Guest Editorial Recent Advances in Heterogeneous Cellular Networks, Part II

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IN order to enhance network capacity, there has been an increasing interest in deploying relays, distributed antennas, and small cellular base stations (e.g., metrocells, picocells, and femtocells), e.g., indoors in residential homes and offices as well as outdoors in amusement parks and busy intersections. These new network deployments, which are composed of a mix of low-power nodes underlying the conventional homogeneous macrocell network, are usually referred to as heterogeneous cellular networks (HCNs). By deploying additional small cells within the local-area range and bringing the network closer to users, HCNs can significantly boost the overall network capacity through a better spatial resource reuse.

Inspired by the attractive features and potential advantages of HCNs, their deployment and development have gained much momentum in the wireless industry and research communities during the past few years. For instance, HCNs are being extensively discussed at the 3GPP forum. However, HCNs also come with their own complications, and there are fundamental challenges and significant technical issues that still need to be addressed for their successful rollout and operation.

This special issue aimed to bring together research HetNet articles from a wide range of perspectives in different industrial and academic communities. The goals are to advance the understanding of the challenges faced over the next decade, solidify accepted models and metrics, and catalog innovative approaches to design and deploy HetNets. We were delighted to receive a total of 110 submissions to the special issue, and accepted manuscripts have been selected after a rigorous review process. Due to the large volume of submissions, the accepted papers will be published in two back-to-back JSAC special issues.

In this second issue, there are 18 accepted papers, which can be broadly categorized under four major research areas: 1) traffic analysis; 2) scheduling, energy efficiency, and cloud aspects; 3) device-to-device communication; and 4) analytically tractable models.

Category 1. Traffic Analysis (Two Papers): User traffic is a crucial factor that impacts the performance of HetNets. While traditional analytical models assume fully loaded networks, the performance obtained may not well represent the actual quality perceived by the users. Therefore, models that take the traffic characteristics into account to obtain more realistic analysis are required. There are two papers in this area that consider different scenarios, but all of them show clearly the impact of the unsaturated traffic conditions.

- **Impact of Traffic Load on OFDMA Femtocells Interference Mitigation**: The authors analyze the impact of the user activity, i.e., transmitting or not, by evaluating the performance of the centralized resource-allocation scheme of the power control protocol and random access protocol. The analysis shows that a simple random access protocol, which does not have any optimization, can perform better than a fair optimized power-controlled network under unsaturated traffic scenarios. However, under saturated traffic scenarios, the fixed orthogonal partitioning of channel bandwidth among femtocells would achieve the best performance for interference management.
- **Traffic-Driven Spectrum Allocation in Heterogeneous Networks**: The authors propose the resource-allocation optimization for HetNets that considers traffic dynamics. The optimization relies on the average packet sojourn time instead of typical sum rate and outage probability as the objective and constraints. Therefore, the optimization aims to support QoS with small cells that could have a highly diverse traffic profile in overlapping cells with complex interference characteristics. The optimization divides the spectrum into different segments according to the possible spectrum sharing combinations. It is shown that optimization is convex. Additionally, the approximation is also applied to the sojourn time to define upper and lower bounds when the exact parameters are not known.

Category 2. Scheduling, Energy Efficiency, and Cloud Aspects (Seven Papers): Due to the sheer number of deployed small cells, resource allocation becomes of utmost importance to reap the benefits of small cell deployments. The following papers deal with the problem of scheduling in light of the limited backhauling, device-to-device communication in

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Digital Object Identifier 10.1109/JSAC.2015.2439453

conjunction with mmWave transmission and energy efficiency aspects.

- **Revisiting Scheduling in Heterogeneous Networks When the Backhaul Is Limited**: The authors study the impact of the limited capacity of backhaul links on user scheduling in a heterogeneous network comprising macro base stations and small cells. A global proportional fair (PF) scheduling problem is formulated, and it is shown that the backhaul capacity limitations have a fundamental impact on user scheduling. It is demonstrated that when the link between the macro base station and the core network is also of limited capacity, each base station can still perform a local scheduling as in the previous case as long as there is a master problem that allocates feasible virtual backhaul capacities to each BS.
- **Exploiting Device-to-Device Transmissions in Joint Scheduling of Access and Backhaul for Small Cells in 60 GHz Band**: This paper proposes a joint transmission scheduling scheme for radio access and backhaul of small cells in the 60-GHz band, where a path selection criterion is designed to enable device-to-device transmissions for performance improvement. Results achieve near-optimal performance and outperform other protocols significantly in terms of delay and throughput. Furthermore, the authors analyze the impact of path selection on the performance improvement of D2DMAC under different selected parameters.
- **Energy-Efficient Transmit Power Control for Multi-Tier MIMO HetNets**: The authors study energy-efficient transmit power control for multi-tier multi-antenna (MIMO) heterogeneous cellular networks (HetNets), where base stations (BSs) in each tier are distributed as a stationary Poisson point process (PPP). A noncooperative energy-efficient power control problem is formulated, where each tier selfishly chooses its transmit power to maximize its energy efficiency (EE). Then, the authors investigate cooperative energy-efficient power control, where all tiers cooperatively choose their transmit powers to optimize their EEs. Simulation results show that the proposed energy-efficient designs improve the network EE compared with the spectral-efficient designs.
- **Transmit Power Minimization in Small Cell Networks Under Time Average QoS Constraints**: The authors address the following question: Given certain time average quality-of-service (QoS) targets for the UTs, what is the minimum transmit power expenditure with which they can be met? This is formulated as a stochastic optimization problem whose solution is the design of the downlink beamforming vectors during each time slot and solved using Lyapunov optimization. This paper also analyzes the impact of delays incurred in information exchange between the SCBSs. Simulation results show that solving the problem with time average QoS constraints provide greater savings in transmit power compared with the instantaneous QoS constraints.
- **Resource Allocation for Energy Efficiency Optimization in Heterogeneous Networks**: This paper addresses the EE optimization problem for downlink two-tier HetNets composed of a single macrocell and multiple picocells. Considering a heterogeneous real-time and non-real-time traffic, transmit beamforming design and power allocation policies are jointly considered in order to optimize the system energy efficiency. The EE resource-allocation problem under consideration is a mixed combinatorial and nonconvex optimization problem, which is very difficult to solve. Thus, the original problem is decomposed with multiple inequality constraints into multiple optimization problems with single inequality constraint. Simulation results confirm the theoretical findings and demonstrate the efficiency of the proposed resource-allocation algorithm.
- **Multi-Objective Energy-Efficient Resource Allocation for Multi-RAT Heterogeneous Networks**: The authors aim to optimize the energy efficiency for resource allocation for multi-RAT HetNet while guaranteeing QoS requirement of each individual user. With multiple users, the authors propose multiple-objective optimization problem and consider Pareto optimality as the solution. The novel metric of Utopia energy efficiency is introduced that defines the maximum achievable energy efficiency for each user. Then, the single-objective optimization problem is developed based on the weighted Tchebycheff method. The authors transform the original problem into the tractable one and implement an iterative algorithm to obtain the solution with fast convergence speed.
- **Heterogeneous Cellular Networks Using Wireless Backhaul: Fast Admission Control and Large System Analysis**: The authors consider an important issue of admission control that aims to limit the traffic in the network with wireless backhaul. Specifically, the admission control is jointly optimized with transmit beamformers, power control, and small cell access point selection. The joint optimization problem is proposed, but because of its complexity, l1-relaxation and iterative algorithm are adopted. The algorithm shows promising efficiency with small to medium sized network, thanks to its low complexity. For large network, the authors apply random matrix theory to obtain near-optimal solutions that are tractable and scalable.

Category 3. Device-to-Device Communication (Two Papers): D2D communication allows mobile users in HetNets to reuse cellular spectrum to perform local peer-to-peer direct transmission, offloading traffic from the cellular base stations. However, users must have incentive to perform D2D communication. Two papers address the incentive mechanism for D2D communication in HetNet environment.

- **Contract-Based Incentive Mechanisms for Device-to-Device Communications in Cellular Networks**: The authors consider HetNets with device-to-device (D2D) communication that can help to offload cellular traffic. However, D2D communication depends on user participation, and thus, to encourage them to establish local direct transmission by reusing cellular spectrum, an incentive mechanism based on contract theory is proposed.

The contract theoretic model takes the users' preferences into account and allows service trading between base stations and users. Simulation shows the success of capacity increases because of favorable D2D communication.

- **Matching and Cheating in Device to Device Communications Underlying Cellular Networks**: Despite benefit from D2D communication, interference can cause performance degradation to cellular users. The authors aim to optimize the system throughput while meeting QoS requirements by applying matching theory to allocate resources to the users. The stable matching algorithms are adopted to maximize social welfare and achieve network stability. Moreover, the model considers cheating in matching that users may not inform the true information. Although cheating can improve the performance of some users, it must not incur unacceptable degradation to other users.

Category 4. Analytically Tractable Models (Seven Papers): Stochastic geometry has emerged as a powerful mathematical tool to successfully analyze various performance metrics of HetNets under different system settings. There are six papers applying stochastic geometry considering dependence, clustering, mmWave, user mobility, energy harvesting, and CloudRAN.

- **Heterogeneous Cellular Network Models with Dependence**: In HetNets, the location of the base station, particularly in the same or different tiers, may be deployed, and thus, their locations are not completely independent, which is against the basic assumption of the PPP. Therefore, the authors propose the stochastic geometry models that consider inter-tier dependence and intra-tier dependence of the points. The models are based on the Poisson hole process (PHP). Moreover, the authors apply the fitted Poisson cluster process to approximate the PHP, which shows good accuracy.
- **Modeling Heterogeneous Cellular Networks Interference Using Poisson Cluster Processes**: The authors argue that because of the complex network structure of HetNets with macro-, pico-, and femtocells, PPP may not provide accurate model for interference when nodes are clustered in a certain area. Therefore, the authors propose to use a Poisson Cluster Process (PCP) and develop the analytical model that the base stations belonging to different tiers can have different transmit power, node density, and link reliability. With the developed model, the authors are able to derive outage probability, the coverage probability, and the average achievable rate, which are important performance metrics for HetNets. The performance comparison clearly shows that the PCP achieves better performance than that of the PPP. Finally, the scheme to jointly maximize the average achievable rate and minimize the outage probability based on the PCP model is proposed.
- **Tractable Model for Rate in Self-Backhauled Millimeter Wave Cellular Networks**: With millimeter-wave (mmWave) technology, cellular networks can benefit from interference isolation that can support self-backhauling in mesh setting. However, this requires high gain directional antennas and dense base station deployment. The authors propose the performance analysis based on stochastic geometry by using Poisson point process (PPP) to model the geographical distribution of the base stations in mmWave cellular networks. The tractable model is able to obtain associated rate distribution. Additionally, the authors validate the model using actual building locations from dense urban settings and empirically derived path-loss models. One important finding is that the spectral efficiency increases with the density of base stations, particularly at the cell edge.
- **Stochastic Geometric Analysis of User Mobility in Heterogeneous Wireless Networks**: Mobility influences the user handoff, which can be horizontal or vertical in multi-tier HetNets. The authors develop the novel analytical models that are able to take spatial randomness and various scales of cell sizes in different tiers into account. The rate of all handoff types is derived for the users with arbitrary movement pattern. Finally, the authors establish the guideline for performing optimal tier selection given user movement speed. This optimal tier selection is obtained as a function of handoff rate and data rate required by users. Simulation is used to validate the model with real user mobility.
- **Analysis of K-Tier Uplink Cellular Networks With Ambient RF Energy Harvesting**: RF energy harvesting becomes an alternative energy supply method for user equipment (UE) in HetNets. The authors develop stochastic geometry model to analyze the UE with energy storage. Energy in the storage is used to transmit data. First, the authors develop a queueing model to analyze the dynamics of energy storage from RF energy harvesting. Then, by using PPPs, the successful transmission probability given enough energy is derived. This performance metric can be used in the network design and optimization, e.g., to derive network coverage probability and to obtain optimal receiver sensitivity.
- **Are Heterogeneous Cloud-Based Radio Access Networks Cost Effective?**: The authors develop the analytical models to calculate deployment cost of CloudRAN HetNets, deployed following various spatial point processes. The model takes realistic setting of HetNets into account, including users, macro and micro base stations, microwave and optical fiber backhaul, and data center. The model presents the expression for the average cost of deploying data center. Next, the authors adopt data processing model to determine the actual parameters used in the model. The results from the analysis can indicate whether the CloudRAN HetNets can be more economical than the traditional LTE network or not. An interesting finding is that the deployment cost of CloudRAN HetNets can increase faster than that of traditional LTE when the user intensity increases under some backhaul technology.
- **HetHetNets: Heterogeneous Traffic Distribution in Heterogeneous Wireless Cellular Networks**: The authors first highlight the shortcoming of the PPP that

fails to capture heterogeneity or nonuniformity of user equipment (UE) locations, and they focus on the heterogeneity in the infrastructure, and heterogeneity in the spatial traffic distribution. Thus, the heterogeneous spatial traffic modeling that allows statistical adjustment is proposed. The adjustment involves UE distribution, i.e., the degree of heterogeneity and the bias toward the base station locations. The model can analyze the impact of heterogeneous and base station correlated traffic on the network performance.

David López-Pérez (S'08–M'10) is a Member of Technical Staff at Bell Laboratories, Alcatel-Lucent, and his main research interests are in HetNets, small cells, interference and mobility management as well as network optimization and simulation. Prior to this, he received the Ph.D. degree in wireless networking from the University of Bedfordshire, U.K., in April 2011 and the B.Sc. and M.Sc. degrees in telecommunicaitons from the Miguel Hernandez University, Spain, in September 2003 and September 2006, respectively. He was a Research Associate at King's College London, U.K., from August 2010 to December 2011, carrying post-doctoral studies, and was with VODAFONE, Spain, from February 2005 to February 2006, working in the area of network planning and optimization. He was also an Invited Researcher at DOCOMO USA Labs, CA, in 2011, and CITI INSA, France, in 2009. For his publications and patent contributions, he is a recipient of both the Bell Labs Alcatel-Lucent Award of Excellence (2013) and Certificate of Outstanding Achievement (2014 and 2013). He was also finalist for the Scientist of the Year prize in The Irish Laboratory Awards (2013). He has also been awarded as a Ph.D. Marie-Curie Fellow in 2007 and Exemplary Reviewer for IEEE Communications Letters in 2011. He is a founding member of IEEE TSCGCC and author of the book *Heterogeneous Cellular Networks: Theory, Simulation and Deployment* (Cambridge University Press, 2012). Moreover, he has published more than 70 book chapters, journal and conference papers, all in recognized venues, and filed more than 25 patents applications. He is or has been guest editor of a number of journals, e.g., IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS and *IEEE Communications Magazine*, a TPC member of top tier conferences, e.g., IEEE Globecom and IEEE PIMRC, and co-chair of a number of workshops.

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