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Pareto-optimal Nash equilibrium in capacity allocation game for self-managed networks

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ABSTRACT

In this paper we introduce a capacity allocation game which models the problem of maximizing network utility from the perspective of distributed noncooperative agents. Motivated by the idea of self-managed networks, in the developed framework the decision-making entities are associated with individual transmission links, deciding on the way they split capacity among concurrent flows. An efficient decentralized algorithm is given for computing a strongly Pareto-optimal strategies, constituting a pure Nash equilibrium. Subsequently, we discuss the properties of the introduced game related to the Price of Anarchy and Price of Stability. The paper is concluded with an experimental study.

1. Introduction

Modern communication networks provide universal systems of data exchange within diversified services and applications. Publicly available communication channels, maintained by Internet service providers (ISPs), are shared by very large numbers of concurrent packet flows. Each of such data transmission usually corresponds to the communication between a client application (invoked by a user) and a server application. On the global scale, users can be seen acting independently and willing to selfishly maximize their utility, reflected in their transmission speed or response delay. One distinctive characteristic of such systems is the lack of central coordination or regulation.

In the presence of limited communication resources, packet transfer protocols need to incorporate congestion avoidance functionalities. It has been shown [36] what kind of users' utility can be maximized with the use of Internet transmission control protocol (TCP) [30]. Many challenging questions arise when one seeks to design a communication network in such a way so as to optimize a given utility measure. In the last years, this line of research has stimulated many advancements in the area of distributed mathematical optimization [11]. Some of the most interesting results were obtained with the use of algorithmic game theory, which has become a method of choice for analyzing properties of distributed protocols.

In this paper we employ this approach to the analysis of distributed transmission rate control problem, formulated within the network utility maximization framework. In the majority of prior research on the network resource allocation games, usually users (clients or flow sources) were modeled as players. Motivated by the idea of self-managed (autonomic) networking, we propose an alternative formulation, in which players are associated only with transmission links. More specifically, in our model, each decision-making agent manages one outgoing router interface, connected directly to some other node. Consequently, with each node there can be associated multiple players, but their decisions correspond to disjoint subsets of flows.

It was argued that the part of network maintenance cost corresponding to human administering/operating of the system is rapidly growing, and becomes negligible in comparison to the devices' prices. It is predicted that such trend will last in the coming years [1]. Therefore, it is crucial to develop mechanisms which enable managing the network resources in an automatic or semi-automatic manner. The aim of the proposed solution is to limit the

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human administrator role only to defining the goals of system's operation. It is assumed that network routers may be considered as autonomous entities, which operate independently. Only limited coordinating communication is allowed between them.

1.1. Related Work

The idea of autonomic networking was introduced by IBM [38]. A similar concept underlies the self-organizing networks (SON) [60]. Recently, SON approach has been extensively studied for the application in 4G LTE mobile networks [29]. In [51] authors argue that some existing protocols like TCP or Open Shortest Path First (OSPF) may be treated as basic solutions for autonomic networking.

The central network resource allocation problem is the network utility maximization problem (NUM), which is also discussed in this paper. As formulated in [37], it provides the basis for further considerations. An extensive survey of the utility-based approach applied to the analysis of network resource allocation can be found in [14]. Moreover, in [35] it was shown that the NUM framework suits well for developing a self-managing mechanism for the Internet.

A survey of the most important approaches in autonomic network management may be found in [18,1]. However, it is worth noting that the most common concepts towards self-management are related to control theoretic approach [16], biological inspired mechanisms [5] and game theory [46].

Game theory is a very powerful framework for studying decision making problems, involving a group of agents acting individually, being rational and competing or cooperating to achieve certain goals [52]. It provides mathematical tools for analyzing the consequences of agents' behavior and enables developing mechanisms, which encourage them to take expected actions. Game theory has been widely studied in the context of many different applications, mostly in economics, but also in politics, biology, philosophy and computer science [45]. An introductory material on game theory may be found in [21,55].

In the recent years a subfield known as algorithmic game theory has emerged [42,57], combining game theory and algorithms design. This was mainly motivated by the need for analysis of interaction of independent agents in the Internet, in such problems as inter-domain routing, peering, online auctions, and online advertising. The problems tackled with the use of algorithmic game theory include establishing the existence of Nash equilibria, computing the Price of Anarchy and Price of Stability, and designing computationally efficient procedures for determining players' strategies. Moreover, employing the mechanism design techniques allows for constructing and analyzing computational procedures executed by collections of machines [54]. We refer to [53] as a comprehensive textbook on algorithmic game theory.

Many interesting results in algorithmic game theory applied to computer networks have been obtained in the last ten years. In [45] two TCP clients are interpreted as players in the *prisoner dilemma* game. Another game-theoretical analysis of TCP is given in [67], focusing on the Vegas version of this protocol. In [32] it is shown that the noncooperative games for flow control problems have Pareto-inefficient Nash equilibria.

In [66] the co-existence of different congestion avoidance protocols is considered. It is shown that some properties related to the NUM approach do not hold in the presence of heterogeneous congestion signals. Such a situation is explained through game theoretical framework.

The important class of games concerning allocation problems in networks (not necessarily communication networks) are congestion games [62]. Typically congestion games are applied to routing problems in computer networks, where the sources (users) are interpreted as players deciding on the selection of paths to transmit data at a given rate [24,34]. The player's strategy consists in deciding how to split this rate among all possible paths from the source to the destination, or, if flows are unsplittable, which routes to use for transmission. In [39,40] the authors propose a methodology of architecting noncooperative games for network resource allocation problem, which may improve overall system performance during provisioning and operating phase of network lifecycle. The solution is obtained for a parallel link network structure. It is shown that for such a case, the occurrence of the Braess paradox [8] may be avoided. Some of these results are extended for a general network. In [31] the congestion game for the rate allocation problem is presented. The variant of a one-link network is analyzed, and it is shown that for such case, the Price of Anarchy is no greater than 4/3. Similarly, the extension for general networks is briefly discussed.

Bottleneck games are a similar class of routing games, in which a different payoff function is used [28]. Although the Nash equilibria for such games usually exist, their performance (estimated via Price of Anarchy values) is usually poor. A game with a relatively low Price of Anarchy is proposed in [33]. In [6] two types of bottleneck games are considered, for splittable and unsplittable flows. It is also shown that for both proposed games the Price of Anarchy is unbounded. However, it is proven that under some mild conditions the Nash equilibrium is socially optimal.

Work [43] considers both congestion game and bottleneck game, in the application to the routing problem. It also proposes a new routing game specifically for the elastic flows. All three approaches are compared. Basing on one example and two real network experiments, some advantages of the introduced game are shown.

In [59] the approach to resource allocation for the networks with quality of service (QoS) based on Differentiated Services [10] architecture is proposed. The sources (flows) are players. They choose one QoS class and the transmission rate in this chosen class. The players' payoffs are proportional to the transmission rate if their QoS requirements are satisfied and zero otherwise. For the proposed noncooperative game, a simple algorithm computing Nash equilibrium is presented. The extension of this concept is given in [26].

The joint problem of QoS routing and capacity allocation problem is considered in [22]. In the proposed game, two groups of players are introduced, namely capacity players (each related to one link) and network users (each related to one pair of source and destination). Each capacity player