User-Centric Clustering Aided Design of Ultra Dense Networks

Yan Lin, Rong Zhang, Luxi Yang, Chunguo Li, and Lajos Hanzo

***Abstract*—User-centric clustering is becoming an innovative design principle for ultra dense networks (UDNs) that supports dynamically fluctuating adaptive network topologies. In this article, we introduce the user-centric UDN (UC-UDN) architecture and provide a tutorial on user-centric clustering design by generalizing the problem under practical constraints. In the context of user-centric clustering, we briefly present diverse promising methods, representative constraint options as well as provide a pair of case studies on design tradeoffs. Finally, the salient future directions of UC-UDNs are identified.**

INTRODUCTION

The explosive proliferation of mobile devices and the popularity of immersive interactive services results in an ever-increasing tele-traffic. To mitigate this problem, network densification may be used for boosting the network's capacity, which can be achieved by the deployment of abundant access points (APs), whilst simultaneously shrinking the cell's coverage area. This is achieved with the aid of a hybrid amalgam of microcells, picocells, femtocells, relay nodes, and remote radio heads (RRHs), which have lower power and cost, as well as have smaller coverage area than macro cells. The resultant hierarchical topology of these compact APs constitutes an ultra dense network (UDN) [1]–[3]. The typical UDN application scenarios are indoor and hotspot areas, including offices, campus networks, stadiums, shopping malls, subways and so on.

However, due to the tide-like effects of large-scale user population movement trends, from home to work and back, the traditional cellular architecture of the UDNs may impose distinct challenges on the user access procedure, when relying on the conventional hexagonal cell shape and cell-centric design. Explicitly, the traditional static network topology imposes severe edge-effects[1], especially during a hard handover process[2]. Additionally, the spatial and temporal variation of the traffic has a significant impact on the involvement of APs, thus determining the network topology of UDNs [4]. To be specific, a high amount of traffic requires more APs to be involved, whilst a low amount of traffic may allow some APs to be powered down. In order to cope with the above impediments, an innovative design alternative relying on the user-centric principle of [5] [6] has emerged, where the user equipment (UE) plays an empowered role. To elaborate, the empowered UE acts as a network element by exploiting its geo-location knowledge for maintaining any specific quality of service (QoS), requirement instead of being controlled by APs. This new architecture is capable of supporting dynamically fluctuating adaptive network topologies, which takes into account the UEs' specific locations for guaranteeing each UE's QoS, as well as the spatial and temporal fluctuation of traffic. As a result, the deleterious edge-effects can be eliminated and smooth soft handovers[3] can be guaranteed. Basically, in user-centric UDNs (UC-UDNs), the user-centric clusters are formed by grouping the most appropriate number of APs together, thus resulting in a user-centric clustering architecture [7]. TABLE I contrasts the distinct characteristics of the traditional UDNs and of the UC-UDNs.

Explicitly, one of the main features of UDNs is that the AP density is comparable to the UE density. As a benefit, there is always an AP in the close proximity of the UE, thus the UEs in UC-UDNs have a potential opportunity to benefit from the cooperation of APs. Notably, the traditional AP selection (e.g. the maximum reference signal received power (max-RSRP) solution) usually supports each UE to be associated with a single AP, whilst allowing each AP to serve multiple UEs. By contrast, in the user-centric clustering architecture multiple APs simultaneously serve each UE relying on the benefits of AP cooperation. Hence, our paramount problem becomes: *How are the user-centric clusters constructed for UC-UDNs* ? Naturally, invoking more APs is potentially capable of increasing the UE's rate by exploiting the family of maturing interference management policies. In other words, in an idealized interference-free regime all APs that are within a specific UE's coverage distance have an opportunity to get involved in its serving AP cluster. To the best of our knowledge, however, the existing literature is predominantly focussed on the associated interference management relying either on refined beamforming design or on tailor-made resource allocation, rather than on radical user-centric clustering design.

To fully exploit the benefits of AP cooperation, user-centric clustering has to be further explored. In a nutshell, the general performance metrics include the aggregated user rate, the

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[1]The "edge effect" implies that the UE at the boundary of two cells may have a poor channel quality.

[2]In wireless mobile networks, the UE moves from the serving AP to another AP, thus requiring a seamless process for maintaining the connection, termed as "handover". In general, the UE first disconnects from the previous AP and then connects to the new AP, which may be referred to as a "hard handover".

[3]In order to avoid dropping a call owing to the lack of adequate resources in the target cell, the UE may be allowed to first connect to the new AP and then disconnect from the previous AP with the aid of the so-called multiple AP-association technique. This kind of handover procedure may be termed as "soft handover".

	UDNs	**UC-UDNs**
Single cell shape	Hexagonal	Amorphous
Network topology	Static	Dynamically fluctuating adaptive
Composition of a single cell	One AP and multiple UEs	One UE and multiple APs
UE edge-effect	Existing	Eliminated
AP handover	Hard handover	Soft handover

TABLE I: Comparison between UDNs and UC-UDNs.

energy consumption, the energy-efficiency, the normalized outage capacity and so forth. Additionally, the user association procedure usually relies on the awareness of the traffic-load, security, backhaul, delay, mobility, computation capability, and so on [8]–[11]. More explicitly, there is a trade-off between the grade of awareness constrained and the performance attained. Accordingly, the user-centric clustering in UDNs requires further research for taking into account different design criteria and the level of constraints.

Against this backcloth, the objective of this article is to provide a tutorial on the general user-centric clustering design relying on compelling solutions. To elaborate, firstly the UC-UDN architecture is reviewed. Then, a general user-centric clustering problem is formulated and a range of attractive solutions is presented. We then continue by discussing a range of practical constraints and highlight a pair of representative tradeoffs between the performance metric and constraint. Finally, we conclude with some promising future research directions.

Architectural Overview

Let us first consider the UC-UDN architecture. Typically, a UC-UDN consists of a macro base station (MBS), a dense set of APs and a dense set of UEs, where the density of APs is comparable to that of the UEs. All APs and UEs are uniformly deployed in the coverage area provided by the over-sailing MBS. In UC-UDNs, the MBS controls the UE handovers as well as assists each UE in selecting multiple APs to form the corresponding user-centric cluster, while these APs take charge of transmitting the data to the UEs. Given the provision of wired/wireless backhaul links, the APs can then exchange their information with the MBS that manages the AP-UE association.

Generally, each UE may be associated with multiple APs relying on joint transmission (e.g. maximum ratio transmission (MRT) based beamforming). Owing to the dense aggregation of the APs, each AP may also serve multiple UEs using orthogonal resource blocks (RBs), thus simultaneously belonging to a range of diverse user-centric clusters. The elimination of the inter-cluster interference relies on the specific interference management policy imposed. In order to focus on the user-centric clustering design, we assume that the user-centric clusters rely on orthogonal RBs. Additionally, the APs are assumed to be inactive, when they are not associated with any UE, and the association between the APs and UEs is based on their distance, which must not exceed a certain threshold. Their distance may be estimated with the aid of localization techniques.

Example: Consider the UC-UDN of Fig. 1, which consists of a MBS, 4 APs and 5 UEs. The dashed area around a UE represents a user-centric cluster of each UE formed in conjunction with its serving AP cluster. For instance, UE 3 is cooperatively served by AP 1 and AP 2. Additionally, for satisfying the target QoS requirement of each UE, these APs are capable of simultaneously serving other UEs as well. For instance, AP 1 can simultaneously serve UE 1, UE 2 and UE 3. In this case, their user-centric clusters are overlapped with each other.

General Problem and Methodology

General Problem

Mathematically, the user-centric clustering problem constitutes a combinatorial optimization problem relying on a specific objective function (OF) and specific constraints. Moreover, the optimization variable is a binary flag, representing the active involvement status of the APs in each of the user-centric clusters. In a nutshell, the user-centric clustering problem can be formulated as

$$\begin{aligned} \max_{\boldsymbol{X}} \quad & f(\boldsymbol{X}) \\ \text{s.t.} \quad & g(\boldsymbol{X}) \leq G, \\ & x_{i,j} = \{0,1\}. \end{aligned}$$

Herein, $x_{i,j}$ is the (i,j) element of $\boldsymbol{X}$, which denotes the binary involvement flag of AP i in the user-centric cluster of UE j. Moreover, $f(\boldsymbol{X})$ represents the performance metric considered, while $g(\boldsymbol{X}) \leq G$ is the constraint considered.

In general, the problem is a discontinuous, non-differentiable and highly non-linear NP-complete problem, which may have numerous local optima[4]. For instance, when considering the aggregated user rate as the performance metric, the OF becomes a logarithmic function of a complex expression related to $\boldsymbol{X}$, having an excessively complex closed-form. Therefore, finding the exact expression exhibiting global optimality becomes mathematically intractable.

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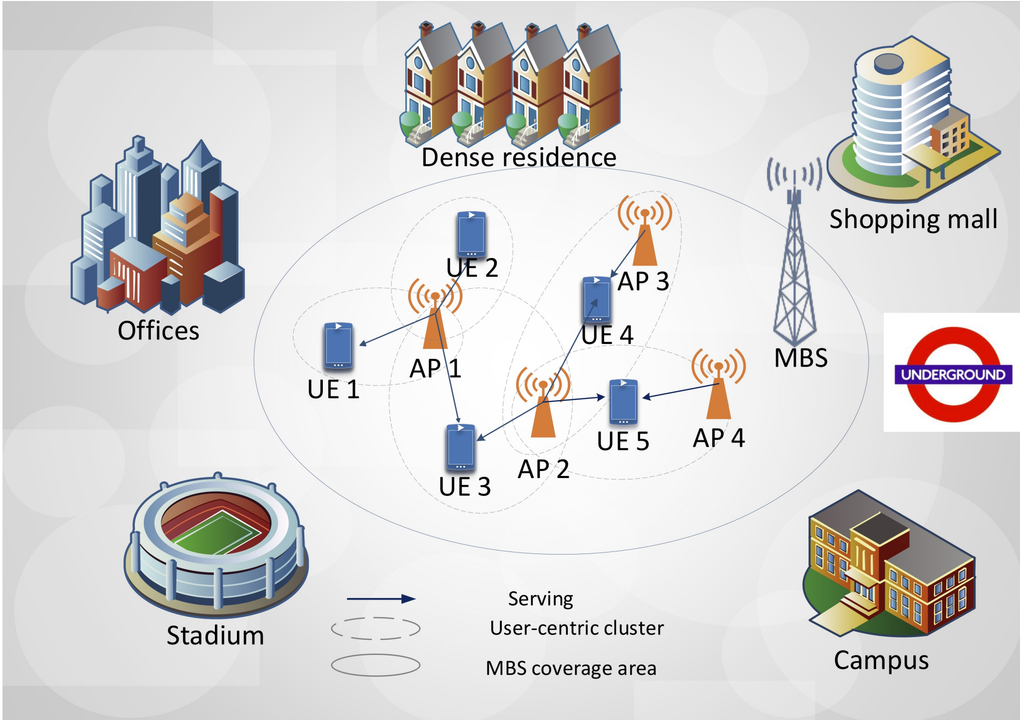

Fig. 1: An example of a UC-UDN.
The dashed area around each UE represents a user-centric cluster of each UE formed in conjunction with its serving AP cluster.

Methodology

In order to efficiently solve the above-mentioned problem, diverse promising methods have been proposed [12]–[15]. To elaborate, the method adopted has to be selected according to the specific problem, broadly classified as:

Exhaustive Search: Theoretically, the optimal user-centric clustering solution can be obtained by an exhaustive search through the finite solution set. In conventional hexagonal cellular networks, the optimal user-centric clustering solution can be found by calculating all possible associations, which is not a challenge. By contrast, the exhaustive search becomes challenging for UC-UDNs due to their high density. The associated computational complexity tends to increase exponentially both with the density of the APs and with that of the UEs.

Matching Theory: As a promising alternative, the bipartite graph matching method [12] has been widely adopted for distributed combinatorial optimization, which was borrowed from the field of economics. In matching-based solutions each of the agents (e.g., UEs or APs) ranks and contrasts the lists of preferred matches to the opposite set. Eventually, the matching process yields a mutually beneficial association solution between the APs and UEs. Therefore, the preferences of the UEs and of the APs have to be well defined for successfully completing this matching process.

Greedy Heuristic: In the context of the intricate user-centric clustering problem, the OF of the associated optimization problem may exhibit many local optima. Hence, we may have no existing algorithms for efficiently solving this kind of mathematically intractable problem. In this case, the family of greedy heuristic algorithms [13] may be able to find a locally optimal solution at each iterative stage with the goal of finding a global optimum. This method yields good solutions by exploiting the greedy property, which refers to making the best possible choice at any moment and then again solve the subproblems that arise later during the iterative search process.

Bio-Inspired Algorithms: The family of bio-inspired algorithms learn from nature and evolution, including evolutionary and swarm intelligence based algorithms as well as ecology-inspired algorithms [14]. During the past few decades, substantial research efforts have been dedicated to solving complex optimization problems. The design of bio-inspired algorithms has to rely on an appropriate formulation of both the problem and of the performance metric used as the fitness function of the legitimate set of solutions.

Reinforcement Learning: Reinforcement learning is an emerging innovative method applied in diverse engineering fields [15], where the agent learns what to do or how to map situations to actions in order to maximize a numerical reward. As a model-free learning approach, Q-learning is capable of finding the optimal policy by estimating the expected value of the cumulative reward, even in the absence of any prior information about the environment. Hence, it becomes promising to adopt Q-learning in the user-centric clustering problem under dynamic scenarios by formulating policies based on historical clustering experiences. However, in UC-UDNs, the state and action space of user-centric clustering has a high dimension, which results in an excessive Q-table size. Hence, we may resort to deep reinforcement learning in UC-UDNs. Nevertheless, the primary challenge lies in how to design an appropriate reward function for our specific performance metric under our constraint, which is still an open issue at the time of writing.

In the following sections, we will present some representative constraint options and then elaborate on a pair of scenarios based upon the general user-centric clustering framework illustrated in Fig. 2.

Representative Constraint Options

From a practical perspective, the design of user-centric clustering should take into account the above-mentioned constraints, which makes the problem quite intricate. In this context, we will briefly present some practical constraint options, which constitute critical topics in next-generation networks, as illustrated in Fig. 3.

Traffic-load: The UC-UDNs achieve an excellent performance by offloading much of the tele-traffic onto APs from the over-sailing macrocell. However, some APs may become overloaded, when supporting numerous UEs, thus adversely affecting the overall fairness of the network. In the example of Fig. 3, the AP which has more than two connections to UEs is regarded as being overloaded. The maximum traffic-load restriction of each AP has to be carefully observed for the sake of load balancing.

Security: Given the unprecedented amount of sensitive private data transmitted over wireless channels, the information-security of user-centric clustering becomes a pressing issue. In the presence of multiple eavesdroppers, the secure transmission of each UE has to be guaranteed. In the context of user-centric clustering design, the APs are also capable of jamming. Considering the scenario of Fig. 3 as an example, the APs have to act as conventional serving APs for the associated UEs as well as acting as jammers for potential eavesdroppers. Therefore, the specific involvement of APs has to be carefully designed in secure UC-UDNs.

Energy management: The energy consumption of the AP supported by the power grid also has to be frugal. Nonetheless, the total energy consumption will increase upon involving more APs for enhancing the throughput, as exemplified in the scenario of Fig. 3. Due to growing concerns associated with global warming, both the total power consumption of the entire network and the transmit power of each AP have to be restricted.

Backhaul: The information exchange required for supporting user-centric clusters relies on the wireless backhaul link (represented by the dashed links illustrated in Fig. 3) between the dense set of APs and the MBS. Thus, the limited backhaul capacity becomes the bottleneck limiting the overall performance of UC-UDNs. Additionally, increasing the number of APs requires much more cooperation amongst the APs via the backhaul links. Hence the limited backhaul capacity has to be judiciously assigned to the user-centric clusters.

Delay: The emerging delay-sensitive applications, such as virtual reality (VR) services, require near-real-time communication and thus impose stringent delay specifications. For the APs, the incoming packets intended for all the associated UEs wait for their transmission in a queuing buffer. Additionally, the transmission delay is related to the user association results. Hence, the delay has to be carefully considered in the user-centric clustering design of UC-UDNs.

Mobility: In mobile systems the network topology and the channel conditions vary in time. Hence, by associating a mobile UE to the nearest AP without any mobility consideration may result in more frequent handovers than in static environments. Thus, the user-centric clustering has to track the dynamic changes both in the network topology and in the channel conditions induced by the user mobility. As a result, the user-centric cluster of a mobile UE (such as a moving vehicle) pursues and accommodates its movement, as illustrated in Fig. 3. Additionally, the handover technique has to avoid overly frequent re-clustering of the APs and UEs, which would impose significant performance losses.

Computational capability: The limited computational capability of smart UEs directly limits the quality of computation experience. Fortunately, the emerging mobile edge computing (MEC) paradigm jointly considers both the computational and communications capability of the radio access network. Consequently, the APs in the immediate vicinity become the MEC servers performing computation offloading in UC-UDNs. Thus the user-centric clustering is also capable of joint computation and communications. However, this also inevitably leads to increasing the required interactions as well as resources. Hence, invoking the MEC servers for user-centric clustering has to carefully consider the associated computational capability restrictions.

In the following, we will discuss both the traffic-load constraint and the security constraint in the context of UC-UDNs.

Case study 1: Traffic-Load constraint

In this section, we characterize the impact of the traffic-load constraint on the user-centric clustering design. The corresponding optimization problem becomes that of maximizing the aggregated user rate, while satisfying the maximum traffic-load constraint of each AP.

Design Guidelines

Criterion: In UC-UDNs, the user-centric clustering procedure exploits the knowledge of the specific locations of the APs and UEs. More explicitly, each AP first acquires the GPS-based locations of the UEs within its coverage area, and then feeds the specific locations of both APs and UEs back to the MBS via the backhaul link. Given this knowledge of locations as well as the transmit-power-based coverage distance knowledge, the MBS finally determines the network topology. Specifically, in the context of user-centric clustering, the MBS will have the knowledge of both the neighbouring APs for each UE and that of the UEs in the coverage area of each AP. Assuming that the locations of L APs and K UEs are known by the MBS, this procedure requires $L \times K$ norm calculations in order to determine the topology. Motivated by this, the coverage distance criterion can be directly adopted for determining the involvement of APs.

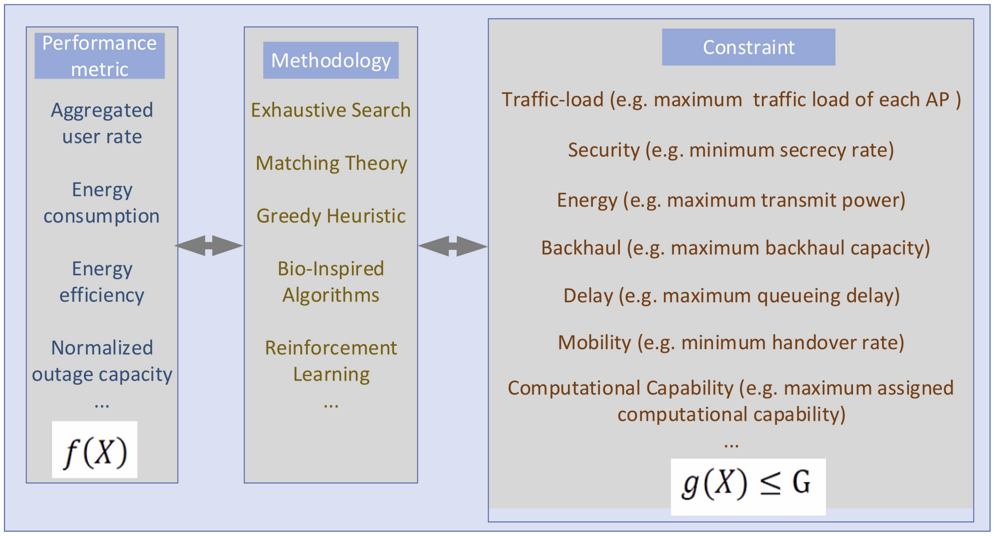

Fig. 2: The framework of user-centric clustering design.

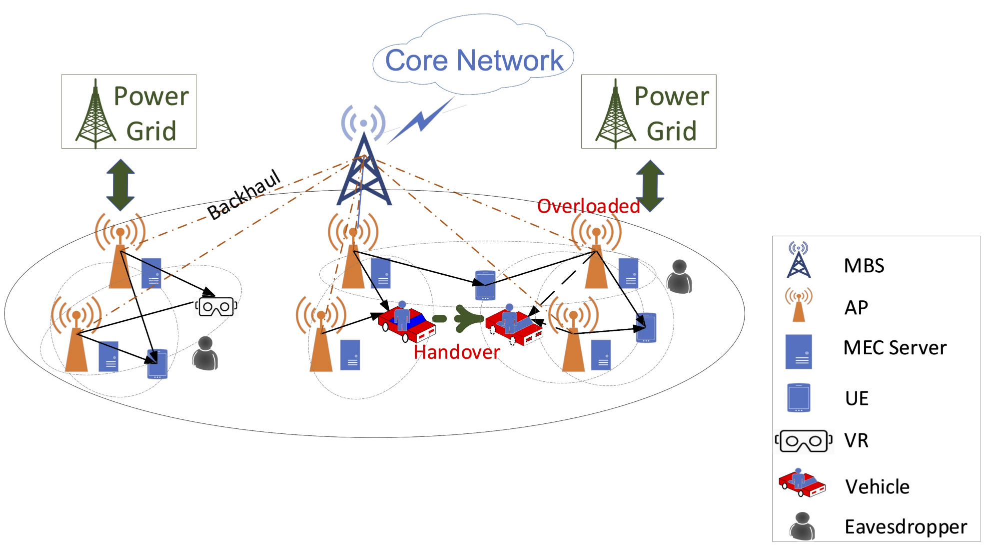

Fig. 3: Scenarios with critical topics.

Method: Mathematically, the optimization problem is intractable, and hence we have no existing algorithms to solve it. It is worth mentioning that in matching theory, the traffic-load-aware user-centric clustering problem constitutes a many-to-many matching. Thus, we resort to the classic bipartite graph matching method for finding a good and stable solution. Naturally, we choose the coverage distance as the preference profile for both the APs and UEs. Given the challenge of solving the many-to-many matching, we propose to first solve a many-to-one matching problem in the first stage, and then complete the many-to-many matching process in the ensuing stages. For more technical details on the procedures please refer to [8].

Key Metric: Per Area Aggregated User Rate v.s. Traffic-load

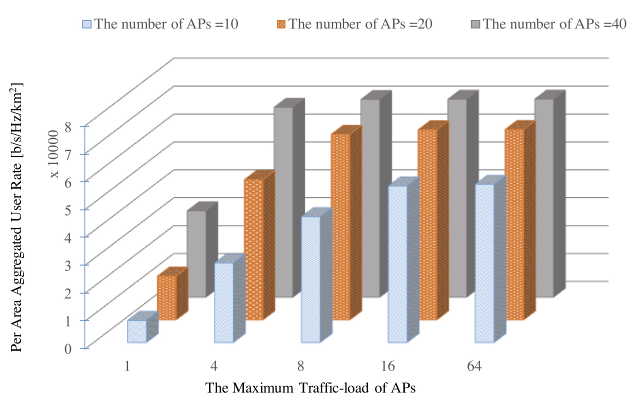

Fig. 4: The per area aggregated user rate versus the maximum traffic-load of APs.
(Area: 0.2×0.2 km^2, UE density: 2.5×10^3/km^2.)

Fig.4 plots the per-area aggregated user rate performance versus the maximum traffic-load of APs for 10, 20 and 40 APs under our proposed solution. It can be observed that the increased maximum traffic-load of APs results in a significantly increased per area aggregated user rate at a low AP density, for instance when the number of APs is 10. The performance at a higher AP density under a lower traffic-load, such as 20 APs and a maximum traffic-load of 4 is also similar. This substantiates that the AP cooperation substantially contributes to the increased user rate, but naturally, at the cost of increasing the total traffic-load.

CASE STUDY 2: SECURITY CONSTRAINT

In this section, we characterize the impact of security constraints on user-centric clustering. Explicitly, we investigate the energy-efficiency versus security tradeoff, represented by the secrecy-energy-efficiency metric versus the minimum security QoS constraint. In order to tackle the problem, we define a novel architecture termed as secure user-centric clustering.

Design Guidelines

Strategies: In a secure UC-UDN, some APs may offer the option of supporting secure transmission by invoking jamming. Explicitly:

- Single-function Strategy: In this strategy, the APs are in a given UE's user-centric cluster acting as its cooperative serving APs for joint data transmission, while those APs that are not in its user-centric cluster may act as cooperative jamming APs supporting secure transmission. In the example shown in the left subfigure of Fig. 5, the secure user-centric cluster of UE 1 consists of two serving APs (i.e. AP 3 and AP 4) and two jamming APs (i.e. AP 1 and AP 5) under the single-function strategy.
- Dual-function Strategy: In this strategy, the APs have the dual functionality of both data transmission and jamming. For the example in the right subfigure of Fig. 5, the secure user-centric cluster of UE 1 has three associated APs (i.e. AP 3, AP 4, AP 5) cooperating for satisfying both the throughput and security requirements relying on the dual function strategy.

Criterion: Apart from the coverage distance as our clustering criterion, the involvement of APs can also be determined with the aid of the rate, the secrecy rate and the secrecy-energy-efficiency performance metrics.

Method: Explicitly, we have to determine the involvement of all APs in the support of each UE, with the aid of a mature secure transmission scheme. However, the resultant problem is mathematically intractable and we have no existing algorithms for solving it. Fortunately, the problem concerned exhibits a distributed nature, which can be readily exploited. Thus, we resort to the greedy heuristic method with the goal of finding a good solution. The basic idea is that each UE first attempts to invoke its nearest APs to satisfy both the throughput and security requirements, and then exhaustively searches through the remaining uninvolved APs to judge whether invoking them would or would not improve the overall secrecy-energy-efficiency. In a nutshell, the secure user-centric clustering procedure consists of a set of search processes relying on the coverage distance, which firstly satisfies the required throughput, meets the security specifications and finally maximizes the energy-efficiency versus security performance [9].

Key Metric: Energy-efficiency Versus Security

Considering the fact that the eavesdropper may be passive (i.e. only listens but does not transmit), its channel state information (CSI) may remain unknown. In this context, we adopt the artificial noise aided jamming technique and the classic null-steering based beamforming method. The left of Fig. 6 unveils the tradeoff between the energy-efficiency and the security. To be specific, we observe from the figure that as the security QoS constraint increases, the secrecy-energy-efficiency is significantly reduced for both solutions. The underlying reason is that an increased number of awake APs is invoked for satisfying the increased minimum security QoS constraint, which can be reflected by the corresponding total power consumption trends, as shown in the right of Fig. 6.

CONCLUDING REMARKS

Incorporating user-centric clustering in UDNs constitutes a promising enabler for guaranteeing each UE's high QoS. We advocated a general user-centric clustering design. Finally, we highlighted a pair of salient constraints, namely the traffic-load and the security. Nonetheless, substantial further research is required.

Multi-OF Optimization: In the face of multiple conflicting OF, such as for example the secrecy-energy-efficiency and the secrecy rate, the user-centric clustering design has to strike a meritorious trade-off. It is beneficial to determine

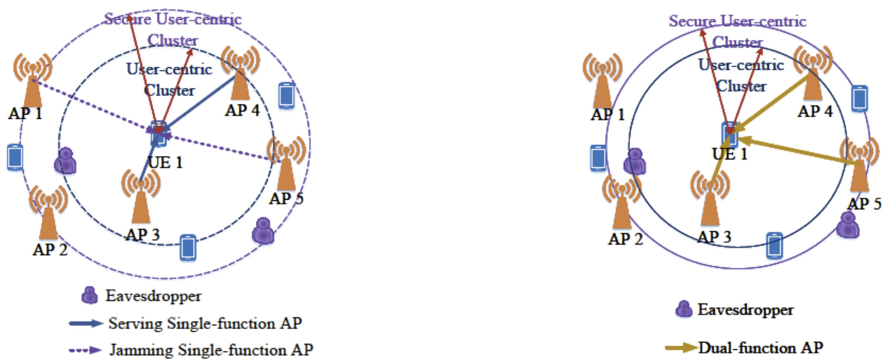

Fig. 5: An illustration of the secure user-centric clustering architecture in UC-UDNs. (Left: single-function strategy; Right: dual-function strategy.)

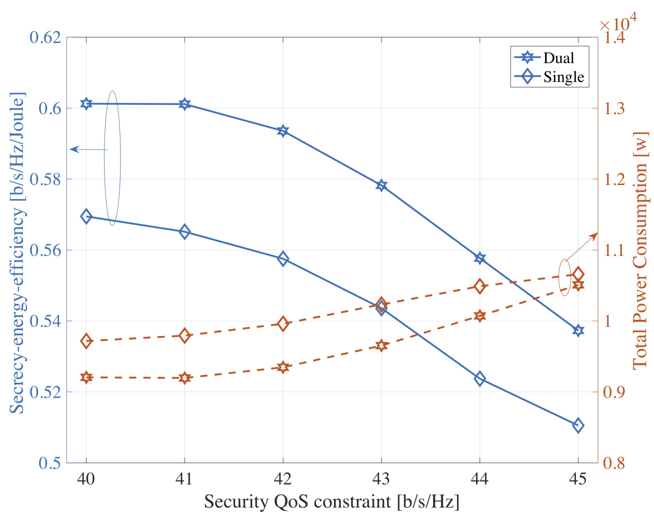

Fig. 6: The energy-efficiency versus the security. (Area: 0.2×0.2 km^2, UE density: 3×10^3/km^2, eavesdropper density: 3×10^2/km^2, throughput QoS constraint: 45 b/s/Hz.)

the optimal Pareto front of all solutions, namely that specific set of solutions, where none of the conflicting metrics can be improved without degrading at least one of the others. However, as the number of OF components is increased, the search-space-size escalates and often becomes excessive. In this scenario near-optimal bio-inspired or learning-aided optimization can be used. Alternatively, we may opt for single-component optimization and impose the remaining parameters as constraints.

Interference Management: In this article, we assumed an idealized, interference-free regime based upon using orthogonal resources for each of the clusters. In fact, the orthogonal resources tend to be insufficient in practical UC-UDNs, hence a powerful dedicated interference management strategy relying on sophisticated resource allocation and/or beamforming design is required. Additionally, the interference management is coupled with the user-centric clustering problem. To further exploit the benefits of UC-UDNs, this pair of coupled problems should be jointly optimized.

Hybrid Networks: Given the extremely high performance requirements, a mixture of network architectures relying on integrating various key enabling techniques has been a dominant trend. Hence, the user-centric clustering design will be extended to hybrid networks by incorporating mmwave solutions, energy harvesting, unmanned aerial vehicles (UAV), device-to-device (D2D) communications, MEC, Internet of Things (IoT), caching and so forth into the UC-UDNs, which bring about new challenges, such as for example the MEC server selection problem of user-centric clustering.

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