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Joint cell selection and resource allocation games with backhaul constraints

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ABSTRACT

In this work we study the problem of user association and resource allocation to maximize the proportional fairness of a wireless network with limited backhaul capacity. The optimal solution of this problem requires solving a mixed integer non-linear programming problem which generally cannot be solved in real time. We propose instead to model the problem as a potential game, which decreases dramatically the computational complexity and obtains a user association and resource allocation close to the optimal solution. Additionally, the use of a game-theoretic approach allows an efficient distribution of the computational burden among the computational resources of the network.

1. Introduction

The increasing use of wireless devices to connect to the Internet and the development of new multimedia services pose new challenges in the design of wireless networks. To meet this growing demand of wireless traffic, one promising approach both in WiFi and in cellular networks is a dense deployment of access nodes, each of them covering a small portion of space and with a high degree of overlapping coverage between them. In this scenario, an ideal backhaul with unlimited capacity for each access node is neither realistic nor efficient from a cost perspective. Instead, existing copper and fiber infrastructure or low-cost wireless technology are expected to be the base of a heterogeneous resource-constrained backhaul [1,2]. Therefore, the backhaul constraints of the access nodes must be considered as well when performing resource management in the radio access since they can be a limiting factor of the network throughput or the QoS experienced by the users of the system [3].

Additionally, in the last years there has been an increasing interest in moving part of the operation of the access nodes to a centralized computing equipment, as is the case with Cloud-RAN [4] or centralized WLAN. The aim of this approach is two-fold: first, centralizing allows reducing the cost of the radio access nodes, and second, it also enables using more advanced signal processing and resource management algorithms that are only viable in a centralized context [5,6]. Although in general these approaches require a low-latency high-capacity backhaul, using centralized solutions is also possible in heterogeneous backhaul scenarios with limited capacity [7]. In this case, the decision on the functionalities to be centralized is flexible and depends on the features of the backhaul network and the computing servers.

One of the main issues in these densely deployed scenarios is the problem of joint cell selection and radio resource management. Although these tasks have been performed typically separately, some recent works have shown that tackling them jointly can improve the network efficiency [8,9]. Nevertheless, this approach generally leads to a complex mixed

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integer non-lineal programming (MINLP) problem that can be solved exactly only for small scenarios. For more realistic scenarios, approximate algorithms must be used instead.

In this context, we propose two potential games that address the problem of joint channel assignment, power allocation and cell selection in a generic and technology-agnostic wireless network. Specifically, our goal is to maximize a modified version of the proportional fairness of the system [10], taking into account both the radio and the backhaul restrictions of the access nodes. These restrictions are imposed by the presence of interference due to spectral reuse and by the limited capacity of the backhaul expected in future dense scenarios. We assume also the presence of a cloud computing platform that allows moving part of the radio resource management functionalities from the access nodes.

Potential games [11] are a useful tool to perform distributed optimization [12,13] thanks to their intrinsic properties: convergence to a pure Nash Equilibrium (NE) is always guaranteed and these equilibria are global maximizers of the potential function defined for the game. Therefore, if we define the potential function as the network utility that we aim to maximize, we can optimize that network utility in a distributed way and achieve a solution close to the optimal one that would be obtained solving exactly the MINLP problem.

The main drawback of potential games when they are applied in a completely-distributed wireless scenario is that players usually require overall information about the remaining players of the network, making the solution not scalable. However, this limitation can be overcome with the cloud-based approach proposed in this work, since all the required information can be stored centrally and the game can be played using the computational resources of the cloud. Therefore, users only have to send to the network feedback information regarding the signal strength of the surrounding access nodes and the network itself will play the game to decide the joint cell selection and resource allocation without any further interaction with them. The procedures used to collect this feedback information depend on the specific wireless technology of the system. For instance, in WiFi it can be obtained with the exchange of Beacon Request/Report frames between stations.

Additionally, our game theoretic approach has two advantages when compared with solving directly the MINLP problem: first, its computational load is much lower, allowing a fast adaptation to changes in the network and decreasing the energy consumption to execute the algorithm, and second, it fits naturally into the distributed paradigm of cloud computing, since the players can be grouped into different virtual machines. The main contributions of our work are as follows:

1. We formally characterize the MINLP problem that arises when we try to maximize the proportional fairness of users in a wireless network. The decision variables in this problem are the serving access node, the downlink transmission power and the allocated channel. We consider that each access node has a limited backhaul capacity and a common set of channels, which causes intercell interference.
2. We propose two potential games to approximate the solution of the previous MINLP problem. In both games the potential function is defined so that the utility function of the players is completely aligned with the objective function of the MINLP problem. Additionally, we analyze the computational complexity and the convergence properties of both games.
3. We evaluate the proposed games by simulation and compare their performance with the optimal solution of the MINLP problem. This optimal solution is obtained with the branch-and-bound algorithm [14]. We also compare the proposed games with a simulated annealing algorithm in terms of performance and computational complexity. Finally, we analyze the behavior of the games in dynamic scenarios.

The remaining of the paper is organized as follows: Section 2 presents the related work. Section 3 describes the system model and the definitions of capacity that will be used. In Section 4 basic concepts of game theory are given and the proposed games are explained in detail. Section 5 presents the formal characterization of the MINLP problem that we aim to solve with the proposed games. Section 6 shows the simulation framework and the obtained results. Finally, some conclusions are provided in Section 7.

2. Related work

In this section we provide an overview of the contributions more related to our work, in particular those focused on joint resource allocation and cell selection; user association with backhaul constraints; and game-theoretic algorithms for resource allocation problems in wireless networks.

User association, channel allocation and power control are typically the most determining factors for system performance in multicell wireless networks and therefore, many works have tackled some of these problems with different performance goals. Joint power control and user association [15–17] and joint channel allocation and user association [18,19] have been thoroughly studied beforehand. However, a joint optimization of the three factors is a much less common topic [8,9]. In [8] a multiobjective optimization problem is formulated to maximize the aggregated throughput of femtocell networks. In this problem, power control, base station assignment and channel allocation are considered decision variables of a MINLP problem that is solved using the branch-and-bound algorithm. In [9] a joint cell selection and power and channel allocation is performed to optimize the max–min throughput of all the cells of a network. Since solving directly this problem is unaffordable, authors propose an alternative optimization-based algorithm which applies branch-and-bound and simulated annealing. In their scenario, access nodes use the same power to communicate with all their associated users and fairness is taken into account to perform load balancing between access points, but not to allocate individual resources to the users. On the contrary, in our work we maximize the proportional fairness of the network, introduce backhaul restrictions and allow the allocation of several channels to the same user. Although we also arrive to a MINLP problem, it cannot be solved with

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