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Joint utility-based uplink power and rate allocation in wireless networks: A non-cooperative game theoretic framework

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ABSTRACT

In this paper a novel utility-based game theoretic framework is proposed to address the problem of joint transmission power and rate allocation in the uplink of a cellular wireless network. Initially, each user is associated with a generic utility function, capable of properly expressing and representing mobile user's degree of satisfaction, in relation to the allocated system's resources for heterogeneous services with various transmission rates. Then, a Joint Utility-based uplink Power and Rate Allocation (JUPRA) game is formulated, where each user aims selfishly at maximizing his utility-based performance under the imposed physical limitations, and its unique Nash equilibrium is determined with respect to both variables, i.e. uplink transmission power and rate. The JUPRA game's convergence to its unique Nash equilibrium is proven and a distributed, iterative and low complexity algorithm for computing JUPRA game's equilibrium is introduced. The performance of the proposed approach is evaluated in detail and its superiority compared to various state of the art approaches is illustrated, while the contribution of each component of the proposed framework in its performance is quantified and analyzed.

1. Introduction

Wireless communication networks are unprecedented in their impact on the world community, industry, and individuals. Along with the number of users that daily utilize wireless networks, the consumed resources as well as the Quality of Service (QoS) performance expectations of the requested services and applications increases dramatically as well. Thus considerable research efforts have been devoted to the resource allocation problem in wireless cellular networks aiming at maximum efficiency. Among the key elements that need to be considered and controlled in such environments are users' transmission power and rate. In the literature, several approaches have been proposed that treat the power control problem separately, in order to determine the minimum feasible required power level (e.g. [1,2]), while satisfying users' QoS requirements. Among others, game theoretic approaches have emerged as promising alternatives in formulating the distributed transmission power control problem via the adoption of proper users' utility functions. Nevertheless, the independent allocation of users' transmission power does not consider the scarcity of network's bandwidth, as well as the necessity of next generation wireless networks to support multimedia services with various transmission rates and QoS requirements.

Our main objective in this paper is to provide a robust and unified methodology and framework that considers the joint treatment of transmission power and rate allocation via a game theoretic approach, by confronting the resulting optimization problem as a two-variable problem, where its energy-efficient stable outcome, i.e. Nash equilibrium, is determined simultaneously with respect to both transmission power and rate. Initially, Section 1.1 provides a comprehensive description of related state of the art work which allows us to better motivate our approach and position our work within the literature, while the key el-

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ements and contributions of our proposed approach are highlighted in Section 1.2.

1.1. Related work and motivation

Towards addressing this problem several works have attempted to consider both transmission power and rate allocation. The basic approaches that have been proposed in the recent literature are mainly the following two:

1. The joint rate and power control is approached from a game theoretic perspective, and modeled as two distinct games, i.e. an uplink transmission rate allocation and an uplink transmission power allocation problem. All users determine first their uplink transmission rate and then given their uplink transmission rate, they apply power control to allocate their uplink transmission powers.
2. The joint rate and power control problem is amended in a single-variable problem of the ratio of uplink transmission rate to the uplink transmission power.

Specifically following the first approach in [3] the authors model and solve separately and in sequential manner the problem of transmission power and rate control. The first game allocates the optimal transmission rates for all users, which in turn provides the second game with a vector of constants $\boldsymbol{c}$ to be used to evaluate the optimal transmission power levels that support the resulting Nash equilibrium transmission rates of the first game. However users' power and rate allocation at two different steps introduces high processing delay resulting in slow convergence and waste of transmission power at the corresponding signal transferring process. This burden has been eliminated in [4], where the authors examine specifically only cases of the values of users' transmission power and rate, and they conclude to a stable point where users closer to the base station benefit with respect to power and rate. In [5,6], authors have chosen to represent users' satisfaction via a specific utility function, i.e. the ratio of the reliably transmitted bits to the base station divided by their corresponding transmission power. Due to the nature of the selected utility function, the separate and sequential solution of power and rate control problems is feasible, and the solution of the joint allocation problem consists of the two individual solutions where the output of the uplink transmission rate allocation problem serves as input to the uplink transmission power allocation problem.

In brief, the main drawback of the first approach is that the optimization problem is solved asynchronously and separately considering the two system's resources, thus the combined outcome of the two distinct optimization problems is less efficient than jointly solving the problem. More specifically the inefficiency of the solutions achieved by this approach is mainly due to the following reasons: (a) the combined outcome depends on the start point of the uplink transmission power, (b) the users do not update their uplink transmission rate and power in the same step, thus inducing additive delay to the convergence of the joint problem and (c) there is no guarantee that the obtained stable point is as efficient as the one achieved if solving the actual joint uplink transmission rate and power control problem where the two resources are updated simultaneously in the same step.

Representative of the second approach is the work introduced in [7] where the same specific form of utility function as described above is adopted (i.e. the ratio of the reliably transmitted bits to the base station divided by their corresponding transmission power), which facilitates the authors to change the two-variable optimization problem to a single-variable problem, via substituting the ratio of user's transmission rate to the corresponding transmission power with a new variable, and solve the corresponding single-variable optimization problem. It is noted however that the application of this approach in realistic cases is limited and can be applied only in specific studies where simplified forms of utility functions are assumed (that is where the ratio of uplink transmission rate to power appears), and as a result its use strongly depends on the formulation of the problem. In this approach the single variable problem is solved with respect to the substituted ratio and in order to determine users' optimal pair of uplink transmission rate and power the maximum value of the one resource is assumed and the other one is determined so as the ratio is equal to the optimal determined one. Even though the users update their uplink transmission rate and power in the same step, it still remains the drawback of the inferiority of the obtained solution when compared to the corresponding one of the actual joint two-variable optimization problem as shown in this paper.

Moreover, additional efforts are reported in the literature to maximize the system throughput via either distributed resource allocation approaches such as the one in [8] where a game theoretic distributed resource allocation approach is proposed by constructing two interrelated games (a power-control game at the user-level and a throughput game at the system level), or heuristic ones as the approach in [9] where a simple heuristic rate allocation scheme which can be interpreted as a practical form of water-filling method is introduced and afterwards an iterative power control algorithm is proposed.

1.2. Paper contribution and approach

In the previously mentioned research works, even in the case where user's transmission power and rate are allocated at the same step, the stable outcome is extracted independently or semi-jointly, resulting in high transmission rates and low power consumption for users close to the base station and very low rate and maximum transmission power for the distant users. The basic characteristics, contributions and differences of our proposed approach and framework can be summarized as follows:

1. We introduce a more holistic approach in the formulation and treatment of the actual joint uplink transmission rate and power optimization problem. Specifically, instead of separately solving the uplink transmission rate and power problem or converting it to a single-variable optimization problem, under specific and restrictive assumptions, we treat the joint resource allocation problem as a two-variable problem,