Games Networks Play
A Game Theoretic Approach to Networks

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Abstract

Traditional network protocols such as TCP/IP require cooperation between traffic sources to achieve optimal network performance. This approach does not always work, as evident by frequent congestion problems in the Internet. Recent research in protocol design using game theory removes this limitation by modeling traffic sources as competing players and results in efficient and fair distribution of resources. This paper provides theoretical background of the game theoretic approach as applied to networks, describes some previously proposed schemes for minimizing network congestion, elaborates on pricing mechanisms and discusses game-theoretic routing solutions. Pricing provides a feasible solution for congestion control but application of distributed algorithmic mechanism design (DAMD) can be adapted for congestion control.

1. Introduction

Optimal resource allocation is one of the most important issues in computer networks and a lot of research has been conducted to find an optimal solution. Resource allocation can broadly be divided into three areas: flow control, routing and congestion control. In this paper, we address the problem of resource allocation for congestion control. Congestion control is a set of techniques ensuring that a network performs at an acceptable level even when the demand of network resources exceeds or is near the capacity of the network. In absence of congestion control, routers drop large numbers of packets which have to be retransmitted and as a result performance of the network drops to an unacceptable level.

A number of approaches have been developed to solve the problem of network congestion, such as the pioneering work by Nagle on congestion control [2], Jacobson's Slow Start, exponential back off [3] and Random Early Detection (RED) [4]. All these techniques worked quite well in restoring confidence in networks by effective congestion control. RED in particular is a very effective technique and has gained recognition and is being implemented on most routers all along the Internet. Research in the field of congestion avoidance and control was extended through Explicit Congestion Notification (ECN) [5]. These network congestion control or avoidance techniques depend heavily on the assumption that the end user will cooperate by lowering its rate once informed of congestion through probing or explicit notification. But it is possible that a source will ignore these notifications and continues with its efforts to acquire additional network resources. It has been shown that a source adopting a selfish policy will be able to get higher throughput than its peers and is called as a rogue source [10]. Game theory provides us a framework through which we can study the behavior of the network in the presence of rogue sources.

Game Theory is a mature field in mathematics that provides a framework in which to model and analyze conflict and cooperation among independent decision makers called players [1, 6]. It analyzes decision making process when two or more players are involved. Each player has a payoff that depends on the action it takes as well as the actions of the other players. The action a player takes depends on three parameters: the strategy space which is the set of moves or strategies available to the player, the information sets which contain information about other players, and the payoff or utility function which quantifies the satisfaction a user can get from a particular outcome. In 1950 John Nash introduced a concept of solution in games, which is known as the Nash Equilibrium. Nash Equilibrium represents a state when no user can increase it utility by changing its strategy given the strategies of all other users.

Game Theory has been applied to a number of areas in computer networks such as congestion control, flow control and multicasting [1] [8] [20]. In this paper we will focus on the game theoretic approach towards congestion control. This approach looks at the network as a game whose players (or users) are the sources, routers and destinations and each player tries to maximize its payoff through its strategy set. Unlike the traditional approach where each user is assumed to be following a mandated protocol, the game theoretic approach makes no such assumption. In fact, this approach goes to the other extreme and considers all users to be selfish and acting

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only in their self-interest. Scott Shenker in his seminal paper [10] identifies the basic premises on which the game theoretic perspective is based: all users are selfish and the performance of any system is only evaluated by the amount of satisfaction that it can deliver to the users. Here the user satisfaction is directly proportional to the amount and quality of service that it gets from the system. The challenge in the game theoretic approach is to design algorithms so that the selfish motives and actions by individual users translate into desired results for the whole system.

The rest of the paper is organized as follows. Section 2 describes the theoretical aspects of game theory the game theoretic model, learning networks and mechanism. Section 3 summarizes some schemes that achieve Nash Equilibrium. Section 4 describes use of pricing techniques to control congestion. Since we believe that routing strategies relate to congestion control therefore section 5 describes application of game theoretic analysis to routing. Concluding remarks are given in section 6

2. Theoretical Aspects of Game Theory in Networks

2.1. The Game Theoretic Model of a Network

The game theoretic model of a network considers n users with some private information. This private information can be its throughput, drop rate, or average delay of packets. The user selects a strategy from its set of possible strategies so that it can increase its gain from the system. The gain also, called the user utility, is known only to the user. The utility of a user determines a user's preferences over its own strategies. Since a user's gain depends upon the strategies adopted by all other users, therefore a user does not attain a utility maximizing strategy immediately. Instead, all users change their strategy until a stable operating point is reached. This equilibrium point for the network is known as the Nash Equilibrium and represents a state where no user can gain by changing its strategy given the strategies of all other users.

A system can achieve multiple Nash Equilibrium points with distinctive properties, there can even be an equilibrium point where no user is gaining any benefit at all. Hence achieving Nash Equilibrium alone is not desirable and only Nash Equilibrium points with certain valuable properties such as efficiency and fairness are desirable [10]. Efficient Nash Equilibrium means that an equilibrium point should produce good results in terms of the user's utility function. Another desirable property at Nash Equilibrium is that the benefit gained from the system should be more or less equal for all users. Since a network is not always at equilibrium, a better criterion for fairness would be that as long as a user is able to increase its utility, the system would be considered as fair.

A system should attain Nash Equilibrium as quickly as possible. Convergence is achieved by users selecting the best possible strategy, based upon the utility from the previous strategy. However this is a simplified model of the system since there can be a user who is relatively more informed, e.g., it can have information about the other user's utility functions, in which case the informed user can influence equilibrium achieved by the system and becomes a leader while the other users follow him. The equilibrium reached in such situations is called as the Stackelberg Equilibrium. Stackelberg equilibrium is not desirable from system's fairness point of view since the utility of the leader in Stackelberg equilibrium is never less than its corresponding Nash equilibrium and the leader can affect the equilibrium point finally attained. Therefore a mechanism should ensure that the Stackelberg equilibrium and Nash equilibrium coincides so that less sophisticated users can be protected from the informed users.

Another requirement is that the convergence to Nash Equilibrium should be robust, which means that as long as the users apply some kind of self-optimizing techniques Nash equilibrium will be finally reached. Self Optimizing techniques are the means by which users increase their utility by observing their utility and changing their strategy accordingly. It was proved by Shenker [10] that convergence could only be robust if there is a unique Nash equilibrium. Moreover, in case of multiple Nash equilibrium points users can get involved in super games, where the players try to influence the Nash equilibrium that the system ultimately achieves. Another option discussed in [12] is to eliminate self-optimization altogether by letting the users directly report their utility functions to the switch, which allocates resources to the users according to the reported utilities. The problem here is that the users would be motivated to lie about their true utilities in order to gain more resources and the challenge is to design mechanisms that encourage truth revelations, such mechanisms are called Revelation Mechanisms. Revelation mechanisms work by ensuring that the benefit gained by lying is always less than the benefit a player would have gained by telling the truth.

2.2. Learning in Networks

Shenker argues that classical game theory cannot be directly applied to networks for various reasons [17. The first reason is that users have very limited information; they don't know the number of other users, their own and other player's payoff functions. Secondly, in the network game, the payoff function and the number of users change over time, hence a change in performance can be due to

strategy change of another user or change in underlying network properties. Moreover, it is also impossible to synchronize the activities of the different users on the Internet due to its geographical spread.
Shenker introduced the idea of learning algorithms [17] where a user acts in a manner which is probabilistically most profitable in the current scenario, by considering a constantly updated history of the strategies and their results. In such algorithms, the user can use random experiments to quickly find the optimum and must be responsive to the constantly changing environment.

2.3. Mechanism Design

Algorithmic Mechanism Design (AMD) intends to design systems in which agent's selfish behavior results in system wide goals [7]. The system wide goals are quantified as the Social Choice Function (SCF), which maps the instantiation of agents into the particular outcome from a universal space of outcomes. Direct Mechanisms ask agents to reveal their utility function and hence achieve desired social goals. The SCF in such a case is called strategy proof. In contrast agents in indirect mechanisms don't have to reveal their utility functions and select a strategy from a strategy space. These mechanisms act in a way that no agent has any incentive to change behavior unilaterally.
Since centralized mechanisms cannot be implemented in the Internet, therefore Distributed Algorithmic Mechanism Design (DAMD) [7] attempts to design mechanisms where the adversarial behavior can be detected without any modifications to the protocol in a distributed fashion. AMD and DAMD both have been successfully applied to problems like task allocation and BGP-based Low Cost Routing. We believe that these techniques can also be applied to congestion control.

3. Congestion Control Schemes

3.1. CHOKE+ Scheme

Akella, Seeshan, et.al modeled the TCP as a game [8]. In a TCP based system, a user starts its transmission with a predefined input rate, which is increased by an additive increase parameter (α) as long as congestion is not detected. When congestion is detected, the rate is decreased by a parameter known as the multiplicative decrease (β). The authors analyzed the efficiency of Nash equilibrium on three variants of TCP by varying the values of α and β separately and simultaneously.
Three different TCP implementations Reno, SACK and Tahoe were evaluated on routers employing either drop tail or RED policy, these schemes are primarily different with respect to their penalty schemes. TCP-Tahoe implements a severe penalty scheme, where transmission is stopped when congestion is detected. TCP-SACK uses a gentler scheme so that the penalty is directly proportional to the loss. A hybrid penalty scheme is implemented in TCP-Reno where the penalty is gentle until a specific threshold after which the severe penalty is imposed.
It was previously shown that the Nash Equilibrium point is efficient only in the case of TCP-Reno, [8]. It is still unfair since it results in additive increase and additive decrease. The most important result is that RED does not prohibit aggressive users, because the probability of packet dropping is uniform for all users. FIFO-drop tail is effective in prohibiting aggressive behavior because the number of packets dropped for a source is directly proportional to its bandwidth. Since FIFO-Drop Tail routers are not exclusively used these days and because RED is widely deployed along with TCP-SACK, the authors conclude that there is need for a preferential drop mechanism to effectively manage congestion.
CHOKE (CHOose and KEep) is a simple mechanism with preferential drop policy [9]. The authors in [8] suggest an extension, CHOKe+, which works according to the following algorithm.

Pick k packets at random from queue

Let m be #packets from the same flow as P

Let $0 <= \gamma 2 < \gamma 1 <= 1$ be constants that indicate the ratio limits between which the packets are dropped or kept.

If
$m > \gamma 1k$, P and the m packets are dropped
Else
if $\gamma 2k <= m < \gamma 1k$, drop P and the m packets only if RED were to drop P.
Else
just drop P according to RED.

Performance results of CHOKe+ with TCP-SACK are very encouraging because efficient Nash equilibrium is attained, aggressive behavior is unattractive at Nash equilibrium, it has a low loss rate and high utility.

3.2. VLRED & EN-AQM

D. Dutta, et. al. [1] studied active queue management (AQM) schemes employed in routers to manage the input queues from overflowing. These schemes are divided into two categories : stateful e.g. Fair Queuing and oblivious

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like RED and FIFO-Drop. Stateful schemes consider the flow of a packet before dropping it while the oblivious schemes don't. Generally, stateful schemes perform better but difficult to deploy compared to the oblivious schemes [1].

The Markovian Internet game [1] comprises players who are end-point selfish users. The rules of the game are determined by the AQM schemes deployed at the routers. An oblivious router has a drop probability p due to an average aggregate load of λ and an average service time of t. A symmetric Nash Equilibrium, if imposed, is when all the users have the same utility function at equilibrium. Drop tail and RED routers do not attain a Nash Equilibrium point because it punishes all flows with the same probability and hence a source has no incentive to behave fairly.

VLRED is a variant of RED that uses a virtual infinite length queue with a drop probability proportional to the queue length, making it more punishing for flows with high rates. It is proved in [1] that VLRED attains Nash Equilibrium but its utility function asymptotically falls to 0. The authors argue that the drop probability of VLRED is a bit too harsh and introduced EN-AQM [1] which ensures the existence of an efficient Nash equilibrium. The drop probability at Nash Equilibrium for average aggregate load (λ) is given by:

$$p = 1 - \frac{1}{3}\sqrt{\frac{1+\sqrt{1-\lambda}}{1-\sqrt{1-\lambda}}} \tag{1}$$

This enforces a bound on the throughput and goodput. The offered load increases but the utility function becomes fairly constant. The only problem with EN-AQM is that its equilibrium point is sensitive to the number of users making it difficult to deploy.

3.3. Diminishing Weight Scheduling

Garg, Karma and Khurana introduce the idea of Diminishing Weight Schedulers (DWS) in [13], which handles congestion control in the presence of selfish users. The basic premise behind DWS is that cutting down the rates of users trying to send data at an unfair rate would encourage well-behaved users. The authors mainly focused on one particular class of DWS called the Rate Inverse Scheduling (RIS), where the diminishing weight function is the inverse of the input rate, so that the more a particular flow tries to grab extra bandwidth the more its input rate reduced.

There are several desirable properties of DWS such as a unique max-min fair rate such that the users attain Nash Equilibrium as well as Stackelberg equilibrium. More importantly, it is proved in [13] that when DWS is deployed even the selfish users would try to estimate their max-min fair rate and send data at this rate.

4. Pricing

A number of researchers have attempted to control congestion by adopting the idea of pricing from economics where the end users are encouraged to avoid congestion by charging them for their contribution to congestion; the price a user has to pay for its share in congestion is called congestion pricing. The network is modeled as an economy by charging the users on the bandwidth they use and the price of the bandwidth is set to reflect the current supply and demand situation.

4.1. Distributed Pricing Scheme

The pricing scheme introduced by Fulp in [19] considers routers as the owners of the resources. Since there are multiple routers in a network, hence there are multiple economies in a single network. Each router has multiple microeconomics for each output port and it sets the prices for each output port based on the current supply and demand situation. This way we have a decentralized economy and a failure at a single point does not affect the whole network.

Time is divided into intervals and the price for the current time interval is based on the demand for bandwidth in the previous time interval and its price in the previous interval. It is ensured that prices fall gradually so that a sudden increase in new buyers can be avoided in case a user with a large portion of the bandwidth quits. There is a network broker, logically located between the edge of the network and the user controls user admission to the network. Since it is possible that users may not be able to purchase the desired bandwidth due to their limited wealth, therefore users are only allowed to buy bandwidth if they can maintain a minimum quality of service with the purchased bandwidth. Simulation results show that this scheme is able to provide 95% utilization of the network and better QoS than min max for a network with large number of users.

4.2. Paris Metro Pricing

The Paris Metro Pricing (PMP) scheme [18] advocates that computer network should be divided into multiple logical networks where each logical network has the same bandwidth but different prices for transmitting data on it. It should be noted that PMP does not guarantee a particular QoS, it works on best effort basis, but unlike traditional networks, high end PMP sub networks would have fewer users and hence a higher expected QoS. PMP can be implemented by utilizing the three unused priority bits in the IP datagram header. This way packet with higher priority would always be treated before lower priority packets at the routers.

4.3. Progressive Second Price Auction Mechanism

Internet is susceptible to fast depletion of resources in event of massive usage because of the Internet's practice of pricing by physical capacity instead of charging according to actual resource utilization. Progressive Second Price (PSP) [16] tries to solve this problem by allocation of network resources through a second best price auction. In a second best auction the winning bidder has the highest bid but pays the amount of the second highest bid. In case of Progressive Second Price the auction is held to sell network resources. Since it is based on dominant strategy principle it ensures that the bidders express their true valuations of the auctioned item. The computational complexity of implementing this is $O(N^2)$ where N is the number of users and hence it proves to be a practical mechanism. It also attains a Nash Equilibrium under the assumption that the users bid according to their valuation of the resource they are demanding [16].

5. Game Theory in Routing

The game theoretic model for routing assumes source routing, where the route for the packets is decided by the source. Source routing is not generally used but it is achievable through the source routing option in IPv4 and IPv6. Routing is very closely connected to congestion control, because an end host may have multiple paths to its destination, each path having different levels of traffic. Therefore if a source selects a path which is already overloaded it will not only delay the delivery of its traffic but also may also cause congestion in the network.

There are two types of source routing: selfish routing where each user decides the route to be taken by only considering its own benefit and coordinated routing where the routes for all the users is decided so that maximum social benefit can be attained. Since we have already seen that a user can easily decide not to follow an agreed protocol therefore Roughgarden assumes selfish routing and quantifies its performance degradation against coordinated routing and showed that the latency of traffic, at Nash equilibrium in selfish routing in M/M/1 queues, is at most half the latency experienced by coordinated routing between the same source destination pairs [15].

5.1. Achieving Network Optima

The goal of a successful mechanism is to engineer a game so that the Nash equilibrium achieved is always optimal. Different strategies can be used for this purpose i.e. pricing [18, 19] or design of service disciplines [8, 13]. The requirement of a priori decision is common among these strategies. Lazar et.al .discusses in [14] a scheme where the optimal equilibrium point is achieved during the operation of the network. Their approach aims at optimizing the routing decisions of a network such that the delay is minimized.

Lazar's model identifies two entities : the non-cooperative users who shares a number of parallel links and aim to efficiently route their own traffic to a common destination., and the other entity is called as the manager, which has the ability to monitor non-cooperative behavior of the users and its goal is to optimize the overall network performance. The manager is able to predict the responses of the users and it selects a strategy such that the overall network performance is optimized. The Manager becomes a leader and the other users become its followers, hence the leader fixes a routing strategy that is optimal for the network and the followers converge to it. As discussed in section 2, an equilibrium attained in this fashion is called as the Stackelberg equilibrium, which is a special case of Nash Equilibrium.

The routing strategy of the manager is fixed as long as the routing strategies of the non-cooperative users don't change. Furthermore the non-cooperative users adjust their routing strategies according to the strategies of the other users and the manager in order to minimize their cost. The authors in [14] prove that the Nash equilibrium thus attained is always unique. It must be noted here that Shenker in [10] claims that a Stackelberg equilibrium is not desirable since the super user can induce an equilibrium point that it desires, but here the Manager plays a social role hence it is not only acceptable but also desirable.

6. Conclusions

Algorithmic Mechanism Design revolves around designing algorithms using game theoretic principles, which ensure that Nash Equilibrium is attained, i.e., the containment of selfish behavior. Distributed Algorithmic Mechanism Design (DAMD) is promising because it realizes the distributed character of the Internet. Unfortunately, DAMD's implementations are hindered by extremely high computational complexities [7]. CHOKE+, VLRED, EN-AQM and diminishing weight scheduling schemes are presented to show the practicability of implementing the game theoretic model to congestion control. These schemes, though successful, are sensitive to number of users. Future work must focus on developing schemes which possess these qualities. Congestion control through pricing exploits the self

regulating property of open markets. The distributed pricing scheme considers each router as an independent market. In Paris Metro Pricing multiple sub networks are created that offer bandwidth at different rates and the expected QoS at the expensive sub network is high. The Progressive Second Price scheme conducts an auction for the allocation of bandwidth among the users; the bandwidth is allocated to the highest bidder but at the price of the second highest bid. On the whole pricing shows greater promise than any other game theoretic model although it also faces implementation difficulties such as determination of consumer's pricing preferences and change in consumer's mindset from time based pricing to bandwidth based pricing.
Routing strategies were reviewed from the game theoretic point of view. First we look at the price of selfish routing and found that the ratio of price of routing traffic in a selfish manner to that of centralized routing is 4/3. Then we show that a network can attain optimum routing in the presence of a leader that leads the system to an efficient Nash Equilibrium. Routing has direct impact on the network's congestion. We infer that using game theoretic routing mechanisms along with game theoretic congestion policies will yield better results. For instance Leader Follower Model in which both mechanisms can rely on one leader.

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