Ultra-Dense Networks: Survey of State of the Art and Future Directions

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***Abstract*—Within the foreseeable future, the growing number of mobile devices, and their diversity, will challenge the current network architecture. Furthermore, users will expect greater data rates, lower latency, lower packet drop rates, etc. in future wireless networks. Ultra Dense Networks (UDN), considered to be one of the best ways to meet user expectations and support future wireless network deployment, will face multiple significant hurdles, including interference, mobility, and cost. In this paper, we review existing research efforts toward addressing those challenges and present future avenues for research. We first develop a taxonomy to review and describe existing research efforts. Next, we focus on inter-cell interference, handover performance, and energy efficiency as the key techniques to addressing the most pressing challenges. Finally, we present several future research directions, including emergent Internet-of-Things (IoT) applications, security and privacy, modeling and realistic simulations, and relevant techniques.**

***Index Terms*—Survey, Ultra Dense Network (UDN), interference management, mobility management, cost management, Internet-of-Things (IoT), security.**

I. Introduction

The next generation wireless network is expected to connect a large number of User Equipment (UEs), support massive machine to machine (M2M) communication, and enable the 1000-fold data traffic increase [13]. Cell size reduction has significantly improved network capacity. As stated in [32], from 1950 to 2000, wireless network capacity has increased 25 fold due to the implementation of wider spectrum frequency bands, 10 fold due to advances in modulation techniques and coding schemes, and 2700 fold through both the reduction of cell size and corresponding decrease in communication distance.

Nonetheless, the current deployment of macro cells is already approaching its theoretical bound. Further deployment of macro cells will not improve performance [52]. The network deployment was evolved from the traditional macro cell only network, known as a Homogenous Network (HomNet), to a Heterogeneous Network (HetNet) in which small cells are distributed throughout the macro cell covered area. To achieve 1000 fold network capacity improvement, the deployment of ultra-dense small cells in a HetNet becomes a viable approach.

As shown in Figure 1, a simplified UDN includes the components: densely deployed small cells, macro Base Stations (BS), network server/controller, moving nodes, and UEs. As we can see, a large number of small cells can support the increasing number of UEs and the mobile UEs perform the connection, disconnection, searching, and reconnection. Also,

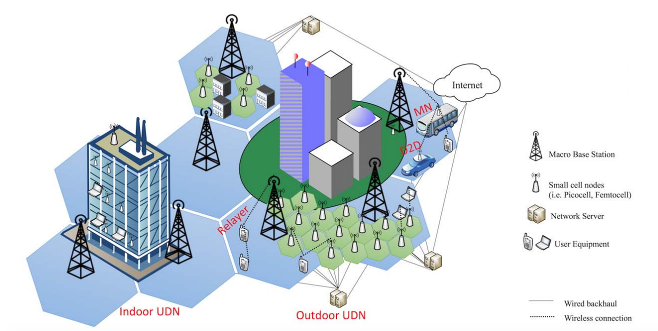

Fig. 1. An example of a UDN

the UEs at a cell edge may need relayer (as forwarding node) for connection, which requires the availability of D2D communication. Likewise, the moving nodes can also help communication between vehicular or UEs (V2V).

The principle features of the UDN are the following: (i) *A large number of small cells and access points (greater than or equal to number of UEs)*. The frequency reuse can be improved by the large number of small cells in the same way that close distance and spectrum sharing works in macro cells. The dense small cells improve the network capacity by offloading macrocell traffic, balancing network loads, and reducing congestion. (ii) *Dense and richly inter-connected cross-tier deployment.* This consists of macro cell, small cell (e.g., Pico, Femto), device to device (D2D) links, relay, etc., which collectively increase the complexity of the network environment. Because of the multi-tier deployment, the different frequency signals are transmitted throughout the overlapping area (e.g., macro cell and small cell). Also, the close distance of small cells leads to a large frequency reuse factor. Thus, advanced interference coordination is crucial to reduce intra-tier interference (e.g., macro-macro, small-small), inter-tier interference (e.g., macro-small), and to support resource management (e.g., energy and spectrum). (iii) *Fast access and flexible switching (e.g., handovers)*. In the dense-deployment environment, the moving UE may frequently switch the connection among access nodes, for the sake of better service, optimal connections, etc. High Quality handover (HO) performance is needed to provide seamless and smooth connections.

In this paper, we review existing research efforts focused on addressing these challenges and present future research directions. We introduce a taxonomy to categorize existing research efforts with respect to three key performance areas: inter-cell interference, handover performance and mobility management, and cost, as well as identifying key techniques to address problems in these areas. We consider existing challenges for UDN. We provide a road map for future research directions, including new approaches to address challenges in interference, mobility, cost management, security, IoT applications, modeling and realistic simulations, and other relevant techniques (i.e., MIMO, mmWave).

The remainder of the paper is organized as follows: In Section II, we identify key issues of UDN and investigate existing research efforts on those issues. Based on an extensive review of existing approaches, we discuss potential solutions to address these issues in Section III. In Section IV, we outline future research directions and summarize our findings in Section V.

II. Key Issues and Existing Research Efforts

In this section, we present a 3D framework to outline the challenges of UDN and categorize existing research efforts based on those challenges, shown in Figure 2. These challenges can be separated into three orthogonal dimensions, i.e., interference, mobility, and cost. Here, X axis shows the interferences in UDN, including $<$ X_1: inter-cell (macro-to-macro) interference, X_2: multi-tier interference, X_3: small-to-small interference $>$. Y axis shows the mobility in UDN, including $<$ Y_1: user-side mobility, Y_2: node-side mobility $>$. Z axis shows the costs in UDN, including $<$ Z_1: deployment, Z_2: energy efficiency, Z_3: spectrum efficiency $>$.

A. *Interference*

To mitigate interference, existing schemes have been developed based on the resource partitioning on frequency-domain, time-domain, and spatial-domain in either network side or UE side, or a combination of network side control and UE assist [55]. The six cubes listed the proposed 3-D framework as shown in Figure 3 show the individual subareas and the interactions among 3 dimensions. For example, $< x_1, y_2, z_3 >$ represents the schemes that mitigate the inter-cell interference in the spatial domain, and are implemented on the network side.

1) Inter-Cell Interference (ICI): Inter-cell interference is caused by spectrum scarcity, where the spectrum resource is not able to cope with the increased demand. The frequency reuse techniques among different cells have been developed to support increasing number of UEs. Nonetheless, in UDN, the ICI will be severe, as the frequency reuse will be potentially increased to a factor greater than 1, and will be further complicated by dense deployment, close distance, irregular deployment, etc. Thus, the ICI Coordination (ICIC) schemes should be enhanced to deal with the inter-cell interference.

The ICI can be mitigated by advanced receivers on the UE side, joint cells scheduling on the network side, or the joint cooperation of both UE and network side components [42].

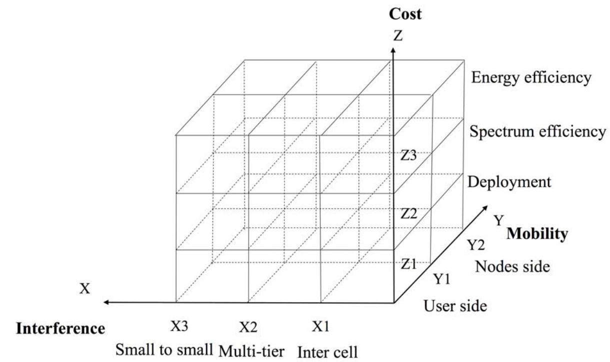

Fig. 2. The Challenges of UDN

In the following, we describe ICI mitigation schemes from time-domain, frequency-domain and spatial-domain aspects.

Time-domain Techniques: The triple $< x_1, y_2, z_1 >$ represents the ICI mitigation schemes based on resource partitioning in the time domain on the network side. As an example, a centralized network controller can be used to effectively reduce the deployment cost by optimizing the deployment location of BS and assigning network resources [46]. The Coordinated Multi Point (CoMP), also known as Cooperative MIMO, Schemes were proposed to reduce inter-cell interference and improve network usage by coordinating transmissions to UEs from multiple macrocell base stations, using Channel State Information (CSI) reports from UEs to "pre-distort" signal so that they add constructively at the intended receiver [29]. Also, the enhanced ICI Coordination (eICIC), which supports HetNet interference mitigation was specified in 3GPP Release 10 [49]. The time-domain resource partitioning based eICIC mitigates the interference by transmitting reference signals at femtocells instead of transmitting both reference signals and data signals at macro cells (e.g., Almost Blank Subframe (ABS)).

The ordered triple $< x_1, y_1, z_1 >$ represents the UE side time domain coordination. Garcia *et al.* in [17] introduced UE-based adaptive clustering, which improves the goodput at each BS. The user centric coordination can be dynamic and optimal, as well as low cost, in comparison with the network controller, which is preferred in UDN [37]. This scheme belongs to $< x_1, y_1, z_1 >$. Also, the joint network control and UE assist scheme in the time domain was proposed in [42] and can be categorized into $<x_1, y_3, z_1>$. Another joint combination is the network side CoMP (i.e., coordinated scheduling) combined with the advanced interference detection or rejection capabilities at the UE side, which can potentially be used in UDN [69].

Frequency-domain Techniques: The triples $< x_1, y_1, z_2 >$, $< x_1, y_2, z_2 >$, and $< x_1, y_3, z_2 >$ represent ICIC techniques in frequency domain, in which both control signals and physical signals in different cells are orthogonal, in order to reduce the interference from signals [34]. Schemes in $< x_1, y_1, z_2 >$ represent the UE side ICIC in the frequency domain. The advanced receiver has the capability of nonlinear interference cancellation for the ICI mitigation. Specifically, the UE reconstructs the interference signal and subtracts it before decoding the received signal. Nonetheless, the drawback of the nonlinear interference cancellation is the high complexity, due to the dynamic modulation scheme and link adaptation [55]. The additional network assistance for the UE interference cancellation can simplify the process in advance, by utilizing the prior interference information [4].

Schemes in $< x_1, y_2, z_2 >$ represent the ICI mitigation schemes in the frequency domain on the network side. The 3GPP release 10 introduced Carrier Aggregation (CA) to mitigate the ICI in the frequency domain [49]. The CA allows two or more LTE component carriers (CC) to implement simultaneous aggregation, achieving larger communication bandwidth and higher data rates [23]. The CA-based ICIC, which splits spectrum into two CCs (one for the reliable physical signal transmission and the other for the data signal transmission with cross carrier scheduling), is another advanced frequency domain resource partitioning scheme [31].

Schemes in $< x_1, y_3, z_2 >$ represent ICI mitigation schemes by both network and UEs in the frequency domain. One scheme belonging to this category is the adaptive Fractional Frequency Reuse (FFR) [16]. The cell edge nodes can use a partial of the frequency band and it is orthogonal to the neighboring cell edge. The cell center nodes can use the other portion of the frequency band. By doing so, the UE can avoid the strong ICI at the cell edge. This partial interference orthogonalization can be achieved either at network side via a static detection mechanism, or at UE side via a dynamic detection mechanism [34].

Spatial-domain Techniques: The spatial domain resource partitioning schemes for the ICI mitigation include $< x_1, y_1, z_3 >$, $< x_1, y_2, z_3 >$ and $< x_1, y_3, z_3 >$. Here, $< x_1, y_2, z_3 >$ refers to the network side ICI in the spatial domain. Sanjay *et al.* in [27] proposed a scheme on the spatial domain resource partitioning in the macro cells BS. Based on their study, the 6-sector-site macro cell deployment gains 88 % network capacity, compared to the 3-sector-site macro cell deployment via exploring the spatial gain. Coordination beamforming is another advanced spatial domain ICI coordination on the network side [55] as well as the multi-cell coordination beamforming, enhanced by the multiple antennas [14]. In addition, the UE side ICIC in the spatial domain is categorized by $< x_1, y_1, z_3 >$. The multiple antennas in the UE side can achieve the linear interference suppression by exploiting the degrees of freedom.

Schemes in $< x_1, y_3, z_3 >$ represent the ICIC schemes by joint combination of network and UE. For example, the UE has better performance on the linear interference suppression with assistance information from the network. For instance, the joint linear interference suppression and inter-cell rank coordination is one of the network assisting UE interference suppression schemes [66]. The low rank coordination in the network side assists the interference suppression at the UE side reducing the UE blank estimation.

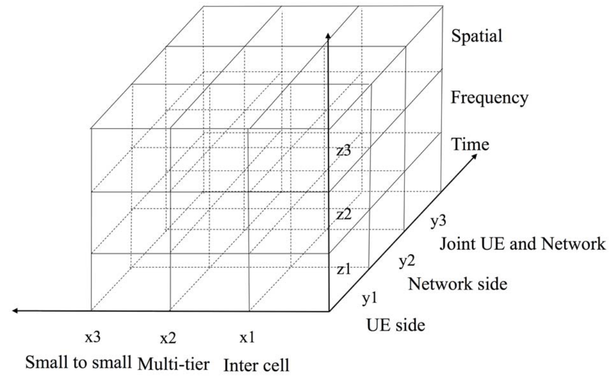

Fig. 3. Interference Mitigation Mechanisms

2) Multi-tier Interference: In the UDN, both the macro cells and small cells are cross deployed throughout the network. The interference caused by multi-tiers include the various emit powers, cell topologies, radio accesses, etc. For example, small cells reuse the frequency band from the macro cell, which brings interference to the Macro cell UE (MUE), especially to the MUEs at the cell edge. The MUEs at the cell edge received signal with strong pathloss and fading. When the small cell uses same sub-channel for communication, the interference to MUE become severe. On the other hand, due to the power control, the MUE at the cell edge will increase the emit power, which causes interference to the Small cell UEs (SUE) [51].

As shown in Figure 4, four cases of multi-tier interference are displayed. The red line in each sub-figures represents the interference signal and the interference direction. For example, in Figure 4(a), the macro cell UE (UE_1) is receiving signals from macro cell. At same time, the signals from small cells may pose interference to UE_1. In Figure 4(b), the small cell UE (UE_2) may receive the interference from macro cell when UE_2 is communicating with small cell. In Figure 4(c), while UE_2 is transmitting to the small cell BS, the transmission signal from UE_1 to the macro cell interferes with the small cell BS. In Figure 4(d), while UE_1 is transmitting to macro cell BS, the UE_2 may pose interference to the macro cell BS when transmitting to the small cell BS.

We next investigate the multi-tier interference mitigation schemes. We also categorize the schemes in the time domain, frequency domain, and spatial domain resource partitioning at UE side, network side, or joint combination, as shown in the 3-D framework in Figure 3. In the following, we introduce those schemes in detail.

Time-domain Techniques: Cell Association and Power Control (CA-PC) can be identified as the schemes for interference mitigation in the time domain. The former is based on the cell splitting, cell range expansion to obtain the spectrum efficiency and reduce network overhead. The latter is based on the minimization of the transmission power for interference mitigation. The joint combination of the distributed BS Association and Power Control (BSA-PC) in [19] is a scheme

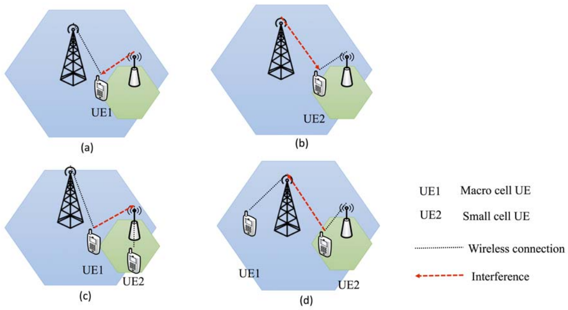

Fig. 4. Multi-tier Interference Cases

for the multi-tier interference mitigation. Ekram *et al.* in [20] indicated the direction of further work on the joint cell association and power control. The promising joint CA-PC can be developed and extended to the resource aware CA-PC, which satisfied multiple objectives (load balance, network throughput, energy efficiency, etc.).

Frequency-domain Techniques: Associated with frequency-domain techniques, $< x_2, y_1, z_2 >$, $< x_2, y_2, z_2 >$ and $< x_2, y_3, z_2 >$ represent the interference mitigation schemes on the UE side, network side, and joint combination, respectively, in the frequency domain. The spectrum arrangement in the multi-tier network with the consideration of the small cells can effectively reduce the interference among multi-tiers. Sungsoo *et al.* in [44] proposed a beamforming codebook restriction scheme, where the SUEs can identify and select the favorable channel to avoid interference. By this opportunistic channel selection, the SUE can benefit from the restricted beamforming gain and the proportional fair scheduler. The numerical results illustrated the effectiveness of the proposed scheme that belongs to $< x_2, y_1, z_2 >$. Yi *et al.* in [57] proposed a femtocell aware spectrum arrangement scheme for uplink multi-tier interference avoidance. In this scheme, the spectrum was split between the macro-only portion and multi-tier portion. The MUEs may use macro-only spectrum when it potentially posts interference to nearby SUEs [51]. This spectrum arrangement scheme belongs to $< x_2, y_2, z_2 >$.

Juang *et al.* in [26] proposed an adaptive FFR scheme to reduce the interference caused by the small cells in close proximity to the macro cell. In this case, the term adaptive signifies the radio resource hopping, in which the small cell BS hops to an available sub-channel for a time duration based on its radio resource. The radio resource partitioning is based on its density and location. The schemes based on the frequency partitioning belong to $< x_2, y_2, z_2 >$. Also, a cognitive-based approach could reduce the multi-tier interference through the interference-aware spectrum use [25]. The small-cell BSs have the capability of spectrum sensing, and utilize available frequency bands with constraint outage from the macro-cell BS. The small-cell BS can use the spectrum scheduling and geo-location information from macro-cell BS to benefit the cognitive-based approach [25].

Spatial-domain Techniques: Multi-tier interference mitigation in spatial domain include $< x_2, y_1, z_3 >$, $< x_2, y_2, z_3 >$ and $< x_2, y_3, z_3 >$. In the UE side, the advanced antenna with the capability of the interference suppression and cancellation can mitigate the potential interference. The multi-antenna technique can be adopted for exploring the spatial diversity gain and spatial multiplexing gain for the interference mitigation [41], [15]. The smart antenna technique achieves interference mitigation by the capability of Digital Signal Processing (DSP) in an antenna array. The smart antenna can explore the interference direction and thus mitigate the interference to some extent [24]. The advanced antenna-based multi-tier interference mitigation schemes in UE side can be categorized in $< x_2, y_1, z_3 >$.

Schemes in $< x_2, y_2, z_3 >$ represent the interference mitigation schemes in the spatial domain on the network side. The clustering algorithm in the network side is one of the spatial domain interference mitigation schemes. This clustering is based on the ratio of the separated frequency, which includes the aforementioned macro-only frequency and multi-tier frequency. The optimal clustering for the overlaid network can contribute to the network performance improvement and interference mitigation. Findings in [30], [40] show that the dynamic clustering algorithm providing the optimal clustering could achieve improved spectrum reuse [30], [40].

Schemes in $< x_2, y_3, z_3 >$ represent the interference mitigation schemes in the spatial domain in the joint combination of UE and network. For example, Hossain *et al.* in [20] proposed a scheme based on beamforming for interference avoidance. The macro cell performs the selection of the beam subset. The selection is based on the feedback of the number of MUEs and the small cell BS intensity. The optimal number of beams can be adaptively selected by the macro BS based on the feedback to mitigate the multi-tier interference and improve system throughput. This interference mitigation scheme can be allocated in the multi-tier network through joint combination (e.g., MUE provides feedback and network side performs optimal beam subset selection).

3) Small-to-small Interference: Due to the large number of the small cells and the irregular deployment topology, the small-to-small interference mitigation schemes were preferably at SUE side or the small-cell BS side in a distributed manner [65], [10]. The main schemes for small-to-small interference mitigation are the interference avoidance and interference cancellation in the small-cell BSs and SUEs.

The time-hopping technique is one of the interference avoidance schemes, which splits the transmission period to N time slots. All SUEs in one small cell randomly selects one time slot for transmission, and SUEs in neighboring cells remain silent during the transmission. In addition, the small cell selects time slots independently for transmission, thus the small-to-small interference can be mitigated in the time domain [9]. Simultaneously, at the small-cell BS side, the antenna performs the interference avoidance via the non-orthogonal antenna sectors. The joint combination method in [9] provided effective interference avoidance and network capacity improvement.

As previously discussed, power control can mitigate the interference through interference-aware adaptive power management. The small-cell BS transmission power adaptation and carrier selection can be effective for downlink (DL) interference mitigation. Similarly, the transmit power limitation in the Uplink (UL) at SUEs and the small cell adaptive attenuation can be effective for UL interference mitigation [61].

B. Mobility

The mobility in UDN is significantly different from the previous multi-tier networks in terms of complexity and performance requirements. Here, the mobility can be specified as the BS selection/reselection (e.g., Handover/Handoff (HO)). The complexity of HO is increased due to the imbalance in transmission power of co-existing small cells and macro cells, as well as the variety of network interfaces. Also, the densely deployed small cells, which have significantly lower coverage area, may increase the complexity of the cell selection and evaluation process due to an increased amount of available BSs. Considering performance, the HO Failure (HOF) and PingPong (PP) are the main metrics to evaluate the HO performance. In addition, energy efficiency should be considered during the measurement of HO, as well as power saving, quality of service (QoS), etc. [1], [63], [3].

The HO can be categorized into two scenarios, horizontal HO and vertical HO. In the horizontal HO, the HO takes place between cells of the same network interface (e.g. between small cells, between macro cells). HO between a small cell and a macro cell is denoted as vertical HO. Both of the HO scenarios are crucial and challenging in UDN. Here, we summarize some state-of-the-art HO management schemes in Table I.

In the HO process, cell discovery/search is the procedure in which a UE explores the signal quality and availability of nearby small cells. The candidate cells are selected based on the measurement of reference signal quality, referred as signal power, SINR, and so on. Then, the optimal small cell will be scheduled and switched. In [39], the small cell discovery scheme was proposed based on the UE enhancement. This discovery is based on periodical search of the inter-frequency among cells. For example, the UE reselects the small cell when one is on other frequency, which is differ from current frequency, assuming its channel quality (e.g., CPICH Ec/Io) is above the pre-defined threshold.

The layered beacon signal-based small cell discovery scheme is implemented at the small-cell BS. The beacon signal consists of two layers (i.e., beacon burst and low power bacon). The low power beacon is to cover the close distance SUEs of small cells, and perform fast reselection. The high power beacon burst signal covers a larger distance. The proposed beacon only causes little impact on the nearby MUEs due to is high burst, but it is effective on the small cell discovery on legacy UEs [2].

Metrics (Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ)) for preferring nearby small cells may not arrange the HO of UEs and small cells effectively [33], [63]. The traditionally maximal RSRP-based schemes may not be fair and effective in UDN, due to the low emitting power of many deployed small cells. Thus, work in [58] proposed the biased RSRP, in which the biased algorithm was introduced to the maximize RSRP. By using the proposed scheme, the small cells and macro cells can be fairly favored and the network traffic can be balanced.

The drawback of RSRP-based prediction is that the signal power is not equal to the signal quality. For example, consider the scenario in which one node with higher transmission power has been connected to by multiple UEs, while one node with lower transmission power has no UE connected. If the UE selects the node with high transmission power based on the RSRP, it may lead to the resource inefficiency and low UE mobility (e.g., QoS). The enhanced RSRQ schemes are the RSRQ-based cell discovery schemes with the consideration of fairness scheduling [21]. Specifically, the Max-Min Fairness (MMF) was introduced in [21] for cell selection and power control, as well as proportional fairness in [50].

Carrier aggregation was raised to reduce the HO time, and improve the HO QoS by the estimation of the signal quality in nearby BSs in one cell. Specifically, when one component carrier has poor transmission quality (signal power, etc.), other carriers in this cell may have similar quality. In this way, the energy consumption and system overhead can be reduced. Nonetheless, the estimation may not be accurate enough. On the contrary, the HO performance may be degraded due to inaccurate estimates [68]. As mentioned, to further improve the accuracy of the estimation, the joint/hybrid UE based and macro assist method is more favorable in the complex environment. The UE makes the decision of the HO on the small cells. The network side decides the HO in the macro cells. Thus, the overhead from the frequent HO in small cells is offloaded by the UE autonomous HO decision [45]. Also, to enhance the mobility management and obtain further network capacity, reinforcement learning can be used. To this end, work in [53] proposed learning-based schemes where BSs store the historical traffic and data rate information as crucial UE scheduling information for the HO QoS enhancement.

C. Resource Management

In comparison with the previous standards, a 5G mobile wireless network has dramatically higher performance requirements. Examples include in the areas of peak transmission rate, spectrum utilization, energy efficiency, etc. To achieve these goals, the UDN combined with a variety of other techniques (e.g., massive Multiple Input Multiple Output (MIMO) antennas) was proposed in [28]. The resource management issues in such a network are critical. In the following, we discuss several resource management issues in UDN from the following perspective: energy management, spectrum management and BS deployment.

1) Energy Management: In UDN, with the dramatic increase in traffic, the energy consumption creates serious challenges to network operators. The most energy consuming

TABLE I. Existing Works on the Mobility Management

Methods	Schemes	Pros	Cons
Small cell discovery	UE enhancement discovery [39]. Small cell discovery by layered beacon [39]	UE-centric small-cell discovery does not require the macro BS search. The coverage area of the small cell discovery and the discovery quality have improved with the impact on current connection	Only work for the future SUE, not the legacy UEs. The interference to nearby MUEs caused by the beacon burst is not negligible. Burst power selection should be carefully considered.
Received signal based prediction	Biased RSRP [58]. Fairness based RSRQ [48]	Small cells can be utilized more effectively, and thus improve resource efficiency. The spectrum efficiency and resource efficiency have improved. More small cells have been utilized.	The bias value is difficult to optimize, as well as the offloading performance from small cells. The signal power may not describe the cell quality well.
Network interface selection	Automatic radio interface selection [8]	Exploring the multi-path gain from the multi-interface UE. The fairness of the UE selection is obtained.	Power consumption is high with the multi-interface UE. The QoS for different applications should be considered for the node selection.
Introduce special node	Interworking Decision Engine (IDE) [36] Split control plane and user plane [67]	Better controlling from control plane gives more efficient, resource utilization, HO performance, as well as network capacity.	In the UDN, the large number of UE and small cells may cause a large volume of traffic in the control plane.
Carrier aggregation	Inter-site carrier aggregation [45]	The estimation of the carriers in one cell can reduce the searching cost and UE energy consumption, and improve the HO efficiency.	The estimation accuracy largely impacts the effectivness of the estimation, and thus may degrade the connectivity and UE QoS.
Joint reinforcement learning	Learning-based cell coordination [53]	The learning-based scheme can effectively enhance the performance of the classic mobility management schemes (i.e., reduce the HOF, improve the, network throughput, etc.).	Due to the large number of BSs, the learning process in each BS leads to high computing overhead, as well as network complexity (energy consumption, etc.).

component in cellular networks is BS, which occupies about 60 %-80 % of energy use. For this reason, a number of research efforts have been developed to propose different strategies to reduce the energy cost of the BS. The first strategy is to improve the air interface efficiency by advanced digital transmission techniques (higher order modulation and coding [18], etc.).

Improving the efficiency can also be pursued at the network level via the BS power control and scheduling. In a small-cell network, not all the BSs are being used equally. Some of them may be in high utilization while others may be idle. This leads to a serious energy waste. To address this issue, research has investigated the concept of energy partitions, where the BSs associate with each other, taking turns in powered-on and powered–off states. This idea has also been used as the basis to rearrange the energy configuration. For example, a distributed power saving algorithm for cellular networks was proposed in [56]. In their developed algorithm, BSs reduce their power by turns with the consideration of their neighbor's current power settings. Cho *et al.* in [12] proposed a distributed scheduling with interference-aware power control for UDN. In their proposed scheme, end users adjust transmit power based on a pre-determined threshold of generating interference to other cell BSs.

At the UE side, the energy efficiency can be improved by using advanced battery techniques. Additionally, in UDN, efficient scanning schemes can be used to reduce energy consumption. When a UE looks for the ideal eNB to connect to, the scanning procedure consumes significant amounts of energy. Particularly, in UDN, the UE will obtain the list of neighboring cells that consist of a number of candidate eNBs. If the full-scanning method is used, the scan time will be extremely long if there are too many eNBs in the list. This calls for the development of efficient scanning mechanisms by leveraging and improving some scanning methods [60], [47].

2) Spectrum Management: Spectrum management is another aspect that will impact the system performance of UDN. Spectrum sharing was brought up initially because of the significant spectrum crunch and inefficient use thereof. The key technology of spectrum sharing is the dynamic spectrum access (DSA) [54]. The techniques to achieve DSA include geolocation databases [5], cognitive radio (CR) [7], etc. In the past, a number of spectrum sharing scheme have developed. Most of the studies on spectrum sharing are based on the primary/secondary strategy, where the secondary user can utilize the channel when the primary user has low utilization. The other approaches are related to the co-primary spectrum sharing, where two or more primary license holders with equal or approximate priority share same spectrum. For example, Luoto *et al.* in [35] proposed co-primary multi-operator resource sharing for small-cell networks. In their work, they proposed four algorithms to solve co-primary multi-operator spectrum sharing problems in both centralized and distributed scenarios.

The existing spectrum sharing methods in traditional wireless networks can provide efficient spectrum usage. Nonetheless, in UDN, there are new challenges for spectrum sharing. For example, the traffic demand has skyrocketed, and building layouts highly affect interference characteristics. These new challenges initiate new research interests. For example, to overcome the issue of the inter-operator interference, Yu *et al.* in [64] proposed an asymmetrical power level-based soft inter-operator interference coordination mechanism. Evanny *et al.* in [43] proposed UDN spectrum sharing policies for indoor and outdoor utilizing the radar bands, which could improve the spectrum sharing.

3) Small-Cell Deployment: Another key factor of the system performance is the deployment of small cells. The densely deployed small cells can highly improve the capacity. However, they cannot be deployed too close to each other because of the potential for interference problems. In UDN, the new challenges for the network deployment are raised by the random deployment, dynamic on-off, and flexible connection to the cellular core network. Thus, the centralized approach may not be effective in the small-cell deployment of UDN. Distributed mechanisms for small-cell deployment were proposed for UDN [59], [11]. For example, Xu *et al.* in [59] proposed a cooperative distributed optimization for the small cella densely deployed.

III. Potential Solutions and Challenges

Based on the taxonomy of the problems and associated schemes in UDN developed in Section II, we summarize the major schemes to address the problems. Here, we conclude that the inter-cell interference can be mitigated by the joint macro-cell BSs and UE assistance. Specifically, the time domain coordinated scheduling, frequency domain signal orthogonalization, and spatial cell coordination with advance antennas can be used in a cooperative manner to mitigate the inter-cell interference.

The multi-tier interference can be potentially addressed by the collaborative frequency coordination and UE spectrum sensing. Also, the joint combinations of cell clustering on the network side and UE advance antenna with interference suppression can mitigate the interference in the spatial domain. The small-to-small interference bears a striking similarity to inter-cell interference, due to its high frequency reuse and close distance. The adaptive power management, adaptive carrier selection, and collaborative spectrum management are the potential small-to-small interference mitigation schemes.

To improve the HO performance (e.g., selecting the best candidate node) in UDN, the UE HO failure and Pingpong should be minimized. Also, the overall network mobility (e.g., average HOF and PP) should be enhanced by the system-level optimization. Specifically, the cell discovery, signal quality prediction, evaluation, and decision should be evaluated.

Although existing research efforts have established the basics on addressing challenges in UDN, these challenges remain unresolved. With existing work, we point out the following challenges that are critical, and need to be addressed.

Controlling Overhead Reduction: These potential solutions require complex and frequent cooperation among UEs, small cells, and macro cells. The necessary information exchange among the controlling nodes or network components requires large volumes of network resources. The controlling communication overhead should be limited and reduced. The interference management scheme would be more preferable in a distributed manner, in order to reduce the signaling overhead and minimize the complexity.

Involving QoE (Quality of Experience) in UDN: Although, prior research efforts proposed a number of mechanisms to mitigate the interference, the coexistence of the different radio access techniques (e.g., different network tiers) needs further study. The various QoS from different user's perspective requirements of UE exist throughout the network. To address the diversity of QoS along with random large-scale UE variation, the dynamic cell cooperation and cell selection with the consideration of the energy consumption needs to be addressed. Traditional QoS stands for the data rate, loss rate, delay, and jitter, etc. The evaluation of QoE, which stands for the user experience with a service by the consideration of the environment, UE itself, and user's preference, requires further investigation in UDN. Thus, the seamless and profound involvement of the QoE concept in the context of UDN poses another challenge.

Network Performance in Outdoor Scenarios: Due to the observation that large data transmissions predominantly occurred in indoor scenarios, the dense deployment of small cells can significantly improve the network capacity and further address the future 1000 fold data traffic demand. On the other hand, compared to the huge volume indoor multimedia traffic and entertainment data traffic, the functional data traffics (navigation, vehicle sensors, weather sensors, etc.) in outdoor scenarios should be carefully considered.

UE Battery Life: The advanced antenna equipped UEs demonstrate the capabilities of the interference cancellation, information collection, spectrum sensing, etc. The battery life of UE, and specifically smartphones, should be considered. In other words, the limited energy supply will be assigned to multiple functions, including complex computing, signal transceiving, and data roaming. Thus, the energy efficiency of smart devices poses another challenge in UDN.

Spectrum Efficiency in Wireless Backhaul: In UDNs, the large number of cell BSs requires a large capacity and high flexibility backhaul network. The traditional wired backhaul network may no longer be applicable, due to its high deployment cost and complexity and high operating cost. The wireless backhaul network has the potential to improve deployment flexibility and reduce infrastructure cost. Due to the large number of cells, the complexity of networking and spectrum resource management pose further challenges.

Integration of Other Advanced Techniques: The densification of small cells can improve the network capacity 10-100 fold [22]. The key enabler is the cooperation and combination with other advanced techniques (e.g., massive MIMO, mmWave, relayer, D2D and cognitive communication). Nonetheless, the complexity comes from the massive negotiation and coordination among those advance techniques. The consideration of interference mitigation, resource efficiency, and cost efficiency poses new challenges.

Security and Privacy: Security and privacy will become crucial in the future of UDN development because of the high densification of the cells and UEs, providing unprecedented information interactions. Likewise, the limited energy supply in UE devices due to the data computing, data roaming, and other functions provide new avenues of security compromise and privacy concern and requires consideration. The increased system complexity, the involved new techniques, and multiple diverse networks will inevitably increase the vulnerability potential. In this circumstance, the security and privacy pose new challenges too.

IV. Future Research Direction

In the following, we outline the future research directions.

Interference, Mobility, and Cost in UDN: Recall that in Section II, we propose a 3D framework to address the problem space on the interference, mobility, and cost in UDN. Specifically, the interference can be categorized to inter-cell interference, multi-tier interference, and small-to-small interference. The mobility can be specified as the handover performance and moving nodes. The cost contains the energy efficiency, spectral efficiency, and deployment cost. Also, an individual 3D framework was proposed to identify the interference mitigation schemes, as well as the mobility and cost. With regard to the several areas that may not yet have existing solutions, and proposed solutions in most of subareas cannot fully solve the issues in UDN, the large problem space that we have explored indicates the possibilities of the potential research directions which need further study.

Apply UDN on Emergent Applications: We are on the cusp of the next major revolution in critical infrastructure systems due to the imminent integration of information communication technologies to make those systems smart. A critical infrastructure system, as a typical cyber-physical system/ (IoT) system, is a system that features a tight integration of computation, networking, and physical elements.

There are a number of challenges to implementing and deploying IoT applications. From the trends of growing smart device adoption, we can infer that there will be trillions of things and associated devices connected to the network. Thus, the network traffic will increase dramatically. How to support such a large scale of connected devices become a critical question. Also, real-time information is commonly required for many IoT applications, including health care system, transportation system, smart grid, public safety emergent response system, etc. They all need instant notifications in the event of a health emergency, traffic accident or congestion, or in the event of disaster. This calls for a wireless network with high performance that can support diverse types of applications.

In UDN, the densely deployed BSs significantly increase the network capacity. In this way, the UDN is able to address the scalability issue of IoT applications. Because of the short distance and high processing power, the UDN is able to transmit data with high speed so that UDN is capable of supporting real-time traffic. This satisfies the need of IoT applications for low latency. Also, the UDN has the compatibility to support traffic under various protocols. This enables different applications sharing the same network. Thus, the diverse demand of IoT applications can be fulfilled by UDN. Thus, we believe UDN will provide great benefits to IoT applications due to its high network capacity, high real-time performance, and high compatibility. Nonetheless, there are a number of new challenges when UDN is in place to support IoT applications.

Security and Privacy: Due to the open access feature of wireless networks, both receivers and eavesdroppers can receive the communication signals in wireless medium. Furthermore, the features of UDN, including the dynamic network topology, complex network components, and high UE diversity and density, and inherent UE resource constraints, raise security and privacy concerns in UDN. For example, in a densely deployed scenario, when single node is compromised, a significantly large number of nodes may become insecure as a result. Thus, the investigation of attacks and their impact on UDN should be exhaustively studied. Then, the effective countermeasures can be designed to mitigate attacks based on the understanding of attacks.

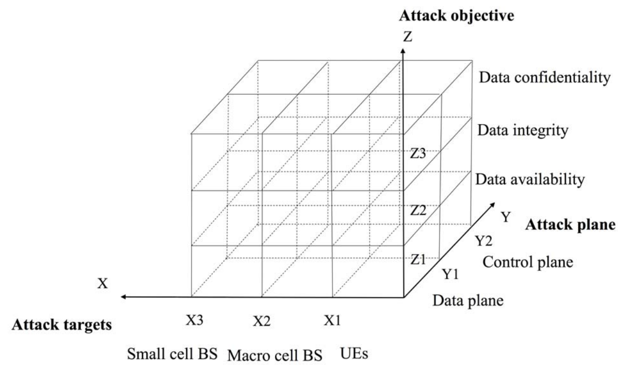

Fig. 5. Attack Space in UDN

To address the security issues in UDN, it is critical to develop a generic framework to explore the attack space as shown in Figure 5. In Figure 5, the X-axis represents the attack targets in UDN, including < X_1: UEs, X_2: Macro cell BSs, X_3: Small cell BSs >. Y-axis represents the attack planes, such as < Y_1: data plane, Y_2: control plane >. Z-axis is the attack objective, including < Z_1: availability, Z_2: integrity, Z_3: confidentiality >. Generally speaking, the adversary is aiming to achieve the attack objectives by attacking targets in data plane or control plane.

To systematically investigate the security challenges in UDN, the attacks analysis should be studied based on each of the cubes that contain the attack targets, attack objectives, and attack plane. Hereafter, based on the investigation on each attack filled in each cube, the corresponding effective countermeasures can be developed. After exploring the space of threats in UDN and understanding their impacts on both system operations and end users, we can develop effective mitigation schemes to defend against these attacks.

Modeling, Simulation, and Test Bed: To date, there are currently no standard UDN deployment methods that support multiple applications in the real world. Furthermore, the effectiveness and efficiency of the UDN in supporting IoT applications has yet to be investigated, especially in real-world scenarios. The modeling and simulation of the UDN is necessary to discover optimal network deployment strategies and the selection of network architectures and protocols. In UDN, modeling and simulation can measure the network performance based on the performance metric in real-world scenarios. Because UDN is a complicated system consisting of various types of network architectures (e.g., cellular networks, WiFi networks, D2D, etc) and components (UEs, small cell BSs, macro cell BSs, Relayers, etc.), the modeling and simulation study should consider those aspects systematically. The integrated simulation on the various applications in UDN combines the joint simulation of both applications and communication networks, which can capture intensive interactions among those entities. Also, introducing real-world deployment scenarios (map, etc.), integrated simulation, and real-world test beds to carry out experiments should be further explored.

Integrating with Other Techniques: UDN needs to integrate with other advanced techniques that could significantly boost the network performance. UDN, millimeter wave, and massive MIMO are considered some main enablers in the next generation mobile wireless networks [6]. Marzetta in [38] investigated the scenario of unlimited antennas in BS and proposed the concept of large scale MIMO or massive MIMO. With massive MIMO, a large number of the antennas were equipped at each BS. Also, the current spectrum below GHZ is fully licensed and occupied, we are pressed to find available frequency bands to cope with further communication demand [62]. The high frequency mmWave is located at frequency range 30-300 GHZ, where more idle frequency bands are available for communication, and are an important spectrum resource. The drawback of adopting high frequency mmWave is the short communication distance, due to its very strong pathloss, rain absorption, and penetration through objects, and the hardware cost. Still, The main features of the UDN are the dense deployment and short transmission distance, where the mmWave is favorable. While significant efforts standard, research and development on these techniques, effectively integrating these techniques requires additional research.

V. Final Remarks

UDN, as the one of leading technology in 5G mobile wireless networks, faces numerous challenges due to the limited resources, high application requirements, etc. In this paper, we have developed a framework to identify and investigate those difficulties in three areas (e.g., interference, mobility and cost). We have explored and compared existing work in developing solutions to the prominent problems across a variety of areas. Based on the existing research efforts and other leading techniques, we have identified a number of potential challenges that still need further investigation and study. Finally, based on the above investigation and conclusions, we have proposed further research directions for future investigations.

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