Ultra-Dense Networks (UDNs) for 5G

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Abstract
This article gives an overview of the current state of UDN development and issues related to 5G RAN.

1. Emerging ultra-dense networks (UDNs)

Since the beginning of mobile industry, cell splitting and densification has been one of the most effective means to deliver ever-increasing capacity and improving user experience. In recent years, UDN has emerged as a prominent solution to meet the challenges of fulfilling IMT-2020 (5G) extremely high capacity density requirements of up to 10 Mbps/m^2. Qualitatively, UDN is a network with much higher density of radio resources than that in current networks, i.e., much denser small cell network in terms of either relative density or absolute density of the BSs. Quantitatively, the definition of UDN varies among the literature. In [1-4], UDN is defined as a network where the BS (or AP) density potentially reaches or even exceeds the user density, which is appropriate to characterize the scenario when the traffic per user increases while the number of users does not. In [5], an UDN is characterized as a network where the inter-site distance is only a few meters. In [6], UDN is identified as a network reaching the point where its capacity grows sub-linearly, due to the growing impact of interference, as the BS density increases.

2. Challenges of UDNs

Interference in an UDN becomes more severe, with higher volatility, and there may be a large number of strong interferers but none dominant. This leads to interference statistics different from those of an existing network with one (or a small number of) dominant interferers [6]. Under the assumption of heavy and uniform traffic load, all the BSs are always active in conventional cellular networks. In these networks with sparsely deployed BSs, the density of users often exceeds the density of BSs, at least during peak time. For such sparse networks, universal frequency reuse has long been believed as optimal to maximize the capacity [7], and the assumption that every BS has at least one user to serve (and hence all BSs should be activated) is reasonable. In a universal frequency reuse sparse network with time division multiple access, the average SE of the network increase with BS density linearly. When the network becomes dense where some BSs have no user to serve but are still activated, the SE first increases slowly and then decreases with BS density [8], and hence the density of BSs can be optimized [8-9]. The assumption of a constant path loss exponent in these papers might mask the UDN effect [6], nonetheless they showed that interference should be handled differently in an UDN. More interesting behaviors of the network can be found in [6, 17] where networks with variable path loss exponents are studied.

Due to the traffic load fluctuation, turning off the BSs in the cells with low or no traffic load is an essential way for UDNs in improving EE as well as reducing interference. In practice, the network traffic fluctuates over different times and locations due to user behavior and mobility, which is especially true for UDNs and naturally calls for BS sleeping. In a universal frequency reuse sparse network with BS sleeping where BS density is less than user density, the average SE still increases linearly with BS density [10] as in the network without BS sleeping. In a universal frequency reuse UDN with BS sleeping where BS density is larger than user density, the SE only logarithmically increases with BS density [1].

Utilizing the massive amount of radio resources optimally in an UDN becomes increasingly complex. Misallocation of increased radio resources can cause higher interference, unbalanced load distributions, and higher power consumption. Furthermore, due to interference, local radio resource allocation may have a global impact to a UDN. In other words, “locality” does not really exist in the UDN, and radio resource allocation has to be done based on a bigger picture of the UDN by taking into account of the tight coupling across the network [11].

Sufficient bandwidth over wired connectivity to directly backhaul each and every BS in an UDN may be practically infeasible. Wireless self-backhauling has been proposed, which consumes valuable radio resources, generates additional interference, and leads to extra latency.

3. Rethink universal frequency reuse

Universal frequency reuse has been made popular since the 3G era. It is also the common practice considered in UDN. Both the SE and EE are impacted by interference in such scenario. Complicated interference coordination in an UDN is undesirable due to the network scale and expensive backhaul. To manage the interference with less information sharing among the BSs, various semi-dynamic interference avoidance methods such as soft frequency reuse have been proposed. As the network becomes denser, i.e., as the ratio of BS density to user density increases, BS sleeping very effectively reduces the interference in the network. To further improve the average SE and EE of an UDN with BS sleeping, partial frequency reuse, i.e., with reuse factor greater than 1, was investigated [4]. When BS sleeping is allowed for the cells without active users, the frequency reuse factor that maximizes the SE or EE upper bound of the network with given ratio of BS density to user density was found, and the SE and EE gains of universal frequency reuse over partial frequency reuse in UDNs were quantified. It’s found that universal frequency reuse is SE-optimal for the networks with arbitrary BS/user density ratios, but is EE-optimal only when the ratio exceeds a threshold. This threshold is highly dependent on the total bandwidth of the network and the number of antennas at each BS. Both the normalized SE and EE gains of universal frequency reuse increase with the BS/user density ratio and slowly approach a constant that is dependent on the reuse factor.

4. Integrated resource allocation, interference management, and traffic steering

There are complex interactions among resource allocation, interference management, and traffic steering in an UDN. Joint considerations of all three to reshape interference and steer traffic load as desired bring forth techniques such as variable and flexible resource reuse patterns, load aggregation/balancing, enhanced UE-BS association, carrier selection and BS on/off, etc., in semi-static time scales (e.g., hundreds of milliseconds or longer). Optimal resource allocation taking into account of traffic distribution, interference, and performance requirements such as total latency have shown considerable improvement in network resource utilization efficiency, which in turns causes less interference and leads to higher SE [12]. Non-localized impact of interference in an UDN requires a large-scale optimization problem to be efficiently solved. Scalable algorithms have been pursued [11-13], including transforming a non-convex programming into a sequence of convex programming, and distributed decision making with network-wide iterations. Moreover, (sub-) optimal solution for an UDN may be pursued via optimal solutions for clusters of BSs by ignoring faraway interferers and considering cluster boundary constraints. Such solution for an UDN cluster of about 100 BSs and 1000 UEs can be obtained within seconds on a regular PC, which is applicable in a practical network.

5. Standards consideration

The above approach also leads to a fast-adapting network, in terms of its BS and carrier on/off status and traffic load redistribution. The cellular standards may consider supporting fast accessible carriers, including fast carrier on/off, fast carrier selection and switching, reduction or removal of always-on signals, streamlined measurement procedures, simplified connection establishment mechanisms, etc. [14] These features facilitate fast load balancing/shifting across BSs and carriers, as well as fast interference coordination and avoidance across BSs and carriers.

To address wireless in-band backhauling, an optimization study targeting the best end-to-end (i.e., multi-hop) performance and accounting for the split between backhaul links and access links was carried out in [15]. Performance benefits demonstrated by numerical results were encouraging, while extending the in-band backhauling without radio resource split or multi-hop will be more attractive.

Finally, in practice, an UDN is likely to be just part of a non-homogeneous network, or part of a hierarchical network. Since the RAN architecture in 5G is more revolutionary having introduced in the CU-DU structure [16], the realization of UDN may benefit from similar approaches of C-RAN.

6. Conclusions

Even without a uniquely agreed quantitative definition, UDN is expected to be an essential element of 5G networks for various deployment scenarios. In addition to implementation related technologies, standards related designs are necessary to realize its full potential. Comparing with the fast development of mmWave or mMIMO technologies, the progress of UDN specific work requires more attention and effort.

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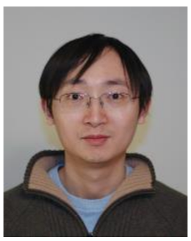

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