



Heterogeneous Cloud Radio Access Networks Based on New Perspective for Enhancing Spectral and Energy Efficiencies

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Abstract- To mitigate the severe inter-tier interference and enhance limited cooperative gains resulting from the constrained and non-ideal transmissions between adjacent base stations in heterogeneous networks (HetNets), heterogeneous cloud radio access networks (H-CRANs) are proposed as cost-efficient potential solutions through incorporating the cloud computing into HetNets. In this article, state-of-the-art research achievements and challenges on H-CRANs are surveyed. In particular, we discuss issues of system architectures, spectral and energy efficiency performances, and promising key techniques. A great emphasis is given towards promising key techniques in H-CRANs to improve both spectral and energy efficiencies, including cloud computing based coordinated multi-point transmission and reception, large-scale cooperative multiple antenna, cloud computing based cooperative radio resource management, and cloud computing based self-organizing network in the cloud converging scenarios. The major challenges and open issues in terms of theoretical performance with stochastic geometry, fronthaul constrained resource allocation, and standard development that may block the promotion of H-CRANs are discussed as well.

Keywords: Heterogeneous cloud radio access networks (H-RANs), heterogeneous networks (HetNets), cloud computing, mobile convergence

I. INTRODUCTION

Demand for high-speed data applications, such as high-quality wireless video streaming, social networking and machine-to-machine communication, has been growing explosively over the past 20 years and it is envisioned that asymmetric digital subscriber line (ADSL)-like user experience will be provided in the fifth generation (5G) wireless systems. This vision implies an average area capacity of 25Gbps/km², which is 100 times higher compared with current fourth generation (4G) systems. Meanwhile, to minimize power consumptions, a 1000X improvement in the energy efficiency (EE) is anticipated by 2020. Unfortunately, the cellular network architecture currently in use is over 40 years old and is not originally designed for achieving good EE performances, but for the coverage and mobility consideration. To meet such challenging goals, revolutionary approaches involving new wireless network architectures as well as advanced signal processing and networking technologies are anticipated.

Heterogeneous networks (HetNets) have attracted intense interests from both academia and industry. The low power nodes (LPN, e.g., pico base station, femto base station, small cell base station, etc.) is identified as one of key components to increase capacity of cellular networks in dense areas with high traffic demands. When traffic is clustered in hotspots, such LPNs can be combined with high power node (HPN, e.g., macro or micro base station) to form a HetNet. HetNets have advantages of serving

hotspot customers with high bit rates through deploying dense LPNs, providing ubiquitous coverage and delivering the overall control signalings to all user equipments (UEs) through the powerful HPNs. Actuarially, too dense LPNs will incur the severe interferences, which restricts performance gains and commercial developments of HetNets. Therefore, it is critical to control interferences through advanced signal processing techniques to fully unleash the potential gains of HetNets.

The coordinated multi-point (CoMP) transmission and reception is presented as one of the most promising techniques in 4G systems. Unfortunately, CoMP has some disadvantages in real networks because its performance gain depends heavily on the backhaul constraints and even degrades with increasing density of LPNs. Further, it was reported that the average spectral efficiency (SE) per performance gains from the uplink CoMP in downtown Dresden field trials was only about 20 percent with non-ideal backhaul and distributed cooperation processing located on the base station in.

To overcome the SE performance degradations and decrease the energy consumption in dense HetNets, a new paradigm for improving both SE and energy efficiency (EE) through suppressing inter-tier interference and enhancing the cooperative processing capabilities is needed in the practical evolution of HetNets. Meanwhile, cloud computing technology has emerged as a promising solution for providing high energy efficiency together with gigabit data rates across software defined wireless communication networks, in which the virtualization of



communication hardware and software elements place stress on communication networks and protocols. Consequently, heterogeneous cloud radio access networks (H-CRANs) are proposed in this paper as cost-effective potential solutions to alleviating inter-tier interference and improving cooperative processing gains in HetNets through combination with cloud computing. The motivation of H-CRANs is to enhance the capabilities of HPNs with massive multiple antenna techniques and simplify LPNs through connecting to a “signal processing cloud” with high-speed optical fibers. As such, the baseband datapath processing as well as the radio resource control for LPNs are moved to the cloud server so as to take advantage of cloud computing capabilities. In the proposed H-CRANs, the cloud computing based cooperation processing and networking gains are fully exploited, the operating expenses are lowered, and energy consumptions of the wireless infrastructure are decreased. Fig. 1 illustrates an evolution milestone from conventional 1G to the H-CRAN based 5G system. In the traditional first, second and third generation (1G, 2G, 3 G) cellular systems, cooperative processing is not demanded because the inter-cell interference can be avoided by utilizing static frequency planning or code division multiple access (CDMA) techniques. However, for the orthogonal frequency division multiplexing (OFDM) based 4G systems, the inter-cell interference is severe because of the spectrum reuse in adjacent cells, especially when a HetNet is deployed.

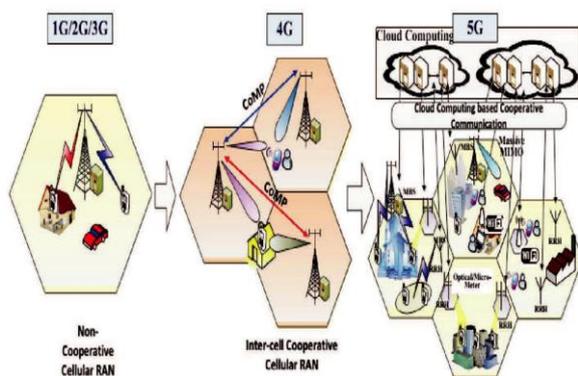


Fig. 1 Cellular System Evolution to 5G

Therefore, the inter-cell or inter-tier cooperative processing through CoMP is critical in 4G. To control the more and more severe interference and improve SE and EE performances, the cooperative communication techniques are evolved from the two-dimensional CoMP to the three-dimensional large-scale cooperative processing and networking with cloud computing. Therefore, for the H-CRAN based 5G system, the cloud computing based cooperative processing and networking techniques are proposed to tackle aforementioned challenges of 4G systems and in turn meet performance demands of 5G systems.

In this article, we are motivated to make an effort to offer a comprehensive survey on technological features and core principles of H-CRANs. In particular, the system architecture of H-CRANs is pre-sented, and SE/EE performances of H-CRANs are introduced. Meanwhile, the cloud computing based cooperative processing and networking techniques to improve SE and EE performances in H-CRANs are summarized, including advanced signal processing in the physical (PHY) layer, cooperative radio resource management (RRM) and self-organization in the upper layers. The challenging issues related to techniques and standards are discussed as well.

II. SYSTEM ARCHITECTURE & PERFORMANCE ANALYSIS OF H-CRANS

Although HetNets are good alternatives to provide seamless coverage and high capacity in 4G systems, there are still two remarkable challenges to block their commercial developments: i). The SE performance should be enhanced because the intra- and inter-cell CoMP need a huge number of signalings in backhaul links to mitigate interferences amongst HPNs and LPNs, which often results in the constrained backhaul links; ii). The ultra dense LPNs can improve capacity with the cost of consuming too much energy, which results in a low EE performance.

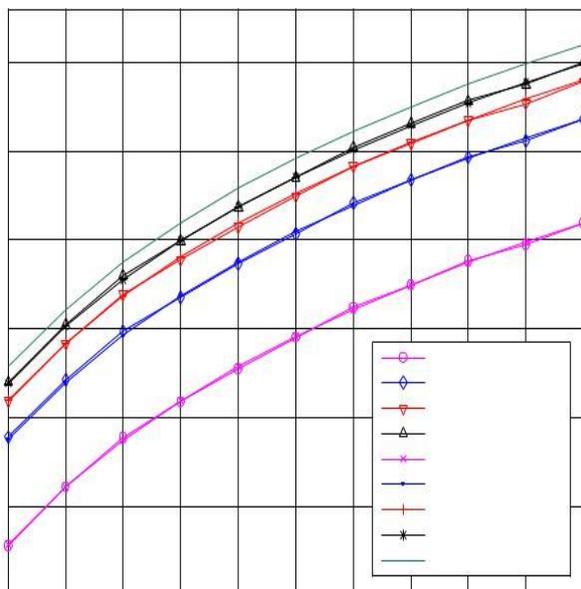
Cloud radio access networks (C-RANs) are by now recognized to curtail the capital and operating expenditures, as well as to provide a high transmission bit rate with fantastic EE performances [4]. The remote radio heads (RRHs) operate as soft relay by compressing and forwarding the received signals from UEs to the centralized base band unit (BBU) pool through the wire/wireless fronthaul links. To distinguish the advantages of C-RANs, the joint decompression and decoding schemes are executed in the BBU pool. Accurately, HPNs should be still critical in C-RANs to guarantee the backward compatibility with the existing cellular systems and support the seamless coverage since RRHs are mainly deployed to provide high capacity in special zones. With the help of HPNs, the multiple heterogeneous radio networks can be converged, and all system control signalings are delivered wherein. Consequently, we incorporate HPNs into C-RANs, and thus H-CRANs are proposed to take full advantages of both HetNets and C-RAN, in which cloud computing capabilities are exploited to solve the aforementioned challenges in HetNets.

A. System Architecture of H-CRANs

Similarly with the traditional C-RAN, as shown in Fig. 2, a huge number of RRHs with low energy consumptions in the proposed H-CRANs are cooperated with each other in the centralized BBU pool to achieve high cooperative gains. Only the front radio frequency (RF) and simple symbol processing functionalities are implemented in RRHs, while the other important baseband physical



decreases circuit energy consumptions in RRHs, thus improves both SE and EE performances.



(a) EE Performance Comparisons with various network
 (b) SE Performance Comparisons with different association number

Fig. 3 EE and SE Performances Evaluations of H-CRANs

As shown in Fig. 3 (a) EE performances in terms of the number of cell-edge UEs are compared amongst 1-tier HPN, 2-tier underlaid HetNet, 2-tier overlaid HetNet, 1-tier C-RAN, and 2-tier H-CRAN, where the same serving coverage, frequency spectrum, transmit power for both RRH and HPN, number of served UEs are assumed. The EE performances decrease with the increasing number of cell-edge UEs in the 1-tier HPN scenario because more resource blocks and power are allocated to the cell-edge UEs for guaranteeing their basic transmission rates. The EE performances are better in 2-tier HetNets than those in 1-tier HPN because a lower transmit power is needed and a higher transmission bit rate is achieved. Further, the EE performances in the 2-tier H-CRAN scenario are better than those in the 1-tier C-RAN because RRHs in C-RANs suffers from the limited coverage that HPN could serve. Meanwhile, the EE performances of 1-tier C-RAN are better than those of both 1-tier HPN and 2-tier HetNet due to gains from the characteristic of cloud computing.

Different UEs may overlap. It is not always optimal that UE associates with the RRH via the maximum received signal strength, or the maximum signal-to-interference-plus-noise ratio (SINR) because the transmit power amongst HPNs and RRHs are significantly different. Meanwhile, larger cluster size can provide better SE performances for the desired UE at the cost of leading to higher fronthaul consumption. Consequently, the RRH/HPN association strategy should optimize the cluster

size for each UE, in which the fronthaul overhead and cooperative gains should be balanced. Further, the association whether with RRHs or HPN has great impact on SE performances of H-CRANs. If UEs only associate with RRHs, the proposed H-CRAN is simplified to the C-RAN. The single nearest and N-nearest RRH association strategies for H-CRANs are tackled in [7]. As shown in Fig. 3(b), the ergodic capacity performances under different number of association RRHs with the varying transmit power of RRHs are compared. The capacity grows monotonically with increasing transmit power because the interference can be avoided due to the centralized cloud computing based cooperative processing. The capacity gain of the 2-nearest RRH association over the single nearest RRH association is significant. However, the capacity gaps among 4, 8 and infinite RRH association strategies are not large, which indicates that no more than 4 RRHs are associated for each UE to balance performance gains and implementation cost.

Besides enhancing SE and EE performances, there is a strong incentive to improve mobility performances in H-CRANs, e.g., there are less handover failure, lower Ping-Pong rate and lower drop ratio for high-mobility UEs than those in C-RAN. Though the handover between adjacent RRHs is administrated in the same BBU pool, which means that most handover signalings are avoided, the RRH re-association and radio resource reconfiguration are still challenging to the mobility performance. Therefore, in the high-density C-RANs, high-mobility UEs are likely to be victims who experience radio link failures (RLFs) before completing the handover process. Fortunately, in H-CRANs, the high-mobility UEs are served by HPNs with reliable connections, and the low-mobility UEs are preferred to access the RRHs. Consequently, by contrast to C-RANs, there are significant mobility performance gains in H-CRANs.

III. PROMISING KEY H-CRAN TECHNOLOGIES

To take full advantages of H-CRANs, the cloud computing based cooperative processing and net-working techniques in PHY, medium access control (MAC) and network layers should be exploited. The cloud computing based CoMP (CC-CoMP) technique as the evolution of the traditional CoMP in 4G systems is utilized to fulfill the interference cancelation and collaboration amongst RRHs and HPNs. The large-scale cooperative multiple antenna (LS-CMA) technique with the large-scale antenna array is adopted to provide additional diversity and multiplexing gains for HPNs. Through CC-CRRM, the radio resources amongst RRHs can be shared and virtualized, and the cross-interference between RRHs and HPNs can be coordinated. Comparing with HetNets and C-RANs, H-CRAN is more complex and costly in network planning and maintaining. Therefore, the cloud computing based self-organizing network (CC-SON) is indispensable to enhance intelligences and lower human costs.



A. Cloud computing based Coordinated Multi-Point (CC-CoMP)

The potential applications of CC-CoMP in H-CRANs exist homogenous and heterogeneous scenarios, which are denoted as intra-tier and inter-tier, respectively. In the intra-tier CC-CoMP shown as scenario 1 in Fig. 4, nodes in the same tier, i.e., amongst HPNs or amongst RRHs, are required to transmit coordinately. Since all RRHs in H-CRANs are connected with the BBU pool, such collaboration can be realized through virtual beam forming, where the beamers can be formed at the BBU pool. Moreover, the inter-tier CC-CoMP showed as scenario 2 in Fig. 4 relies on the collaborations between RRHs and HPNs, and such cross-tier collaborations may put a heavy burden of computational complexity on the BBU pool. Therefore, to ease the burden of BBU pool, distributed schemes in the centralized H-CRAN structure could be partially executed instead.

To mitigate intra-tier and inter-tier interference efficiently, the traditional CoMP in 4G should work in perfect and ideal status to achieve significant cooperative processing gains, which arouses high complexities, increased synchronization requirements, complicated channel estimation efforts, and huge signaling overhead. Fortunately, as the evolution of CoMP, the CC-CoMP relies on the large-scale spatial cooperative processing in the centralized BBU pool, in which most challenges of CoMP are alleviated. The biggest challenging for CC-CoMP is that the full-scale coordination requires the processing of very large channel matrix consisting of channel coefficients from all UEs to all RRHs/HPNs, leading to high computational complexity and channel estimation overhead.

Accurately, only a small fraction of the entries in the channel matrix have reasonable gains because any UE is only close to a small number of neighbor RRHs/HPNs. Consequently, the sparsity or near-sparsity channel matrices can be utilized during designing the efficient CC-CoMP, where the core problem is to what extent the channel matrix for CC-CoMP can be compressed without substantially compromising the system performance. On one hand, the improvement of SE performances might be very limited when the scale size of CC-CoMP is small. On other hand, by setting the participants overly, the exchanging signaling overhead and their channel state information (CSI) amount are intractable. Further, the accuracy and instantaneity of CSI decline with the increasing scale size, which degrades SE performances severely. Therefore, it is critical to clarify the boundary conditions in which CC-CoMP can achieve significant gains in H-CRANs. To decrease the implementation complexity, a joint RRH selection and power minimization beamforming problem was proposed in, where a bi-section group sparse beamforming (GSBF) algorithm and an iterative GSBF algorithm are proposed.

It is demonstrated that the proposed bi-section GSBF algorithm is a better option if the number of RRHs is huge due to its low complexity, while the iterative GSBF algorithm can be applied to provide better performances in a medium-size network.

B. Large-Scale Cooperative Multiple Antenna Processing (LS-CMA)

The LS-CMA technique, also known as massive MIMO, is equipped with hundreds of low-power antennas at a co-located HPN site, which is presented to improve capacity, extend coverage, and decrease antenna deployment complexity. Due to the law of large numbers, the channel propagation condition can be hardened, which can ensure that the transmission capacity increases linearly as the number of antennas increases, and EE performances can be improved as well. Compared with the traditional single antenna configuration, the LS-CMA for HPNs can increase the capacity 10 times or more and simultaneously improve the radiated EE performances on the order of 100 times in, where the 100-element linear array is deployed in HPNs, and the ideal backhaul is assumed.

Unlike RRHs, HPN needn't to upload all observations to the centralized BBU pool for the base-band large-scale signal processing. By using HPNs with LS-CMA, instead of deploying a huge number of RRHs in some coverage areas, the constrained fronthauls between RRHs and the BBU pool can be released. Moreover, as shown in Fig. 5, compared to HPNs without LS-CMA, or the conventional C-RAN scenarios, the HPNs with LS-CMA reduce their interferences to the adjacent RRHs/HPNs since LS-CMA can serve a large area, which widens the serving distance and dilutes the density of active RRHs.

C. Cloud Computing based Cooperative Radio Resource Management (CC-CRRM)

To fully unleash the potential advantages of H-CRAN, the intelligent CC-CRRM is urgent and there are various technical challenges involved. First, CC-CRRM needs to support real-time and bursty mobile data traffic, such as mobile gaming, vehicle-to-vehicle communications and high-definition video streaming applications. Therefore, CC-CRRM should have the time delay aware ability. Most of the traditional RRM are based on heuristics and there is lack of theoretical understanding on how to design delay-aware CC-CRRM. Second, the CC-CRRM has to be scalable with respect to H-CRAN size, while the traditional RRM are infeasible due to the huge computational complexity as well as signaling latency / complexity involved. These challenges become even worst for H-CRANs because there are more than RRHs connected to the BBU pool through the constrained fronthaul. Unlike conventional cross-layer RRM, which is designed to optimize the resource of a single base station, the CC-CRRM involves shared radio resources among all RRHs/HPNs, and thus the scalability in terms of computation and signaling is a key obstacle.



D. Cloud Computing based Self-Organizing H-CRANs (CC-SON)

In the network layer of H-CRANs, the self-organizing functionnaires are critical to guarantee the giant RRHs and HPNs work with high SE and EE performances. Self-organizing network (SON) technology is able to minimize human interventions in networking processes, which was proposed to reduce operational costs for service providers in LTE cellular systems and HetNets.

Considering a huge number of parameters should be configured and optimized, the topology is dynamical due to switching on/off RRHs adaptively, and the radio resources are shared and cooperatively processed, CC-SON in H-CRANs is the key to integrate network planning, configuration, and optimization into a unified automatic process requiring minimal manual interventions with the centralization of cloud computing. CC-SON allows operators to streamline their operations, not only reducing the complexity of managing co-channel interference in H-CRANs, but also saving operational costs to all RRHs and HPNs. CC-SON is used to harmonize the whole network management approaches and improve the overall operational efficiency. On the other hand, the availability of CC-SON solutions leads to identify powerful optimization strategies, mitigate co-channel interferences and improve EE performances.

Different from the hybrid SON architecture in HetNets, due to the existence of centralized BBU pool, the self-configuration, self-optimization, and self-healing functionalities in CC-SON are implemented in the hierarchical SON architecture, in which the centralized structure is utilized in the BBU pool for all RRHs, and the distributed structure is adopted between the BBU pool and HPNs. For the self-configuration, since RRHs are utilized to provide a high capacity transparently, the physical cell identifier (PCI) assignment is not necessary for RRHs, and only the radio resource should be self-assigned to each RRH intelligently. However, both self-configuration and PCI and radio resource should be fulfilled in HPNs.

These self-configuration cases for HPNs should be handled with the help of the centralized BBU pool. For the self-optimization of H-CRANs, energy saving and mobility robustness optimization are two key cases, in which RRHs should be turned on/off automatically, and the overlap coverage of RRHs and HPNs should be intelligently compensated with each other. For the self-healing, the outage detection and performance compensation are executed mainly in the BBU pool, and the shared radio resources among RRHs can be adaptively re-configured to compensate the outage coverage. Note that these aforementioned SON cases are triggered by the minimization of drive test mechanisms. The specified CC-SON related algorithms should be researched further for H-CRANs in the future.

III. CHALLENGES AND OPEN ISSUES IN H-CRANs

Although there have been some progresses and initial achievements in the aforementioned potential system architecture, performance analysis, key techniques for H-CRANs, there are still many challenges ahead, such as the theoretical performance analysis with stochastic geometry, optimal resource allocation with the constrained fronthaul, and standard development. Some classical challenges as samples are discussed in this section.

A. Performance Analysis with Stochastic Geometry

With the cellular network evolving from conventional grid cellular network to HetNets, it is highly desirable to study the capacity of HetNets, where locations of LPNs and UEs follow with the stationary Poisson point process (PPP). Owing to its tractability, PPP model leads to simple closed-form expressions for key metrics such as coverage probability and average rate over the entire network. Considering the capacity scales with the limited fronthaul, the optimal rate allocation that maximizes overall sum rates in C-RAN was analyzed in, in which the fronthaul link rates are demonstrated to scale logarithmically with the SINR at each node.

As a tractable tool of modeling interference, stochastic geometry can be utilized to capture the characteristic of the locations of RRHs/HPNs and hence develop accurate performance results, e.g. coverage probability, average capacity and area spectral efficiency. However, the differences between the H-CRANs and the conventional HetNets and C-RANs in utilizing the stochastic geometry are twofold. First, interference coordination is much more feasible due to the centralized computation in the BBU pool for H-CRAN than that for HetNet. Interference cancellation and collaboration in the spatial domain is confined to HetNets due to the constrained cross-tier backhaul, whereas it is possible to perform more efficient large-scale cooperative signal processing algorithms in H-CRANs, e.g. CC-CoMP and LS-CMA, to achieve higher performance gains. Based on the stochastic geometry, it is significant to propose a tractable yet practical strategy to derive the analytical closed-form expressions for SE and EE performances. Based on these expressions, the impact of imperfect fronthaul link can be evaluated and near sparse beamforming schemes can be designed jointly with the RRH selection and power allocation. Second, H-CRANs can obtain additional performance gains over C-RAN from the mobility enhancement. A tractable mobility model should be constructed to analytically evaluate performance gains in terms of handover success ratio and sojourn time.

B. Performance Optimization of Constrained Fronthaul

The non-ideal fronthaul links between RRHs and the BBU pool deteriorate overall SE and EE performances of H-CRANs, where both the limited capacity and time latency



constraints are inevitable in practice. Besides, when the network scale grows larger, it's impractical to assume that all ideal CSIs of the entire network are tractable.

The constraints of the fronthaul affect SE performances in several ways. The total transmission bit rate per RRH should not be larger than the capacity of its corresponding fronthaul link. The insufficient fronthaul capacity prevents RRH to make full use of available radio resources. Such problem becomes even more severe when CC-CoMP, LS-CMA and CC-CRRM are utilized. Besides, the time latency of the fronthaul also plays a key handicap to optimize both SE and EE performances. Most obviously, the time latency make CSI outdated, which results in deteriorating the accuracy of sparse beamforming.

IV. CONCLUSION

In this article, we have provided a summary of recent advancements in the computing convergence of heterogeneous wireless networks. The heterogeneous cloud radio access network (H-CRAN) is proposed as a promising new paradigm to achieve high SE and EE performances through the combination of cloud computing and HetNets. The system architecture, performance analysis, cloud computing based cooperative processing and networking techniques for the proposed H-CRANs have been surveyed. In particular, the key large-scale cooperative processing and networking techniques including cloud computing based CoMP, CRRM, SON have been briefly summarized. Further, potential challenges and open issues in H-CRANs have been discussed as well. The presented key techniques and potential solutions for H-CRANs provide breakthroughs of theories and technologies for the advanced next generation wireless communication systems.

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