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Technical advances in the design and deployment of future heterogeneous networks

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Abstract

The trend in wireless communications systems is the enhancement of the network infrastructure with the introduction of small cells, where a specific geographical area is served by low-range, low-power access points. The result is the creation of a heterogeneous topology where macrocells coexist with a variety of small-cell types. In this editorial article we briefly summarize the recent technical advances in the design and deployment of future heterogeneous networks addressed in the papers that compose this special issue. In particular the following aspects are considered: the design of interference and radio resource management algorithms, the analysis of the energy efficiency and power control issues in heterogeneous networks, the concept of coordination in small cell networks, key backhaul aspects of HetNets, deployment issues and overall management strategies.

1 Introduction

In recent years, there has been a systematic growth in the demand of wireless resources from the operators in order to accommodate the increasing data users' requirements. Such a situation is caused by many reasons, from which the following three factors influence the traffic increase the most: *a*. the transition from voice centric to data centric services and the proliferation of the relevant applications, *b*. the rapid increase of the number of hi-tech and relatively cheap wireless terminals, and *c*. the cost reduction for wireless data usage. Furthermore, it has been noticed that significant portion of the traffic is performed in indoor locations. In such a context, the traditional cellular network planning approaches—that rely only on finding the optimal placement of the macrocells—are no longer appropriate to handle the current users' demands. The recent trend is to enhance the network infrastructure with the introduction of small cells, where the considered geographical area is served by low-range, low-power access points creating a heterogeneous topology where multiple small-cell types coexist (e.g., picocells, microcells, femtocells, or Wi-Fi zones). These deployments allow significant capacity enhancements and better coverage conditions that can be particularly beneficial for enhancing the bit rates and energy consumption of the users that are located at the edge of the macrocells. Such advanced topologies, composed of multiple cell sizes and involving the combination of different radio access technologies, are usually known as heterogeneous networks or simply as HetNets. While some of the small-cell devices are deployed and installed by the operators, e.g., in outdoor locations, others (e.g., femtocells) are installed directly by the end users, usually in indoor locations, offering better coverage and increased portability within the user premises. The significant reduction of the cell radius and the lower transmit power levels create high potential for smart and effective resource and interference management to increase the system capacity. Moreover, the availability of various wireless access technologies by the end users provides an attractive opportunity to the cellular network operators for efficient traffic offloading (e.g., to Wi-Fi networks). Due to such attractive features, the HetNets concept has been considered by the standardization bodies as a promising direction for next-generation cellular networks. However, the practical deployment of HetNets still needs to face some critical issues and challenges such as the requirement of efficient interference coordination mechanisms, cross-layer dependencies, or stability of backhaul design. Such observation inspires numerous researchers to put their effort in this research field and constitutes the main motivation for organizing this special issue which is dedicated to recent advances in design and deployment issues for these future heterogeneous networks.

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This special issue was opened for paper submission in June 2014. Totally, 37 papers have been submitted before the submission deadline (beginning of September 2014). After a strict and detailed peer review process, only 20 papers have been recommended by guest editors for final acceptance by journal editors.

The papers cover various areas of research, from deployment strategies, to interference management and QoS guarantee analysis algorithms, and to energy-efficiency and mobility management. In the following, the papers are briefly presented, categorized into thematic groups according to their content.

2 Interference and Radio Resource Management in HetNets

The first group of papers deals with various aspects of interference and radio resource management and load balancing.

The paper "Scalable HetNet Interference Management and the impact of limited Channel State Information" by Chiumento et al. [1] proposes a distributed heuristic algorithm for interference mitigation in heterogeneous LTE networks which is aware of network load and propagation conditions. The method is scalable and makes use of an iterative Hungarian algorithm to reduce the interference effect and improve the quality of service of starved users. For practical considerations, the authors studied the impact of the necessary quantization of channel state information on the interference management solution and showed through simulations that the signaling overhead can be contained while the performance is improved.

The paper "Interference characterization and mitigation for different LTE-A deployments" by Fernandez-Lopez et al. [2] focuses on the interference characterization and resource usage in different LTE-Advanced network deployments. The study investigates the impact of the strongest interferer and its variability with time, and delves deeper into the reasons for the observed interference patterns. The time evolution of these metrics is studied, analyzing the required dynamism for interference mitigation solutions in these topologies.

The paper "Enhanced Multi-Band Carrier Aggregation Scheduling for LTE-Advanced QoS/QoE and Cost/Revenue Optimization" by Robalo et al. [3] discusses an integrated Common Radio Resource Management (iCRRM) for inter-band carrier aggregation between two LTE-A system operation bands. The paper analyzes the effect of carrier aggregation through two multi-band scheduling algorithms on system performance expressed in terms of summed capacity and users' quality of service/experience parameters. Moreover, a cost and revenue analysis is explored from the operator/service provider's perspective and the simulation results show the substantial improvements obtained using the carrier aggregation.

The paper "A model for virtual radio resource management in virtual RANs" by Khatibi et al. [4] addresses the virtualization concept to offer capacity-as-a-service by aggregating and managing the physical radio resources to create virtual wireless links. It considers a heterogeneous scenario with multiple radio access techniques and virtual network operators and proposes a radio resource management model to maximize the weighted throughput of the network and the fairness among the services of the virtual operators.

The paper "Load balancing mechanisms for indoor temporarily overloaded heterogeneous networks" by Aguilar-Garcia et al. [5] investigates the problem of temporal or spatial fluctuations of traffic in heterogeneous networks that may result to overload situations. It proposes novel load balancing methods based on fuzzy logic controllers (FLC) which evaluate temporarily overloaded situations and resize cell coverage areas by an adaptive process of adjusting cell transmission power. The proposed methods have been assessed and compared with the literature by using a dynamic LTE system-level simulator which uses an airport departure area model for the overload scenario.

"Efficient Radio Resource Management approaches for Heterogeneous Wireless Networks" have been proposed by Omheni et al. [6]. The authors have observed that heterogeneous wireless networks communication is a mixture of different wireless technologies, and integration of these technologies in the same network can cause several challenges such as seamless handover and call admission control. To deal with some of these challenges, a media-independent handover (MIH) framework has been standardized. The principle goal of this standard is to propose a general interface for the handover by abstracting the link layer intelligence to higher layers. This article proposes a combined call admission control and bandwidth adaptation approach for heterogeneous wireless network.

3 Energy Efficiency and Power Control Issues in Heterogeneous Networks

The second group consists of papers that deal with the energy efficiency and power control mechanisms.

The paper "Energy Efficient Design of Two-tier Femtocell Networks" by Wang et al. [7] investigates the energy efficiency of sleeping strategies in two-tier macro-femtocell networks. Using the stochastic geometry tool, the coverage user probability, power consumption, and energy efficiency are derived under different sleeping strategies and femtocell access policies. A novel sleeping strategy taking into account the activity level of base stations and users' locations is proposed, and the total power consumption is optimized. Simulation experiments show the gain in energy efficiency of the

proposed sleeping scheme and interesting discussions on the effects of the cells sleeping probabilities, noise, and power control on the energy efficiency are provided.

The paper "Neighbor-friendly autonomous power control in wireless heterogeneous networks" by Torrea-Duran et al. [8] proposes the neighbor-friendly iterative waterfilling (NF-IWF) algorithm. It is an autonomous algorithm for power control in HetNets that protects victim users from neighboring cells through a penalty factor in the power allocation level. It derives the gain in data rate for the victim users in comparison with other existing strategies such as iterative waterfilling, soft frequency reuse, and equal power allocation.

The paper "Dynamic Switching off Algorithms for pico base stations in Heterogeneous Cellular Networks" by Wu et al. [9] focuses on the problem of energy consumption in dense HetNets during low traffic periods. It introduces a sleep mode to the pico base stations in order to adapt the resources to the actual traffic load fluctuations over time and area. It proposes two centralized algorithms to dynamically switch off the unnecessary pico base stations. They rely on a utility function that accounts for different metrics reflecting the existing traffic load and interference conditions. The authors analyzed the algorithms performance by means of simulations, obtaining that significant energy consumption reductions can be achieved.

The work "Femtocell Power Control Methods based on Users Context Information in Two-Tier Heterogeneous Networks" by Kurda et al. [10] focuses a two-tier macrocell/femtocell overlaid heterogeneous network based on orthogonal frequency division multiple access (OFDMA) technology. It has been assumed that although the co-channel spectrum allocation provides larger bandwidth for both macrocell and femtocells, the resulting cross-tier interference may prevent macrocell users in the vicinity of femtocells to achieve their minimum required signal-to-interference-plus-noise ratio (SINR) in downlink. Therefore, new femtocell power control strategies have been proposed for mitigating the interference experienced by macrocell users while preventing the femtocell throughput degradation. In particular, the proposed power control schemes make use of femto and macro users' context information in terms of positioning for setting the appropriate prioritization weights among the current victim macro users and the femto users in outage.

In the work entitled "Joint Voronoi Diagram and Game Theory Based Power Control Scheme for the HetNet Small Cell Networks" by Xu et al. [11], the authors propose the Joint Voronoi diagram and game theory-based power control scheme as a two-step approach. The first step focuses on the optimization of the small-cell cluster deployment planning within the coverage of the macrocell. Then, the second step addresses the mitigation of cross-tier interferences while protecting the guaranteed users and high-mobility users usually served by the macrocells.

4 Coordination in Small Cell Networks

The third group of papers focuses on various coordination issues in the context of small-cell networks.

The paper "Self-coordination of parameter conflicts in D-SON architectures: A Markov Decision Process Framework" by Moysen et al. [12] addresses the conflict issue between concurrent self-organizing network (SON) functions. A general functional architecture and a theoretical framework based on the theory of Markov decision process (MDP)s is proposed for the self-coordination of different actions taken by different SON functions. To cope with the complexity of the overall SON problem, the MDP is divided onto simpler subMDPs modeling the SON functions and solved by means of reinforcement learning (RL). The simulation experiments showed the effectiveness of the self-coordination approach in terms of system performance by achieving a good compromise among conflicting actions.

In the paper "Self-optimized Heterogeneous Networks for Energy Efficiency" by Fan et al. [13], the authors propose an active/sleep scheduling strategy for base stations (BSs) as an effective way to match capacity to demand and also improve energy efficiency. Environmental awareness and self-organizing features are exploited in this work where the proposed scheme is based on the user activity sensing of small-cell BSs.

5 Key Backhaul Aspects of HetNets

The fourth group of papers considers issues related to backhauling in HetNets.

The paper "Coordinated multi-point transmission for relaxation of self-backhauling bottlenecks in heterogeneous networks" by Haile et al. [14] focuses on the backhauling solutions for HetNets and proposes the use of CoMP as a solution for self-backhauling. The paper provides first an analytical model to assess the capacity improvements that can be achieved with respect to the case where no CoMP is applied. Then, a similar analysis based on simulations in a complete and realistic scenario is also provided, concluding that the use of CoMP brings significant throughput enhancements and spectral efficiency gains.

The paper "Cache-enabled Small Cell Networks: Modeling and Tradeoffs" provided by Bastug et al. [15] discusses the network model where small base stations (SBSs) have caching capabilities as a means to alleviate the backhaul load and satisfy users' demand. The SBSs are stochastically distributed over the plane according to a Poisson Point Process (PPP) and serve their users

either (i) by bringing the content from the Internet through a finite rate backhaul or (ii) by serving them from the local caches. The closed-form expressions for the outage probability and the average delivery rate have been derived as a function of the SINR, SBS density, target file bitrate, storage size, file length, and file popularity.

In the paper entitled "Proposal and Analysis of Integrated PTN architecture in the Mobile Backhaul to improve the QoS of HetNets" by Cortés-Polo et al. [16], the authors present a study on recent advances and open research issues on mobility protocols in conjunction with Multi-Protocol Label Switching (MPLS)-based packet transport networks (PTNs) to provide QoS in wireless heterogeneous networks. Various mobile management protocols and their interaction with the mobile backhaul and packet core network are briefly introduced. A new architecture called Integrated Proxy Mobile MPLS-TP (IPM-TP) is also outlined to reduce the signaling cost and improve the QoS in high-mobility HetNets scenarios.

6 Deployment and Management in Small Cell Networks

The papers in the fifth group tackle selective problems of small-cell network deployment and management.

The paper "Mobility Management in HetNets: A Learning Based Perspective" by Simsek et al. [17] proposes a history-based context-aware mobility management (MM) procedure for small-cell HetNets. It makes use of reinforcement learning techniques and inter-cell coordination for improving the handover and throughput performance of UEs. More specifically, the BSs learn their long-term traffic loads and optimal cell range expansion and schedule their UEs based on their velocities and historical data rates that are exchanged among the tiers. System level simulations demonstrate the performance enhancement of the proposed approach compared to traditional MM method in terms of throughput and handover failure probability.

The paper "A femtocell location strategy for improving adaptive traffic sharing in heterogeneous LTE networks" by Ruiz Aviles et al. [18] proposes a planning strategy for placing femtocell access points in LTE networks, targeting in the maximization of the performance of automatic traffic sharing algorithms. The proposed strategy is assessed by simulating classical traffic sharing algorithms in an office scenario with different femtocell location plans, resulting in useful conclusions especially when the traffic is unevenly distributed.

The paper "Analytical Modeling of Cognitive Heterogeneous Cellular Networks over Nakagami-m Fading" by Panahi and Ohtsuki [19] utilizes the spatial Poisson (PPP) theory for the node locations and presents a tractable model to derive the outage probability of a typical femto and macro user in a two-tier heterogeneous network. The analysis provides insight into system design guidelines. Closed-form expressions were derived for these outage probabilities by considering the Nakagami-m fading channel for each link.

The paper "Deployment analysis and optimization of heterogeneous networks under the spectrum underlay strategy" by Martínez-Vargas and Andrade [20] provides deployment analysis and optimization for a macro-femto scenario, by considering interference constraints to maximize the data rate of the HetNet. To achieve this, spectrum underlay scenarios have been identified in which HetNets would be expected to operate, setting different SINR thresholds.

7 Conclusions

In this brief editorial paper we have briefly summarized the content of the papers submitted and accepted for publication in the special issue entitled "Technical advances in the design and deployment of future heterogeneous networks". Several aspects of the highest importance related to HetNets have been discussed, providing new insights to the heterogeneous networks to the whole community. Remembering that numerous problems remain still unsolved we believe that this special issue will significantly contribute to the development of this fascinating and very promising research area.

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