacons. Hence, there are two types of user association designs for WPT in cellular networks: 1) Downlink based user association for maximizing the harvested energy, which increases the user's transmit power; 2) Uplink based user association for minimizing the uplink path-loss, which increases the received signal power at the serving BS [60], [196]. As such, the uplink-downlink decoupling access studied in [144], [146], [185] is a promising approach to achieve both maximum downlink harvested energy and minimum uplink path-loss. However, these research topics have not been well investigated at the time of writing, and hence they require further exploration.

C. Summary and Discussions

The deployment of renewable energy sources to supplement the conventional power grid for powering BSs indisputably underpins the trend of green communication. However, the intermittent nature of renewable energy sources requires a rethinking of the traditional user association rules designed for conventional cellular networks relying on constant grid power supply. The existing research contributions regarding user association for renewable energy powered networks aim for maximizing the exploitation of renewable energy, while maintaining the QoS guarantees. On the other hand, the smart grid, as one of the use cases envisioned for 5G networks [208], has paved the way for energy cooperation in networks. Energy cooperation between BSs allows the BSs that have excessive harvested renewable energy to assist other BSs that have an energy deficit via renewable energy transfer. To the best of our knowledge, user association in energy cooperation enabled networks is still an open field, and is expected to become a rewarding research area.

Additionally, the existing research contributions on energy harvesting networks investigate user association in networks relying on either renewable energy powered BSs or RF energy harvesting assisted users. User association design in networks combining renewable energy powered BSs and RF energy harvesting assisted users is still untouched and is expected to be a promising approach for 5G networks. In such a network scenario, BSs are capable of harvesting renewable energy from the environment, such as solar power and wind power, while users are powered by RF energy harvesting, thereby having the promise of dramatically reducing the energy consumption of BSs as well as prolonging the battery recharge time. Nevertheless, in this context, both the renewable energy harvested by the BSs and the RF energy harvested by the users will simultaneously play a crucial role in determining the user association, where the user association algorithm should be carefully redesigned for adequate QoS provision and energy consumption reduction.

VII. USER ASSOCIATION IN NETWORKS EMPLOYING OTHER TECHNOLOGIES FOR 5G

In the previous sections, user association was investigated by emphasizing the impact of key 5G techniques including HetNets, massive MIMO, mmWave, and energy harvesting. Needless to say that there are other important technologies for 5G. Their impact on user association will be discussed in this section.

A. Self-Organizing Networks

In the SONs with the ability of self-configuration, self-optimization, and self-healing, the amount of required manual work is minimized in order to reduce the OPEX [209]. The specific requirements and use cases for SONs have been

summarized and discussed in standards and industry organizations, such as 3GPP and the next-generation mobile networks alliance [210]. In SONs, there are multiple use cases for network optimization such as capacity and coverage optimization (CCO) as well as mobility load balancing (MLB) [63]. In [63], α-optimal user association was adopted and an algorithm for optimizing both the user association and the antenna-tilt setting was introduced for the CCO and MLB SON use cases. In [211], the coordination of RSS-based handover and load balancing of SON algorithms was examined in the context of LTE networks, which aimed at combining the strengths of both algorithms.

B. Device-to-Device Communication

D2D communication supports direct transmission based proximity services between devices without the assistance of the BS or the core network, in an effort to improve the spectrum and energy efficiency [64], [212]. D2D communication can be operated in inband D2D mode (similar to the cognitive radio networks) or outband D2D mode. However, one of the key characteristics of D2D is the involvement of the cellular network in the control plane [64]. In [213], flexible mode selection with truncated channel inversion power control was analyzed in underlay D2D cellular networks, where users chose the D2D mode or were connected with BSs based on the uplink quality. In [214], D2D link cell association was studied and an optimization approach was proposed for reducing signalling load and latency in network control based D2D links. In [215], the D2D link was established based on the social influence of the D2D transmitter that owns the popular content of common interest.

C. Cloud Radio Access Network

As a new mobile network architecture consisting of RRHs and BBUs, C-RAN is capable of efficiently dealing with large scale control/data processing. The rationale behind this approach is that baseband processing is centralized and coordinated among sites in the centralized BBU pool, which reduces both the CAPEX and OPEX [65]. In addition, the C-RAN mitigates the inter-RRH interference by using efficient interference management techniques such as CoMP. In [216], joint downlink and uplink user association and beamforming design for C-RANs was proposed for minimizing the power consumption under downlink and uplink QoS constraints. In [217], the user association optimization problem was formulated for minimizing the network's latency, and a three-phase search algorithm was introduced for solving it. In [218], user-centric association was adopted for maximizing the downlink received signal-to-noise ratio (SNR) in the C-RAN with the aid of stochastic geometry, where both the coverage probability and downlink throughput were analyzed.

D. Full-Duplex Communication

Full-duplex communication is capable of potentially doubling the spectrum efficiency by allowing simultaneous downlink and uplink transmission within the same frequency band [219]. However, self-interference (SI) suppression becomes critical in full-duplex systems, since it will seriously deteriorate the reception quality. Many SI mitigation methods have

been studied. More particularly, in [66], [219], the authors comprehensively investigated various SI mitigation methods by considering both passive and active techniques. In [220], a hybrid scheduling scheme was presented, where the users were scheduled in half-duplex or full-duplex mode to avoid imposing excessive interference on the network. In [221], the feasibility of decoupled uplink-downlink user association in full-duplex two-tier cellular networks was investigated, and a matching game was formulated for maximizing the total uplink and downlink throughput.

E. Summary and Discussions

Although the aforementioned techniques can effectively enhance spectrum efficiency and energy efficiency with lower CAPEX and OPEX, their features pose substantial challenges to user association design. For example, in self-organizing cellular networks, user association has to be adapted to the specific requirements imposed by SON. When full-duplex communication is employed in cellular D2D networks, three cases may be distinguished, namely 1) the D2D link is half-duplex, and the normal link via the BS is full-duplex; 2) the D2D link is full-duplex, and normal link via the BS is half-duplex; and 3) both the D2D link and the normal link via the BS are full-duplex. For each case, user association has to be carefully redesigned to reduce the interference. In the C-RAN, considering that inter-RRH interference can be efficiently mitigated via cooperation among RRHs, user association algorithms designed for interference coordination are obsolete. In addition, user-centric association may become preferable to the current BS-centric one as a large number of RRHs will be deployed in the C-RANs [218].

Current research efforts have provided a good understanding of the aforementioned technologies. Nevertheless, the number of studies of user association mechanisms for networks employing SONs, D2D, C-RAN and full-duplex communication is limited. Hence, more research into this direction is needed in the future.

VIII. SUMMARY AND CONCLUSION

The pertinent user association algorithms designed for HetNets, massive MIMO networks, mmWave scenarios and energy harvesting networks have been surveyed, which constitute four of the most salient enabling technologies envisioned for future 5G networks. In order to systematically survey the existing user association algorithms, we have presented a related taxonomy. Within each of the networks considered, we have highlighted the inherent features of the corresponding 5G enabling technology, which have a substantial impact on the user association decision, and then categorized the state-of-the-art user association algorithms. However, given the intricate and perpetually evolving 5G network conditions, the related research relying on sophisticated machine learning techniques is still in its infancy. Hence, a range of challenging open issues regarding user association in 5G networks have also been summarized in this paper. Indeed, user association has to be investigated in more depth as a community-effort in order to better accommodate the inherent features of 5G enabling technologies, so as to realize the full potential of 5G networks.

When designing and optimizing a wireless system, the most influential factor in predetermining the overall performance of the system is the specific choice of the metric to be optimized. For example, when we aim for an increased bandwidth efficiency, we opt for high-throughput modulation schemes, which are however not energy-efficient. The opposite is true for the family of power-efficient, but low-throughput m-ary orthogonal modulation, which operates at low SNRs.

In this spirit, in order to make our discussions well-balanced, we have used five classic metrics throughout this treatise, namely the outage/coverage probability, bandwidth efficiency, energy efficiency, QoS and fairness. It is feasible to specifically choose the user association metrics in order to satisfy the prevalent user requirements. For example, when the users request high-definition video streaming services, the bandwidth efficiency may be the preferred metric to be optimized, whilst compromising the energy efficiency and vice versa. The choice of this metric is much more crucial than the choice of the optimization algorithms and tools invoked for optimizing it!

Bearing in mind the fact that 5G is expected to become the fusion of heterogeneous wireless technologies, the user association problem should be tackled by giving careful cognizance to the specific 5G scenario encountered, in order to satisfy the tight specifications of the enabling techniques considered in this survey. For example, in the areas where massive MIMO-aided macrocells and mmWave small cells are employed, user association should be designed based on the detailed recommendations of Section V-C.

In the context of energy-efficient harvesting-aided networks the BSs may be powered by renewable energy sources. As such, the energy consumption constraints play a crucial role in influencing the user association design, as mentioned in Section VI. When the handsets are recharged with the aid of RF WPT, the BSs may act as RF energy sources. For example, in such scenarios the user association techniques may be specifically designed for receiving the maximum possible amount of RF energy. Naturally, a diverse variety of other compelling user association designs are possible for the sake of enhancing the attainable performance by considering the basic design principles outlined above.

REFERENCES

[1] Cisco, "Cisco visual networking index: Global mobile data traffic forecast update 2014–2019," White paper, Feb. 2015.

[2] J. Andrews *et al.*, "What will 5G be?," IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[3] FP7 European Project. Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society (METIS) [Online]. Available: https://www.metis2020.com/

[4] FP7 European Project. 5th Generation Non-Orthogonal Waveforms for Asynchronous Signalling (5GNOW) [Online]. Available: http://www.5gnow.eu/

[5] FP7 European Project. Interworking and Joint Design of An Open Access and Backhaul Network Architecture for Small Cells Based on Cloud Networks (iJOIN) [Online]. Available: http://www.ict-ijoin.eu/

[6] FP7 European Project. Distributed Computing, Storage and Radio Resource Allocation Over Cooperative Femtocells (Tropic) [Online]. Available: http://www.ict-tropic.eu/

[7] FP7 European Project. Mobile Cloud Networking (MCN) [Online]. Available: http://www.mobile-cloud-networking.eu/site/

[8] FP7 European Project. Convergence of Fixed and Mobile Broadband Access/Aggregation Networks (COMBO) [Online]. Available: http://www.ict-combo.eu/

[9] FP7 European Project. Evolving Mobile Internet With Innovative Terminal-to-Terminal Offloading Technologies (MOTO) [Online]. Available: http://www.fp7-moto.eu/

[10] FP7 European Project. Physical Layer Wireless Security (PHYLAWS) [Online]. Available: http://www.phylaws-ict.org/

[11] Horizon 2020. [Online]. Available: https://ec.europa.eu/programmes/horizon2020/

[12] 5G Infrasrucute Public Private Partnership [Online]. Available: http://5g-ppp.eu/

[13] IMT-2020 (5G). [Online]. Available: http://www.imt-2020.cn/en/

[14] 5G Forum, Korean 5G Will Lead the Globe [Online]. Available: http://www.5gforum.org/eng/main/

[15] NYU Wireless. [Online]. Available: http://nyuwireless.com/research/

[16] E. Hossain and M. Hasan, "5G cellular: Key enabling technologies and research challenges," IEEE Instrum. Meas. Mag., vol. 18, no. 3, pp. 11–21, Jun. 2015.

[17] 3GPP TS, 36.300 v12.5.0, Release 12, "Evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-UTRAN); overall description: Stage 2," Mar. 2015.

[18] N. DOCOMO, "Performance of eICIC with control channel coverage limitation," 3GPP TSG RAN WG1 Meeting 61, R1-103264, May 2010.

[19] A. Ghosh *et al.*, "Heterogeneous cellular networks: From theory to practice," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 54–64, Jun. 2012.

[20] J. Andrews, "Seven ways that HetNets are a cellular paradigm shift," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 136–144, Mar. 2013.

[21] J. Andrews, S. Singh, Q. Ye, X. Lin, and H. Dhillon, "An overview of load balancing in HetNets: Old myths and open problems," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 18–25, Apr. 2014.

[22] M. Peng, C. Wang, J. Li, H. Xiang, and V. Lau, "Recent advances in underlay heterogeneous networks: Interference control, resource allocation, and self-organization," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 700–729, Second quart. 2015.

[23] Y. L. Lee, T. C. Chuah, J. Loo, and A. Vinel, "Recent advances in radio resource management for heterogeneous LTE/LTE-A networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2142–2180, Fourth quart. 2014.

[24] D. Feng, C. Jiang, G. Lim, J. Cimini, L.J., G. Feng, and G. Li, "A survey of energy-efficient wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 167–178, First Quart. 2013.

[25] J. Rao and A. Fapojuwo, "A survey of energy efficient resource management techniques for multicell cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 154–180, First Quart. 2014.

[26] L. Budzisz *et al.*, "Dynamic resource provisioning for energy efficiency in wireless access networks: A survey and an outlook," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2259–2285, Fourth quart. 2014.

[27] J. Wu, Y. Zhang, M. Zukerman, and E. Yung, "Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 803–826, Second quart. 2015.

[28] L. Wang and G.-S. Kuo, "Mathematical modeling for network selection in heterogeneous wireless networks: A tutorial," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 271–292, First quart. 2013.

[29] R. Trestian, O. Ormond, and G.-M. Muntean, "Game theory-based network selection: Solutions and challenges," *IEEE Commun. Survey Tuts.*, vol. 14, no. 4, pp. 1212–1231, Fourth quart. 2012.

[30] H. ElSawy, E. Hossain, and M. Haenggi, "Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 996–1019, Third Quart. 2013.

[31] F. Boccardi, R. Heath, A. Lozano, T. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

[32] P. Agyapong, M. Iwamura, D. Staehle, W. Kiess, and A. Benjebbour, "Design considerations for a 5G network architecture," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 65–75, Nov. 2014.

[33] C.-X. Wang *et al.*, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[34] E. Hossain, M. Rasti, H. Tabassum, and A. Abdelnasser, "Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 118–127, Jun. 2014.

[35] G. Wu, C. Yang, S. Li, and G. Li, "Recent advances in energy-efficient networks and their application in 5G systems," *IEEE Wireless Commun.*, vol. 22, no. 2, pp. 145–151, Apr. 2015.

[36] H. Zhang, C. Jiang, and J. Cheng, "Cooperative interference mitigation and handover management for heterogeneous cloud small cell networks," *IEEE Wireless Commun.*, vol. 22, no. 3, pp. 92–99, Jun. 2015.

[37] H. Song, X. Fang, and L. Yan, "Handover scheme for 5g c/u plane split heterogeneous network in high-speed railway," *IEEE Trans. Veh. Technol.*, vol. 63, no. 9, pp. 4633–4646, Nov. 2014.

[38] H. S. Ghadikolaei, C. Fischione, G. Fodor, P. Popovski, and M. Zorzi, "Millimeter wave cellular networks: A MAC layer perspective," arXiv preprint arXiv:1503.00697, Mar. 2015.

[39] D. Lopez-Perez, I. Guvenc, G. De la Roche, M. Kountouris, T. Quek, and J. Zhang, "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 22–30, Jun. 2011.

[40] V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell networks: A survey," *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sep. 2008.

[41] A. Damnjanovic *et al.*, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 10–21, Jun. 2011.

[42] E. Björnson, E. G. Larsson, and T. L. Marzetta, "Massive MIMO: 10 myths and one grand question," arXiv preprint arXiv:1503.06854, Mar. 2015.

[43] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, "Energy and spectral efficiency of very large multiuser MIMO systems," *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

[44] E. G. Larsson, F. Tufvesson, O. Edfors, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[45] J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 160–171, Feb. 2013.

[46] S. Singh, M. N. Kulkarni, A. Ghosh, and J. G. Andrews, "Tractable model for rate in self-backhauled millimeter wave cellular networks," arXiv preprint arXiv:1407.5537, Jul. 2014.

[47] Wireless MAC and PHY Specifications for High Rate WPANs Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension, IEEE Standard Part 15.3, 2009.

[48] *PHY/MAC Complete Proposal Specification (TGad D0.1)*, IEEE802.11-10/0433r2, 2010.

[49] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[50] T. S. Rappaport *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!," IEEE Access, vol. 1, pp. 335–349, May 2013.

[51] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.

[52] D. Zhao, C. Huang, Y. Chen, F. Alsaadi, and S. Cui, "Resource allocation for multiple access channel with conferencing links and shared renewable energy sources," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 3, pp. 423–437, Mar. 2015.

[53] L. Huang and M. Neely, "Utility optimal scheduling in energy-harvesting networks," *IEEE/ACM Trans. Netw.*, vol. 21, no. 4, pp. 1117–1130, Aug. 2013.

[54] D. Liu, Y. Chen, K. K. Chai, and T. Zhang, "Optimal user association for delay-power tradeoffs in HetNets with hybrid energy sources," in *Proc. IEEE 25nd Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2014, pp. 1857–1861.

[55] T. Han and N. Ansari, "On optimizing green energy utilization for cellular networks with hybrid energy supplies," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 3872–3882, Aug. 2013.

[56] D. Liu, Y. Chen, K. K. Chai, T. Zhang, and K. Han, "Joint user association and green energy allocation in HetNets with hybrid energy sources," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2015, pp. 1542–1547.

[57] Y. L. Che, L. Duan, and R. Zhang, "Spatial throughput maximization of wireless powered communication networks," arXiv preprint arXiv:1409.3107, Oct. 2014.

[58] Y. Liu, L. Wang, M. Elkashlan, T. Q. Duong, and A. Nallanathan, "Two-way relaying networks with wireless power transfer: Policies design and throughput analysis," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2014, pp. 4030–4035.

[59] K. Huang and X. Zhou, "Cutting the last wires for mobile communications by microwave power transfer," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 86–93, Jun. 2015.

[60] A. H. Sakr and E. Hossain, "Analysis of K-tier uplink cellular networks with ambient RF energy harvesting," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 10, pp. 2226–2238, Oct. 2015.

[61] H. Tabassum, E. Hossain, M. Hossain, and D. Kim, "On the spectral efficiency of multiuser scheduling in RF-powered uplink cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3586–3600, Jul. 2015.

[62] L. Wang, M. Elkashlan, R. W. Heath Jr., M. D. Renzo, and K.-K. Wong, "Millimeter wave power transfer and information transmission," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–6.

[63] A. Fehske, H. Klessig, J. Voigt, and G. Fettweis, "Concurrent load-aware adjustment of user association and antenna tilts in self-organizing radio networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 5, pp. 1974–1988, Jun. 2013.

[64] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801–1819, Fourth Quart. 2014.

[65] A. Checko *et al.*, "Cloud ran for mobile networks—A technology overview," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 405–426, First Quart. 2015.

[66] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, "Full duplex techniques for 5G networks: Self-interference cancellation, protocol design, and relay selection," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 128–137, May 2015.

[67] H. Dhillon, R. Ganti, F. Baccelli, and J. Andrews, "Modeling and analysis of K-tier downlink heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 550–560, Apr. 2012.

[68] H. Dhillon, R. Ganti, and J. Andrews, "Load-aware modeling and analysis of heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 4, pp. 1666–1677, Apr. 2013.

[69] R. Hu and Y. Qian, "An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 94–101, May 2014.

[70] A. Mesodiakaki, F. Adelantado, L. Alonso, and C. Verikoukis, "Energy-efficient context-aware user association for outdoor small cell heterogeneous networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 1614–1619.

[71] L. Su, C. Yang, Z. Xu, and A. Molisch, "Energy-efficient downlink transmission with base station closing in small cell networks," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, May 2013, pp. 4784–4788.

[72] D. Liu, Y. Chen, K. K. Chai, and T. Zhang, "Joint uplink and downlink user association for energy-efficient HetNets using Nash bargaining solution," in *Proc. IEEE 79th Veh. Technol. Conf. (VTC Spring)*, May 2014, pp. 1–5.

[73] H. Zhu, S. Wang, and D. Chen, "Energy-efficient user association for heterogenous cloud cellular networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 273–278.

[74] E. Chavarria Reyes, I. Akyildiz, and E. Fadel, "Energy consumption analysis and minimization in multi-layer heterogeneous wireless systems," *IEEE Trans. Mobile Comput.*, vol. 14, no. 12, pp. 2474–2487, Dec. 2015.

[75] D. Liu, Y. Chen, K. K. Chai, and T. Zhang, "Nash bargaining solution based user association optimization in HetNets," in *Proc. IEEE 11th Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2014, pp. 587–592.

[76] D. Liu, Y. Chen, K. K. Chai, T. Zhang, and M. Elkashlan, "Opportunistic user association for multi-service HetNets using Nash bargaining solution," *IEEE Commun. Lett.*, vol. 18, no. 3, pp. 463–466, Mar. 2014.

[77] Y. S. Soh, T. Quek, M. Kountouris, and H. Shin, "Energy efficient heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, pp. 840–850, May 2013.

[78] W. C. Cheung, T. Quek, and M. Kountouris, "Throughput optimization, spectrum allocation, and access control in two-tier femtocell networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 561–574, Apr. 2012.

[79] W.-C. Liao, M. Hong, and Z.-Q. Luo, "Max-min network flow and resource allocation for backhaul constrained heterogeneous wireless networks," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, May 2014, pp. 845–849.

[80] D. Bethanabhotla, O. Y. Bursalioglu, H. C. Papadopoulos, and G. Caire, "Optimal user-cell association for massive MIMO wireless networks," arXiv preprint arXiv:1407.6731, Jul. 2014.

[81] R. Jain, *The Art of Computer Systems Performance Analysis*. Hoboken, NJ, USA: Wiley, 1991.

[82] Y. Xu, R. Hu, L. Wei, and G. Wu, "QoE-aware mobile association and resource allocation over wireless heterogeneous networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2014, pp. 4695–4701.

[83] D. Fooladivanda, A. Al Daoud, and C. Rosenberg, "Joint channel allocation and user association for heterogeneous wireless cellular networks," in *Proc. IEEE 22nd Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2011, pp. 384–390.

[84] J. Ghimire and C. Rosenberg, "Resource allocation, transmission coordination and user association in heterogeneous networks: A flow-based unified approach," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 1340–1351, Mar. 2013.

[85] Q. Ye, B. Rong, Y. Chen, M. Al-Shalash, C. Caramanis, and J. Andrews, "User association for load balancing in heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2706–2716, Jun. 2013.

[86] K. Shen and W. Yu, "Distributed pricing-based user association for downlink heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1100–1113, Jun. 2014.

[87] G. Hardin, "The tragedy of the commons," Science, vol. 162, pp. 1243–1248, 1968.

[88] P. Fishburn, *Utility Theory for Decision Making*, Hoboken, NJ, USA: Wiley, 1970.

[89] Y. Yi, J. Zhang, Q. Zhang, and T. Jiang, "Spectrum leasing to multiple cooperating secondary cellular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2011, pp. 1–5.

[90] L. Chen, B. Wang, X. Chen, X. Zhang, and D. Yang, "Utility-based resource allocation for mixed traffic in wireless networks," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2011, pp. 91–96.

[91] V. N. Ha and L. B. Le, "Distributed base station association and power control for heterogeneous cellular networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 1, pp. 282–296, Jan. 2014.

[92] O. Semiari, W. Saad, S. Valentin, M. Bennis, and B. Maham, "Matching theory for priority-based cell association in the downlink of wireless small cell networks," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, May 2014, pp. 444–448.

[93] N. Namvar, W. Saad, B. Maham, and S. Valentin, "A context-aware matching game for user association in wireless small cell networks," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, May 2014, pp. 439–443.

[94] M. Haddad, P. Wiecek, E. Altman, and H. Sidi, "A game theoretic approach for the association problem in two-tier HetNets," in *Proc. 25th Int. Teletraffic Congr. (ITC)*, Sep. 2013, pp. 1–9.

[95] W. Saad, Z. Han, R. Zheng, M. Debbah, and H. Poor, "A college admissions game for uplink user association in wireless small cell networks," in *Proc. IEEE INFOCOM*, Apr. 2014, pp. 1096–1104.

[96] M. Hong and Z.-Q. Luo, "Distributed linear precoder optimization and base station selection for an uplink heterogeneous network," *IEEE Trans. Signal Process.*, vol. 61, no. 12, pp. 3214–3228, Jun. 2013.

[97] F. Pantisano, M. Bennis, W. Saad, S. Valentin, M. Debbah, and A. Zappone, "Proactive user association in wireless small cell networks via collaborative filtering," in *Proc. Asilomar Conf. Signals Syst. Comput.*, Nov. 2013, pp. 1601–1605.

[98] H. T. Samson Lasaulce, *Game Theory and Learning for Wireless Networks: Fundamentals and Applications*. Amsterdam, The Netherlands: Elsevier, 2011.

[99] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2009.

[100] D. Liu, L. Wang, Y. Chen, T. Zhang, K. K. Chai, and M. Elkashlan, "Distributed energy efficient fair user association in massive MIMO enabled HetNets," *IEEE Commun. Lett.*, vol. 19, no. 10, pp. 1770–1773, Oct. 2015.

[101] M. Haenggi, *Stochastic Geometry for Wireless Networks*. Cambridge, U.K.: Cambridge Univ. Press, 2012.

[102] N. Bhushan *et al.*, "Network densification: The dominant theme for wireless evolution into 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 82–89, Feb. 2014.

[103] N. DOCOMO, "Performance of eICIC with control channel coverage limitation," *3GPP TSG RAN WG1 Meeting 61*, R1-103264, May 2010.

[104] Kyocera, "Potential performance of range expansion in macro-pico deployment(r1-104355)," 3GPP TSG RAN WG1 Meeting-62, Aug. 2010.

[105] I. Guvenc, "Capacity and fairness analysis of heterogeneous networks with range expansion and interference coordination," *IEEE Commun. Lett.*, vol. 15, no. 10, pp. 1084–1087, Oct. 2011.

[106] H.-S. Jo, Y. J. Sang, P. Xia, and J. Andrews, "Outage probability for heterogeneous cellular networks with biased cell association," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2011, pp. 1–5.

[107] T. Kudo and T. Ohtsuki, "Cell range expansion using distributed Q-learning in heterogeneous networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2013, no. 1, pp. 1–10, 2013.

[108] R1-104968, "Summary of the description of candidate eICIC solutions," G. Std., Aug. 2010.

[109] S. Deb, P. Monogioudis, J. Miernik, and J. Seymour, "Algorithms for enhanced inter-cell interference coordination (eICIC) in LTE HetNets," *IEEE/ACM Trans. Netw.*, vol. 22, no. 1, pp. 137–150, Feb. 2014.

[110] H.-S. Jo, Y. J. Sang, P. Xia, and J. Andrews, "Heterogeneous cellular networks with flexible cell association: A comprehensive downlink SINR analysis," *IEEE Trans. Wireless Commun.*, vol. 11, no. 10, pp. 3484–3495, Oct. 2012.

[111] S. Singh, H. Dhillon, and J. Andrews, "Offloading in heterogeneous networks: Modeling, analysis, and design insights," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2484–2497, May 2013.

[112] S. Singh and J. Andrews, "Joint resource partitioning and offloading in heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 888–901, Feb. 2014.

[113] W. Bao and B. Liang, "Structured spectrum allocation and user association in heterogeneous cellular networks," in *Proc. IEEE INFOCOM*, Apr. 2014, pp. 1069–1077.

[114] S. Sadr and R. Adve, "Tier association probability and spectrum partitioning for maximum rate coverage in multi-tier heterogeneous networks," *IEEE Commun. Lett.*, vol. 18, no. 10, pp. 1791–1794, Oct. 2014.

[115] Y. Lin, W. Bao, W. Yu, and B. Liang, "Optimizing user association and spectrum allocation in hetnets: A utility perspective," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1025–1039, Jun. 2015.

[116] S. Corroy, L. Falconetti, and R. Mathar, "Dynamic cell association for downlink sum maximization in multi-cell heterogeneous networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2012, pp. 2457–2461.

[117] H. Zhou, S. Mao, and P. Agrawal, "Approximation algorithms for cell association and scheduling in femtocell networks," *IEEE Trans. Emerging Topics Comput.*, vol. 3, no. 3, pp. 432–443, Sep. 2015.

[118] M. Feng, T. Jiang, D. Chen, and S. Mao, "Cooperative small cell networks: High capacity for hotspots with interference mitigation," *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 108–116, Dec. 2014.

[119] R. Madan, J. Borran, A. Sampath, N. Bhushan, A. Khandekar, and T. Ji, "Cell association and interference coordination in heterogeneous LTE-A cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1479–1489, Dec. 2010.

[120] R. Sun, M. Hong, and Z. Luo, "Joint downlink base station association and power control for max-min fairness: Computation and complexity," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1040–1054, Jun. 2015.

[121] H. Pervaiz, L. Musavian, and Q. Ni, "Joint user association and energy-efficient resource allocation with minimum-rate constraints in two-tier hetnets," in *Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 1634–1639.

[122] L. P. Qian, Y. J. Zhang, Y. Wu, and J. Chen, "Joint base station association and power control via benders' decomposition," *IEEE Trans. Wireless Commun.*, vol. 12, no. 4, pp. 1651–1665, Apr. 2013.

[123] A. Mesodiakaki, F. Adelantado, L. Alonso, and C. Verikoukis, "Energy-efficient user association in cognitive heterogeneous networks," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 22–29, Jul. 2014.

[124] A. M. Geoffrion, "Generalized benders decomposition," *J. Optim. Theory Appl.*, vol. 10, no. 4, pp. 1–24, 1972.

[125] Y. Chen, S. Zhang, S. Xu, and G. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30–37, Jun. 2011.

[126] G. Auer *et al.*, "How much energy is needed to run a wireless network?," *IEEE Wireless Commun.*, vol. 18, no. 5, pp. 40–49, Oct. 2011.

[127] X. Chen and R. Hu, "Joint uplink and downlink optimal mobile association in a wireless heterogeneous network," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 4131–4137.

[128] T. Zhou, Y. Huang, and L. Yang, "User association with jointly maximising downlink sum rate and minimising uplink sum power for heterogeneous cellular networks," *IET Commun.*, vol. 9, no. 2, pp. 300–308, 2015.

[129] S. Luo, R. Zhang, and T. J. Lim, "Downlink and uplink energy minimization through user association and beamforming in C-RAN," *IEEE Trans. Wireless Commun.*, vol. 14, no. 1, pp. 494–508, Jan. 2015.

[130] H. Beyranvand, W. Lim, M. Maier, C. Verikoukis, and J. Salehi, "Backhaul-aware user association in FiWi enhanced LTE-A heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 2992–3003, Jun. 2015.

[131] N. Wang, E. Hossain, and V. K. Bhargava, "Joint downlink cell association and bandwidth allocation for wireless backhauling in two-tier HetNets with large-scale antenna arrays," *IEEE Trans. Wireless Commun.*, 2016.

[132] Z. Cui and R. Adve, "Joint user association and resource allocation in small cell networks with backhaul constraints," in *Proc. 48th Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2014, pp. 1–6.

[133] A. De Domenico, V. Savin, and D. Ktenas, "A backhaul-aware cell selection algorithm for heterogeneous cellular networks," in *Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 1688–1693.

[134] F. Pantisano, M. Bennis, W. Saad, and M. Debbah, "Cache-aware user association in backhaul-constrained small cell networks," in *Proc. 12th Int. Symp. Model. Optim. Mobile Ad Hoc Wireless Netw. (WiOpt)*, May 2014, pp. 37–42.

[135] R. Ford, C. Kim, and S. Rangan, "Opportunistic third-party backhaul for cellular wireless networks," in *Proc. Asilomar Conf. Signals Syst. Comput.*, Nov. 2013, pp. 1594–1600.

[136] S. Sadr and R. Adve, "Handoff rate and coverage analysis in multi-tier heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2626–2638, May 2015.

[137] P. Coucheney, E. Hyon, and J.-M. Kelif, "Mobile association problem in heterogenous wireless networks with mobility," in *Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun.(PIMRC)*, Sep. 2013, pp. 3129–3133.

[138] S. Moharir, S. Krishnasamy, and S. Shakkottai, "Scheduling in densified networks: Algorithms and performance," in *Proc. 52nd Annu. Allerton Conf. Commun. Control Comput. (Allerton)*, Sep. 2014, pp. 683–690.

[139] C. Dhahri and T. Ohtsuki, "Q-learning cell selection for femtocell networks: Single- and multi-user case," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2012, pp. 4975–4980.

[140] C. Dhahri and T. Ohtsuki, "Adaptive Q-learning cell selection method for open-access femtocell networks: Multi-user case," *IEICE Trans. Commun.*, vol. E97.B, no. 8, pp. 1679–1688, 2014.

[141] H. Wang, C. Rosa, and K. Pedersen, "Dual connectivity for LTE-advanced heterogeneous networks," *Wireless Netw.*, pp. 1–14, 2015.

[142] M. Kim, S. Y. Jung, and S.-L. Kim, "Sum-rate maximizing cell association via dual-connectivity," in *Proc. Int. Conf. Comput. Inf. Telecommun. Syst. (CITS)*, 2015, pp. 1–5.

[143] K. Smiljkovikj *et al.*, "Capacity analysis of decoupled downlink and uplink access in 5G heterogeneous systems," arXiv preprint arXiv:14107270, 2014.

[144] K. Smiljkovikj, P. Popovski, and L. Gavrilovska, "Analysis of the decoupled access for downlink and uplink in wireless heterogeneous networks," *IEEE Wireless Commun. Lett.*, vol. 4, no. 2, pp. 173–176, Apr. 2015.

[145] S. Singh, X. Zhang, and J. G. Andrews, "Joint rate and SINR coverage analysis for decoupled uplink-downlink biased cell associations in hetnets," arXiv preprint arXiv: 1412.898, 2014.

[146] F. Boccardi *et al.*, "Why to decouple the uplink and downlink in cellular networks and how to do it," arXiv preprint arXiv:1503.06746, Mar. 2015.

[147] T. Nakamura *et al.*, "Trends in small cell enhancements in LTE advanced," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 98–105, Feb. 2013.

[148] 3GPP, "Mobility enhancements in heterogeneous networks," TR 36.839 v11.0.0, Sep. 2012.

[149] W. Fischer, "The markov-modulated poisson process (mmpp) cookbook," *J. Perform. Eval.*, vol. 18, no. 2, Sep. 1993.

[150] 3GPP, "Study on small cell enhancements for EUTRA and E-UTRAN-Higher layer aspects (3gpp tr 36.842)," 2013.

[151] 3GPP, "3gpp work items on small cells v0.0.4," 2014.

[152] WGC, White Paper in Wireless Research Forum.

[153] S. Jha, K. Sivanesan, R. Vannithamby, and A. Koc, "Dual connectivity in lte small cell networks," in *Proc. Globecom Workshops (GC Wkshps)*, 2014, pp. 1205–1210.

[154] C. Xiong, G. Li, S. Zhang, Y. Chen, and S. Xu, "Energy- and spectral-efficiency tradeoff in downlink OFDMA networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3874–3886, Nov. 2011.

[155] J. Rao and A. Fapojuwo, "On the tradeoff between spectral efficiency and energy efficiency of homogeneous cellular networks with outage constraint," *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1801–1814, May 2013.

[156] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[157] E. Björnson, J. Hoydis, M. Kountouris, and M. Debbah, "Massive MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits," *IEEE Trans. Inf. Theory*, vol. 60, no. 11, pp. 7112–7139, Nov. 2014.

[158] L. Wang, H. Q. Ngo, M. Elkashlan, T. Q. Duong, and K.-K. Wong, "Massive MIMO in spectrum sharing networks: Achievable rate and power efficiency," *IEEE Syst. J.*, 2015.

[159] A. He, L. Wang, Y. Chen, M. Elkashlan, and K. K. Wong, "Massive MIMO in K-tier heterogeneous cellular networks: Coverage and rate," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, San Diego, CA, USA, Dec. 2015, pp. 1–6.

[160] A. He, L. Wang, M. Elkashlan, Y. Chen, and K.-K. Wong, "Spectrum and energy efficiency in massive MIMO enabled hetnets: A stochastic geometry approach," *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2294–2297, Dec. 2015.

[161] Y. Xu and S. Mao, "User association in massive MIMO hetnets," arXiv preprint arXiv:1501.03407, Jan. 2015.

[162] K. Hosseini, W. Yu, and R. S. Adve, "Large-scale MIMO versus network MIMO for multicell interference mitigation," *IEEE J. Sel. Areas Commun.*, vol. 8, no. 5, pp. 930–941, Oct. 2014.

[163] V. Jungnickel *et al.*, "The role of small cells, coordinated multipoint, and massive MIMO in 5G," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 44–51, May 2014.

[164] D. Bethanabhotla, O. Bursalioglu, H. Papadopoulos, and G. Caire, "User association and load balancing for cellular massive MIMO," in *Proc. Inf. Theory Appl. Workshop (ITA)*, Feb. 2014, pp. 1–10.

[165] A. G. Gotsis, S. Stefanatos, and A. Alexiou, "Optimal user association for massive MIMO empowered ultra-dense wireless networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2015, pp. 2238–2244.

[166] H. Yang and T. L. Marzetta, "Total energy efficiency of cellular large scale antenna system multiple access mobile networks," in *Proc. IEEE Online Conf. Green Commun. (GreenCom)*, Oct. 2013, pp. 27–32.

[167] E. Björnson, M. Kountouris, and M. Debbah, "Massive MIMO and small cells: Improving energy efficiency by optimal soft-cell coordination," in *Proc. 20th Int. Conf. Telecommun.*, May 2013, pp. 1–5.

[168] E. Björnson, L. Sanguinetti, J. Hoydis, and M. Debbah, "Designing multi-user MIMO for energy efficiency: When is massive MIMO the answer?," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2014, pp. 242–247.

[169] E. Björnson, L. Sanguinetti, and M. Kountouris, "Deploying dense networks for maximal energy efficiency: Small cells meet massive MIMO," arXiv preprint arXiv:1505.01181, May 2015.

[170] M. Elkashlan, T. Q. Duong, and H. H. Chen, "Guest editorial-Millimeter wave communications for 5G-Part I: Fundamentals," *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 52–54, Sep. 2014.

[171] TR 36.808, *Evolved Universal Terrestrial Radio Access (E-UTRA); Carrier Aggregation; Base Station (BS) radio transmission and reception*.

[172] H. T. Friis, "A note on a simple transmission formula," in *Proc. IRE 34*, 1946, pp. 254–256.

[173] T. Bai and R. W. Heath Jr., "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 1100–1114, Feb. 2015.

[174] J. Zhang, A. Beletchi, Y. Yi, and H. Zhuang, "Capacity performance of millimeter wave heterogeneous networks at 28GHz/73GHz," in *Proc. Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 405–409.

[175] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave (mmWave) communications for 5G: Opportunities and challenges," arXiv preprint arXiv:1502.07228, Feb. 2015.

[176] G. Athanasiou, P. Weeraddana, and C. Fischione, "Auction-based resource allocation in millimeterwave wireless access networks," *IEEE Commun. Lett.*, vol. 17, no. 11, pp. 2108–2111, Nov. 2013.

[177] Y. Xu, G. Athanasiou, C. Fischione, and L. Tassiulas, "Distributed association control and relaying in millimeterwave wireless access networks," arXiv preprint arXiv:1307.7553, Jul. 2013.

[178] G. Athanasiou, P. Weeraddana, C. Fischione, and L. Tassiulas, "Optimizing client association for load balancing and fairness in millimeter-wave wireless networks," *IEEE/ACM Trans. Netw.*, vol. 23, no. 3, pp. 836–850, Jun. 2015.

[179] K. Sakaguchi *et al.*, "Millimeter-wave evolution for 5G cellular networks," arXiv preprint arXiv:1412.3212, Dec. 2014.

[180] B. Xu, Y. Chen, M. Elkashlan, and T. Zhang, and Kai-Kit Wong, "User association in massive MIMO and mmWave enabled HetNets powered by renewable energy," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, 2016, pp. 1–6.

[181] R. Mahindra, H. Viswanathan, K. Sundaresan, M. Y. Arslan, and S. Rangarajan, "A practical traffic management system for integrated LTE-WiFi networks," in *Proc. ACM MobiCom '14*, 2014, pp. 189–200.

[182] F. Zhou, L. Feng, P. Yu, and W. Li, "Energy-efficiency driven load balancing strategy in LTE-WiFi interworking heterogeneous networks," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, 2015, pp. 276–281.

[183] R. C. Daniels, J. N. Murdock, T. S. Rappaport, and R. W. Heath, "60 GHz wireless: Up close and personal," *IEEE Microw. Mag.*, vol. 11, no. 7, pp. 44–50, Dec. 2010.

[184] S. Rangan, T. Rappaport, E. Erkip, Z. Latinovic, M. R. Akdeniz, and Y. Liu, "Energy efficient methods for millimeter wave picocellular systems," in *Proc. IEEE Commun. Theory Workshop*, 2013, pp. 1–25.

[185] H. Elshaer, F. Boccardi, M. Dohler, and R. Irmer, "Downlink and uplink decoupling: A disruptive architectural design for 5G networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2014, pp. 1798–1803.

[186] H. Dhillon, Y. Li, P. Nuggehalli, Z. Pi, and J. Andrews, "Fundamentals of heterogeneous cellular networks with energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2782–2797, May 2014.

[187] Y. Song, M. Zhao, W. Zhou, and H. Han, "Throughput-optimal user association in energy harvesting relay-assisted cellular networks," in *Proc. 6th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2014, pp. 1–6.

[188] J. Rubio, A. Pascual-Iserte, J. del Olmo, and J. Vidal, "User association for load balancing in heterogeneous networks powered with energy harvesting sources," in *Proc. Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 1248–1253.

[189] D. Liu, Y. Chen, K. K. Chai, T. Zhang, and C. Pan, "Adaptive user association in HetNets with renewable energy powered base stations," in *Proc. 21st Int. Conf. Telecommun. (ICT)*, May 2014, pp. 93–97.

[190] T. Zhang, H. Xu, D. Liu, N. Beaulieu, and Y. Zhu, "User association for energy-load tradeoffs in HetNets with renewable energy supply," *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2214–2217, Dec. 2015.

[191] S. Jangsher, H. Zhou, V. Li, and K.-C. Leung, "Joint allocation of resource blocks, power, and energy-harvesting relays in cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 3, pp. 482–495, Mar. 2015.

[192] D. Liu, Y. Chen, K. K. Chai, and T. Zhang, "Distributed delay-energy aware user association in 3-tier HetNets with hybrid energy sources," in *Proc. Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 1109–1114.

[193] D. Liu, Y. Chen, K. K. Chai, and T. Zhang, "Backhaul aware joint uplink and downlink user association for delay-power trade-offs in HetNets with hybrid energy sources," *Trans. Emerging Telecommun. Technol.*, 2015, doi: 10.1002/ett.2968.

[194] T. Han and N. Ansari, "Ice: Intelligent cell breathing to optimize the utilization of green energy," *IEEE Commun. Lett.*, vol. 16, no. 6, pp. 866–869, Jun. 2012.

[195] B. Wang, Q. Kong, W. Liu, and L. Yang, "On efficient utilization of green energy in heterogeneous cellular networks," *IEEE Syst. J.*, pp. 1–12, 2015.

[196] A. H. Sakr and E. Hossain, "Analysis of multi-tier uplink cellular networks with energy harvesting and flexible cell association," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2014, pp. 4525–4530.

[197] Y. Cao, N. Wang, G. Kamel, and Y.-J. Kim, "An electric vehicle charging management scheme based on publish/subscribe communication framework," *IEEE Syst. J.*, pp. 1–14, 2015.

[198] D. Ng, E. Lo, and R. Schober, "Energy-efficient resource allocation in OFDMA systems with hybrid energy harvesting base station," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3412–3427, Jul. 2013.

[199] HUAWEI. Green Energy Solution [Online]. Available: http://www.huawei.com/uk/solutions/go-greener/hw-076723.htm

[200] J. Gong, S. Zhou, and Z. Niu, "Optimal power allocation for energy harvesting and power grid coexisting wireless communication systems," *IEEE Trans. Commun.*, vol. 61, no. 7, pp. 3040–3049, Jul. 2013.

[201] Y. Cui, V. Lau, and Y. Wu, "Delay-aware BS discontinuous transmission control and user scheduling for energy harvesting downlink coordinated MIMO systems," *IEEE Trans. Signal Process.*, vol. 60, no. 7, pp. 3786–3795, Jul. 2012.

[202] M. Zheng, P. Pawelczak, S. Stanczak, and H. Yu, "Planning of cellular networks enhanced by energy harvesting," *IEEE Commun. Lett.*, vol. 17, no. 6, pp. 1092–1095, Jun. 2013.

[203] D. Liu, Y. Chen, K. K. Chai, T. Zhang, and M. Elkashlan, "Two dimensional optimization on user association and green energy allocation for HetNets with hybrid energy sources," *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4111–4124, Nov. 2015.

[204] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid- the new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, Fourth Quart. 2012.

[205] Y.-K. Chia, S. Sun, and R. Zhang, "Energy cooperation in cellular networks with renewable powered base stations," *IEEE Trans. Wireless Commun.*, vol. 13, no. 12, pp. 6996–7010, Dec. 2014.

[206] Y. Guo, J. Xu, L. Duan, and R. Zhang, "Joint energy and spectrum cooperation for cellular communication systems," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3678–3691, Oct. 2014.

[207] J. Xu and R. Zhang, "CoMP meets smart grid: A new communication and energy cooperation paradigm," *IEEE Trans. Veh. Technol.*, vol. 64, no. 6, pp. 2476–2488, Jun. 2015.

[208] Nokia, "5G use cases and requirements," 2014.

[209] H. Hu, J. Zhang, X. Zheng, Y. Yang, and P. Wu, "Self-configuration and self-optimization for LTE networks," *IEEE Commun. Mag.*, vol. 48, no. 2, pp. 94–100, Feb. 2010.

[210] M. Peng, C. Wang, J. Li, H. Xiang, and V. Lau, "Recent advances in underlay heterogeneous networks: Interference control, resource allocation, and self-organization," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 700–729, Second Quart. 2015.

[211] A. Lobinger, S. Stefanski, T. Jansen, and I. Balan, "Coordinating handover parameter optimization and load balancing in LTE self-optimizing networks," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, 2011, pp. 1–5.

[212] Y. Liu, L. Wang, S. A. R. Zaidi, M. Elkashlan, and T. Q. Duong, "Secure D2D communication in large-scale cognitive cellular networks: A wireless power transfer model," *IEEE Trans. Commun.*, vol. 64, no. 1, pp. 329–342, Jan. 2016.

[213] H. ElSawy, E. Hossain, and M.-S. Alouini, "Analytical modeling of mode selection and power control for underlay D2D communication in cellular networks," *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 4147–4161, Nov. 2014.

[214] C. Vlachos and V. Friderikos, "Optimal device-to-device cell association and load balancing," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2015, pp. 5441–5447.

[215] O. Semiari, W. Saad, S. Valentin, M. Bennis, and H. V. Poor, "Context-aware small cell networks: How social metrics improve wireless resource allocation," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 5927–5940, Nov. 2015.

[216] S. Luo, R. Zhang, and T. J. Lim, "Downlink and uplink energy minimization through user association and beamforming in C-RAN," *IEEE Trans. Wireless Commun.*, vol. 14, no. 1, pp. 494–508, Jan. 2015.

[217] H. Zhang, W. Wang, X. Li, and H. Ji, "User association scheme in Cloud-RAN based small cell network with wireless virtualization," in *Proc. IEEE Comput. Commun. Workshops (INFOCOM WKSHPS)*, 2015, pp. 384–389.

[218] S. A. R. Zaidi, A. Imran, D. C. McLernon, and M. Ghogho, "Characterizing coverage and downlink throughput of cloud empowered hetnets," *IEEE Commun. Lett.*, vol. 19, no. 6, pp. 1013–1016, Jun. 2015.

[219] D. Kim, H. Lee, and D. Hong, "A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2017–2046, Fourth Quart. 2015.

[220] S. Goyal, P. Liu, S. S. Panwar, R. A. Difazio, R. Yang, and E. Bala, "Full duplex cellular systems: Will doubling interference prevent doubling capacity?," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 121–127, May 2015.

[221] S. Sekander, H. Tabassum, and E. Hossain, "A matching game for decoupled uplink-downlink user association in full-duplex small cell networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2015, pp. 1–6.

Dantong Liu (S'13) received double B.Sc. degrees (with first class Hons.) in telecommunications engineering from Beijing University of Posts and Telecommunications, Beijing, China, and Queen Mary University of London, London, U.K., and the Ph.D. degree in electronic engineering from Queen Mary University of London, London, U.K., in 2012 and 2015, respectively. Since August 2015, she has been with the Chief Technology and Architecture Office (CTAO) of Cisco Systems Inc. Her research interests include radio resource allocation optimization in HetNets, cooperative wireless networks, and smart energy systems. She serves as technical program committee (TPC) member for GLOBECOM 2015, ComManTel 2015, ATC 2015, ICSINC 2015, VTC 2016-Spring, and ICC 2016.

Lifeng Wang (M'16) received the M.S. degree in electronic engineering from the University of Electronic Science and Technology of China, Chengdu, China, and the Ph.D. degree in electronic engineering from Queen Mary University of London, London, U.K., in 2012 and 2015, respectively. He is the Postdoctoral Research Fellow with the Department of Electronic and Electrical Engineering, University College London (UCL), London, U.K. His research interests include millimeter-wave communications, Massive MIMO, HetNets, Cloud-RAN, cognitive radio, physical layer security, and wireless energy harvesting. He received the Exemplary Reviewer Certificate of the IEEE COMMUNICATIONS LETTERS in 2013. He has served as TPC member for many IEEE conferences such as the IEEE GLOBECOM and ICC.

Yue Chen (S'02–M'03–SM'15) received the bachelor's and master's degree from Beijing University of Posts and Telecommunications, Beijing, China, the Ph.D. degree from Queen Mary University of London (QMUL), London, U.K., and the MBA degree from Open University, London, U.K., in 1997, 2000, 2003, and 2013, respectively. Currently, she is an Associate Professor with the School of Electronic Engineering and Computer Science, QMUL. She is also the Director of Joint Ventures who is responsible for research and teaching collaborations between QMUL and other prestigious institutions. Her research interests include intelligent radio resource management for wireless networks; MAC and network layer protocol design for LTE-A networks; cognitive and cooperative wireless networking; HetNets; smart energy systems; and Internet of Things. She has served as a TPC member for many IEEE conferences and member of the IET China Steering Group, the IET Qualification Board, and the Quality Review Advisory board at several universities in the U.K.

Maged Elkashlan (M'06) received the Ph.D. degree in electrical engineering from the University of British Columbia, Vancouver, BC, Canada, 2006. From 2006 to 2007, he was with the Laboratory for Advanced Networking, University of British Columbia. From 2007 to 2011, he was with the Wireless and Networking Technologies Laboratory, Commonwealth Scientific and Industrial Research Organization (CSIRO), Dickson, A.C.T. Australia. During this time, he held an adjunct appointment at University of Technology Sydney, Ultimo, N.S.W., Australia. In 2011, he joined the School of Electronic Engineering and Computer Science, Queen Mary University of London, London, U.K., as an Assistant Professor. He also holds visiting faculty appointments at the University of New South Wales, Sydney, N.S.W., Australia, and Beijing University of Posts and Telecommunications, Beijing, China. His research interests include communication theory, wireless communications, and statistical signal processing for distributed data processing, heterogeneous networks, cognitive radio, and security. He currently serves as an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and the IEEE COMMUNICATIONS LETTERS. He also serves as the Lead Guest Editor for the special issue on *Green Media: The Future of Wireless Multimedia Networks* of the *IEEE Wireless Communications Magazine*, the Lead Guest Editor for the special issue on *Millimeter Wave Communications for 5G* of the *IEEE Communications Magazine*, the Guest Editor for the special issue on *Energy Harvesting Communications* of the *IEEE Communications Magazine*, and the Guest Editor for the special issue on *Location Awareness for Radios and Networks* of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. He received the Exemplary Reviewer Certificate of the IEEE Communications Letters in 2012. He was the recipient of the Best Paper Award at the IEEE International Conference on Communications (ICC) in 2014, the International Conference on Communications and Networking in China (CHINACOM) in 2014, and the IEEE Vehicular Technology Conference (VTC-Spring) in 2013.

Kai-Kit Wong (M'01–SM'08–F'16) received the B.Eng., M.Phil., and Ph.D. degrees in electrical and electronic engineering from the Hong Kong University of Science and Technology, Hong Kong, in 1996, 1998, and 2001, respectively. He is a Full Professor and the Chair in wireless communications with the Department of Electronic and Electrical Engineering, University College London, London, U.K. Prior to this, he took up faculty appointments as Research Assistant Professor with the University of Hong Kong, Pok Fu Lam, Hong Kong, and Lecturer with the University of Hull, Kingston upon Hull, U.K. He also previously took up visiting positions at the Smart Antennas Research Group, Stanford University, Stanford, CA, USA, and the Wireless Communications Research Department, Lucent Technologies, Bell-Labs, Holmdel, NJ, USA. He is Fellow of IET. He has been a Senior Editor of the IEEE COMMUNICATIONS LETTERS since 2012 and is presently also serving on the editorial boards of the IEEE WIRELESS COMMUNICATIONS LETTERS (since 2011), the IEEE COMSOC/*KICS Journal of Communications and Networks* (since 2010), *IET Communications* (since 2009), and *Physical Communications* (Elsevier) (since 2012). He also previously served as an Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS from 2005 to 2011, a Review Editor for the IEEE COMMUNICATIONS LETTERS from 2009 to 2012 and an Associate Editor for the IEEE SIGNAL PROCESSING LETTERS from 2009 to 2012.

Robert Schober (S'98–M'01–SM'08–F'10) was born in Neuendettelsau, Germany, in 1971. He received the Diplom (Univ.) and Ph.D. degrees in electrical engineering from the University of Erlangen-Nuermberg, Erlangen, Germany, in 1997 and 2000, respectively. From May 2001 to April 2002, he was a Postdoctoral Fellow with the University of Toronto, Toronto, ON, Canada, sponsored by the German Academic Exchange Service (DAAD). Since May 2002, he has been with the University of British Columbia (UBC), Vancouver, BC, Canada, where he is now a Full Professor. Since January 2012, he has been an Alexander von Humboldt Professor and the Chair for Digital Communication at the Friedrich Alexander University (FAU), Erlangen, Germany. His research interests include communication theory, wireless communications, and statistical signal processing. He is a Fellow of the Canadian Academy of Engineering and the Engineering Institute of Canada. He is currently the Editor-in-Chief of the IEEE TRANSACTIONS ON COMMUNICATIONS. He was the recipient of several awards for his work including the 2002 Heinz MaierCLeibnitz Award of the German Science Foundation (DFG), the 2004 Innovations Award of the Vodafone Foundation for Research in Mobile Communications, the 2006 UBC Killam Research Prize, the 2007 Wilhelm Friedrich Bessel Research Award of the Alexander von Humboldt Foundation, the 2008 Charles McDowell Award for Excellence in Research from UBC, a 2011 Alexander von Humboldt Professorship, and a 2012 NSERC E.W.R. Steacie Fellowship. He was also the recipient of best paper awards from the German Information Technology Society (ITG), the European Association for Signal, Speech, and Image Processing (EURASIP), the IEEE WCNC 2012, the IEEE GLOBECOM 2011, the IEEE ICUWB 2006, the International Zurich Seminar on Broadband Communications, and European Wireless 2000.

Lajos Hanzo (M'91–SM'92–F'04) received the degree in electronics in 1976, and the doctorate degree in 1983. In 2009, he received an honorary doctorate from the Technical University of Budapest, Budapest, Hungary, and while in 2015, from the University of Edinburgh, Edinburgh, Scotland. During his 38-year career in telecommunications, he has held various research and academic posts in Hungary, Germany, and the U.K. Since 1986, he has been with the School of Electronics and Computer Science, University of Southampton, Southampton, U.K., where he holds the Chair in telecommunications. He has successfully supervised about 100 Ph.D. students, coauthored 20 John Wiley/IEEE Press books on mobile radio communications totalling in excess of 10 000 pages, published 1500+ research entries at IEEE Xplore, acted both as TPC and the General Chair of IEEE conferences, presented keynote lectures. Currently, he is directing a 60-strong Academic Research Team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council (EPSRC) U.K. He is an Enthusiastic Supporter of industrial and academic liaison and offers a range of industrial courses. He is also the Governor of the IEEE VTS. From 2008 to 2012, he was the Editor-in-Chief of the IEEE Press and a Chaired Professor also at Tsinghua University, Beijing, China. His research is funded by the European Research Council's Senior Research Fellow Grant. He has 23 000+ citations. He is a Fellow of FREng, FIET, EURASIP, and DSc. He was the recipient of a number of distinctions. He was also the recipient of the European Research Council's Advanced Fellow Grant and the Royal Society's Wolfson Research Merit Award.