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Distributed joint resource and power allocation in self-organized femtocell networks: A potential game approach

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A B S T R A C T

Femtocells, which are widely deployed within a macrocell, are considered to be a novel technology that leads to the escalation of indoor coverage and capacity. However, due to lack of coordination between the femtocell and the macrocell, designing a distributive resource and power allocation is a challenging task. In this study, a potential game (PG)-theoretic approach is proposed for joint resource and power allocation (JRPA), which is demonstrated to exhibit unique Nash Equilibrium. Specifically, femto-base stations, which are considered as the players of the PG, learn the strategies in terms of resource and power allocation by taking into account the interest of other entities. To this end, the utility function of players is designed such that it minimizes the impact interference and the satisfaction for improving the femtocell capacity, without jeopardizing the macrocell performance. Precisely, the utility function incorporates all the sources of interference such as co-tier and cross-tier, and also the reward of each player in terms of capacity. The proposed PG-based JRPA is solved by employing the better response dynamics, which selects the resources and the power levels by utilizing a particle swarm optimization-constriction factor model. The performance of PG-based JRPA is analyzed in regard to average femtocell capacity and system capacity. Additionally, two different traffic cases are considered: high load traffic and low load traffic. For the sake of comparison, random allocation is employed. Simulation results are carried out in terms of the performance metrics, which includes convergence, min-max capacity, varying resource blocks, femtocell density and fairness. The results illustrate the superior performance of the proposed PG in terms of the aforementioned performance metrics.

1. Introduction

Femtocell is a novel solution that has been proposed for enhancing the coverage as well as the capacity of next generation cellular networks, specifically for indoor users. Researchers have proven that 90% of data and 60% of voice originate from the indoor environment (Manseld, 2008). Therefore, hierarchical macro/femto-cell network architecture is an appropriate choice for meeting the quality of service (QoS) requirement of indoor users. Although the conventional macro-cellular services provide coverage to the indoor users, they cannot meet their high-throughput demand due to penetration losses. In order to deal with penetration losses, two straightforward options can be adopted, such as increasing the power and reducing the transmission distance. However, the aforementioned options are not feasible in a real scenario; first, increasing the transmit power can have sever interference impact on other parties in the network and second, deploying more base stations is not a cost effective solution. Therefore, based upon the above-mentioned concerns, exploiting femtocell is a viable alternative.

Femtocell is a low power device serviced by small home base stations or femto-base stations (HBS). Another important point in this regard is that HBS can use the existing digital subscriber line, fiber optic or a dedicated wireless link for connecting to the cellular network (Chandrasekhar et al., 2008). Various other benefits from the customer and operator perspective have been identified. From the customers' perspective, high throughput, reduced power and reliable communication are achievable due to the reduced distance between femtouser (FUE) and HBS. As far as the operator point of view is concerned, femtocell helps in offloading the traffic from the macro- to the femto-network (Femtocell-based network). The words femtocell and HBS are used interchangeably throughout this study.

A hierarchical macro/femto-cell network is usually implemented in a shared rather than split spectrum environment, and this is due to the spectrum scarcity. Owing to a shared channel environment, interference is the most critical part that severely deteriorates the performance of the network. Principally, there are two major components of interference: co-tier and cross-tier (Saquib

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et al., 2012). In this study, we are considering the co-tier component comprises of interference among femtocells and macrocells, whereas the cross-tier is between femtocell and macrocell. Centralized network planning is impracticable here because of two main concerns; first, lack of coordination of femtocell with macrocells and second, random deployment of the femtocells. Therefore, it is imperative to deal with interference sources in a distributive manner. Distributive resource management is more of vital importance for an increase in number of users, which is indeed the case in future networks (Mhiri et al., 2013). This has led to the incorporation of self-organization in the current cellular network, which is of paramount significance. Various benefits can be realized in this regard such as scalability, agility and stability (Aliu et al., 2013). This concept stems from the cognitive radio that deals with the organization of the network with little or no centralized entity intervention. Dynamic resource management by exploiting the concept of self-organization is the most critical task within a femtocell network. Thus, it is natural to investigate resource and power allocation in a self-organizing manner with the concern of maximizing the average femtocell capacity without jeopardizing the macrocell capacity. The competitive interaction of HBS with resources in a self-organizing framework motivates us to explore the game-theoretic approach for the joint resource and power allocation (JRPA) in the hierarchical macro/femto-cell network. The concern of incorporating the joint strategies in the proposed potential game (PG) is owing to the increased spectral efficiency by exploiting the power allocation along with resource allocation. In addition, the interference can be managed optimally by also incorporating power allocation.

In this study, a self-organization scheme in terms of JRPA is proposed for the downlink transmission by exploiting a game-theoretic framework. The network is comprised of hierarchical macro/femto-cells with the closed group formation, in which certain users can only be connected to a HBS. Inspired by a cognitive radio technology, each HBS, which is termed as the player of game, interacts within the environment dynamically and learns the strategies in terms of resources and power levels in a distributive manner. Game theory has extensively been employed in cognitive radios for distributive resource management (Altman et al., 2006; Nie, 2005; Mustika et al., 2010). PG is employed here as the game-theoretic framework for the said joint allocation task. The concern of the implication of PG is that the convergence to a unique Nash Equilibrium (NE) is guaranteed, if the PG belongs to the class of exact PG. The utility and potential function plays a critical role in classifying a PG to be an exact PG. The utility function for the proposed PG, which has prime importance in the convergence to NE is designed in a manner that takes into account both co-tier and cross-tier interference, and also the reward in terms of capacity for each player. More precisely, the utility function quantifies the level of satisfaction the player gets while interacting with the environment. Each player aims to maximize the utility function and by doing this, interference is mitigated accordingly. In other words, inculcating all the interference sources into the utility function avoids not only the selfish nature of the players but also the convergence to NE.

1.1. Contributions

This study focuses on the JRPA in the downlink by employing a game-theoretic framework. In our proposed PG, HBSs are taken as the players of the game and learns the strategies in a distributive manner. The main contributions of our investigation are categorically defined as

1. PG is used here to model the game-theoretic framework. However, the assumption present here is that channel gains of other players are available and these are acquired on the control channels repeatedly.
2. The utility and potential function of the proposed PG is designed in a manner that the interest of each player is aligned with others in the network. Furthermore, the proposed PG is proven to be an exact PG which guarantees the convergence to unique NE.
3. Particle swarm optimization (PSO) is utilized as an optimization tool on each player which selects the best strategy for each turn of the game. Precisely, constriction factor (CF), a variant of PSO is utilized for having faster convergence.
4. The performance of the proposed PG-based JRPA is analyzed regarding average femtocells capacity and system capacity. Moreover, two difference traffic scenarios are considered: high load traffic (HLT) and low load traffic (LLT). For the sake of comparison, random allocation is used here.
5. Simulation results are computed concerning the performance metrics such as convergence, min-max capacity, impact of varying resources, effect of femtocell density and fairness.

1.2. Related work

The related work that we carried out is divided into two parts, which include the interference mitigation in femtocell networks by various approaches (Claussen et al., 2008; Chanrasekhar et al., 2009; Yun and Shin, 2011; Shahid et al., 2013; Galindo-Serrano et al., 2010) and game-theoretic approaches in cognitive radio and femtocells networks (Gabry et al., 2014; Xiao et al., 2012; Gllego et al., 2012; Nadkar et al., 2012; Xu et al., 2013; Mustika et al., 2011).

Various self-organization schemes have been proposed in the literature within the context of the femtocell environment. The authors in Claussen et al. (2008) present a power control algorithm for pilot and data channel in the Universal Mobile Telecommunication Union. In their proposition, each HBS limits the power in a manner so that average power received is equal to the one received from the closest one. They have not incorporated any spectrum sharing scheme in their investigation, which can further elevate the performance. The authors in Chanrasekhar et al. (2009) propose a utility based signal to interference and noise ratio (SINR) that reduces the cross-tier interference in a femtocell network. However, they have not catered the co-tier interference component, which is also termed as the bottle neck in performance enhancement for the shared channel environment. The authors in Yun and Shin (2011) design a self-organization based spectrum sharing framework for mitigating the co-tier interference. Moreover, they have assumed split spectrum architecture between macro- and femto-cell networks. This assumption is not appropriate considering the efficient spectrum utilization. The authors in Shahid et al. (2013) propose a self-organized heuristic approach for resource allocation and power control in femtocells networks. In their proposed framework, each HBS executes an optimization algorithm for mitigating both the sources of interference. However, the proposed scheme achieves better performance at the cost of increased information exchange among femtocells, which is generally not feasible. The authors in Galindo-Serrano et al. (2010) employ a novel docitive Q-learning concept for both cross-tier and co-tier interference minimization in femtocells networks. The docition is achieved by learning from the most experienced neighbor. However, a negative point in this regard is that in Q-learning all the strategies need to be traversed before the learning of optimal strategies.

Game-theoretic approaches have been proposed in cognitive radios and also femtocell environment. The authors in Gabry et al. (2014) investigate the secondary transmitter strategy in cognitive radio channels. The cooperation between secondary and primary