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A fully distributed algorithm for user-base station association in HetNets☆

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ABSTRACT

The dense deployment of small-cell base stations in heterogeneous networks (HetNets) requires efficient resource allocation and interference management techniques. Especially, the problem of associating users to base stations (BSs) and allocating frequency channels must be revised and carefully studied. Finding the optimal solution of such problem is NP-hard. Further, it requires huge amount of information exchange between the BSs. In order to efficiently solve this problem in a distributed manner, we model it using non-cooperative game theory. The proposed game model is proved to not always admit pure Nash equilibria (PNEs), even though simulations show that, for slow fading channels, a PNE exists for most instances of the game. It is shown that, when the game admits PNEs, its prices of anarchy and stability are close to one. By modifying the players' actions set and hence obtaining a new game model, we guarantee the existence of PNEs at the expense of performance degradation. Next, a fully distributed algorithm, based on a learning mechanism, is proposed. It requires no communication between the BSs and needs only one bit of feedback. Simulations show that the fully distributed algorithm has tight-to-optimal performance and solves efficiently the trade-off between complexity, information exchange and performance. We benchmark the proposed algorithm against the centralized optimal algorithm, the maximum signal to interference-plus-noise ratio algorithm, the best response dynamics algorithm and the randomized weighted majority algorithm.

1. Introduction

The unprecedented growth of mobile data traffic gives rise to many challenges in today's cellular networks. Hence, novel resource allocation and interference management solutions are needed to deal with this exponential growth. Cellular networks have shifted from the deployment of traditional and expensive high-power macro-cell base stations (BSs) toward the deployment of small-cell BSs (SCBSs) [2] (a small-cell may denote either a micro-, pico-, or femto-cell). Dense heterogeneous networks (HetNets), where various BSs coexist, are emerging as a key solution to the increasing demand for reliable and high speed wireless access [3]. The advantages of small-cells include low-power transmission, ease of deployment and low cost of installation and maintenance. They are widely regarded as the ideal candidate for future generations of cellular networks in order to enable better coverage, offload macro-cell traffic and achieve higher data rates [4].

In HetNets, the interference among BSs of the same kind is referred to as co-tier interference whereas the interference among different kind of BSs is referred to as cross-tier interference [5]. Though the latter interference can be managed using spectrum splitting approaches [6], the former interference is difficult to manage especially when there is no communication between distributively deployed BSs. To better manage the co-tier interference, several techniques have been introduced in the literature such as power allocation, frequency allocation, and user-BS association [3]. In this paper, we are interested in the user-BS association and the frequency allocation problem (called UBFCA hereinafter) in a HetNet. Roughly speaking, UBFCA is defined as the problem of finding an association of the users to the BSs while each user is served in one frequency channel (FC) such that its signal to interference-plus-noise ratio (SINR) is greater than a threshold value. In [7], a restricted version of the problem assuming a single FC was formulated and proved to be NP-hard. In this paper, we are interested in solving a more general version in a fully distributed manner. Hence, we propose to model UBFCA using non-cooperative game theory. We design a fully distributed algorithm that approaches the highly complex centralized optimal solution and we compare it against state-of-the-art algorithms. The proposed algorithm is fully

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distributed (or uncoupled dynamics [8]) in the sense that the BSs exchange zero information between them. Also, it needs only one bit of information feedback between the BSs and the users.

The next subsection provides the most recent related work and presents a detailed analysis for each one.

1.1. Related work

Related work can be divided into: (i) centralized solutions where the decision lies on a central coordinator [9–13] and (ii) distributed solutions where the decision is taken independently at the BSs [14–19]. An exhaustive survey on user-BS association can be found in [20].

In [9], the joint user-BS association and power control problem in HetNets is formulated where the objective is to maximize, in a centralized manner, the minimum SINR of the users subject to a power constraint at each BS. This problem is shown to be NP-hard and heuristic solutions are proposed. Anyhow, the formulated problem differs from the one tackled in this paper since we maximize the number of associated users while guaranteeing minimum quality of service (QoS) to the associated users. Reference [10] considers the problem of user-BS association and spectrum allocation in HetNets. It adopts stochastic geometry to derive the theoretical mean utility based on the coverage rate. Reference [11] solves the user association and spectrum allocation problem in HetNets while minimizing the number of active BSs. This is shown to lead to an improvement in energy efficiency. The paper also considers stochastic packet arrivals to user traffic queues and imposes a QoS requirement for the users represented in terms of delay. The authors propose a centralized re-weighted ℓ_1 minimization algorithm and study its convergence. In [12], the authors aim to improve the energy efficiency in HetNets by reducing the energy consumption and maximizing system throughput. First, to reduce the energy consumption, the authors study different energy-efficient and load-aware user association schemes. Next, to maximize the overall system throughput, the authors propose a ressource allocation scheme based on efficient reuse of macro-cell spectrum. The proposed solutions are centralized and require huge amount of information exchange. Reference [13] solves the user association in HetNets and wireless local area networks. They formulate the problem as a mixed-integer nonlinear programming problem in order to maximize the sum rate. The authors transform the complex problem to a convex one based on variable relaxation and propose a centralized heuristic algorithm to solve it. To sum up, the works presented in [9–13] propose complex procedures and centralized solutions that use high information exchange and extensive signaling.

Reference [14] solves the user-BS association based on a pricing scheme and on Lagrangian dual analysis. A dual coordinate descent method is proposed. The paper also extends the problem to the multiple-input-multiple-output (MIMO) case and optimizes the beam-forming variables. It focuses on a system model different from the one tackled in this paper and moreover, the proposed solutions are not fully distributed. In [15], the authors study the problem of bandwidth allocation and cell association in downlink massive MIMO HetNets with limited backhaul capacity. The problem is modeled as a mixed integer nonlinear programming problem. A decomposition method is applied to solve the relaxed problem. Then, based on Lagrangian dual analysis, the authors propose a distributed algorithm to solve the problem. Despite the distributed nature of their algorithm, the quantity of information exchange that it uses is proportional to the number of BSs and users. Papers [16,17] study the problem of cell association through load balancing techniques based on message passing and learning algorithms, respectively. A graphical approach is used in [16] for the message passing procedure in order to balance the load of the cells. The proposed approach uses high information exchange as the BSs and users must exchange multiple messages before convergence. In [17], the load balancing problem is solved by minimizing an alpha-fairness objective function under outage constraints. The authors model the problem using potential game theory and propose log-linear and binary-linear learning algorithms to solve the proposed game that is shown to reach pure Nash equilibria (PNEs). Reference [18] considers the user association problem in massive MIMO HetNets. The authors formulate the problem as a convex network utility maximization problem and designed a centralized sub-gradient algorithm and a decentralized online algorithm. The authors of [19] model the problem of joint user association and spectrum allocation in massive MIMO HetNets as a nonconvex combinatorial optimization problem. To deal with this complex problem, they decompose it into two subproblems. Finally, they propose an iterative distributed algorithm based on Lagrangian dual decompostion to solve each subproblem. To sum up, the works in [14–19] propose algorithms that are not fully distributed or work under different system model assumptions.

Other related work that are also worth mentioning since they investigate the application of learning algorithms in wireless networks, although they focus on other types of problems such as power allocation or link activation are presented in [21–23]. In [21], the authors formulate the link activation problem as a non-cooperative game and study its convergence to a mixed NE. The transmitter-receiver links are already established whereas the problem is to determine which links to be simultaneously activated. The same system model is considered in [22,23] where the authors designed no-regret algorithms that converge to suboptimal performance. They used the fully distributed algorithm, known as randomized weighted majority (RWM) algorithm, to solve a similar game model to ours but for the link activation problem.

1.2. Contributions

To the best of our knowledge, the available solutions in the literature either: (i) do not solve UBFCA in a fully distributed manner or (ii) focus on different problems and system models. The contributions of this paper are summarized as follow:

- We propose a non-cooperative game model for UBFCA that exhibits good performance compared to the social optimum. Unfortunately, we show that the game does not admit pure Nash equilibria (PNEs) in general. By slightly modifying the players' actions and payoffs, the game is guaranteed to admit PNEs at the expense of performance degradation.
- We adapt the well-known learning rule, *win-stay-lose-shift* (WSLS) [24]–called mWSLS for *modified* WSLS, and propose a fully distributed algorithm to solve UBFCA. Further, we present a modified version of mWSLS, called LB-mWSLS, that balances the network load between the BSs. mWSLS can be implemented in a fully distributed manner; with zero communication between the BSs (known as uncoupled dynamics). Further, it needs only one bit of information feedback from users to the BSs.
- We adapt the known best response dynamics (BRD) algorithm to solve UBFCA. We learn that even though the game does not admit PNEs in general, such scenarios are very unlikely to happen considering slow fading channel gains. In other words, the BRD algorithm converges to PNEs in most, if not all, instances of the game.
- We benchmark mWSLS against the centralized social optimum solution, the distributed BRD algorithm, the distributed maximum signal to interference-plus-noise ratio (max-SINR) algorithm [25] and randomized weighted majority (RWM) algo-