The Tragedy of the Internet Routing Commons

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***Abstract*—Over the last years, the research community has been deeply concerned about the scalability issues that the Internet routing is facing. In this paper we study the economic incentives for the Global Routing Table (GRT) explosive growth by considering a commons model in which the GRT is a public resource. In particular, we analyze the motivations the Autonomous Systems (ASes) have for deaggregating their assigned address blocks. We evaluate the efficiency of the global routing system, the properties of the game equilibria and we examine its relation to the optimal social welfare point of the considered game setup. We prove that the GRT, just like any common natural resource, "remorselessly generates tragedy", following Hardin's game theoretic analysis on the *tragedy of the commons*. Finally, we introduce in the model a payment mechanism that aims to avoid the tragedy of the Internet routing commons.**

***Index Terms*—Network Modeling, BGP, Game Theory, Traffic Economics, Traffic Engineering**

I. Introduction

The Internet community has been facing important challenges concerning the scalability of the global routing system [1], [2], [3]. The interdomain routing relies on the Border Gateway Protocol (BGP) to exchange reachability information between the Autonomous Systems (ASes). All the routing information is stored in the *Global Routing Table* (GRT). Thus, routers are permanently involved in a constant exchange of network prefixes and other routing information to keep every router informed on how to reach hundreds of thousands of other networks on the Internet.

It has been argued that the computation power and memory requirements for a router that could sustain the growing Internet can be met in light of the advances being made in multi-core processor design and large memories [4]. However, even if the technology can cope with the scalability challenges, the necessary periodic upgrades resulting from the dramatic increase of the routing table may significantly increase Internet operator's expenditures on new equipment, challenging the economic viability of the Internet as we know it.

The rapid size amplification of the GRT can be partially explained as a result of the increasing popularity of the Internet and, consequently, of the large number of new users that attach to it [5]. Even if this is certainly true, the growth due to the augmentation in number of reachable networks is not the only cause for the BGP routing table expansion [2]. There are different other factors that triggered this rapid growth, like multi-homing and traffic engineering [3].

Evidently, the increased number of prefix allocations partially explains the growth of the Global Routing Table. However, a single address space allocation may translate in multiple routing table entries in the GRT as a result of *address space fragmentation*. Therefore, when a new block is allocated by an Internet Registry, this prefix may be broken into several smaller prefixes that are then announced in the Internet, inducing a faster growth rate of the GRT than the rate with which the new address blocks are being allocated.

This process is commonly known as *deaggregation*. Such behaviour is not without controversy, as it acts counter to the goals of the current Classless Inter Domain Routing (CIDR) architecture, which encourages aggressive address aggregation [6]. However, the *benefits of deaggregation* can be quantified in terms of traffic engineering capabilities or level of network security. Deaggregation proponents claim that this provides a very effective and fine-grained method of performing the traffic engineering much needed in the current Internet. By increasing the granularity of the advertisements through the use of variable prefix lengths, the Internet Service Providers (ISPs) achieve a better control of the distribution of their traffic over transit links. Certain networks may choose to announce more-specific prefixes than the ones allocated with the purpose of increasing their security. In particular, the ASes sourcing deaggregated prefixes protect the network from prefix hijacking or other types of malicious attacks. The technical reasons for which the networks are using these more-specific prefixes have been studied in more detail in [1], [2].

It has been shown that, in theory, the current BGP routing tables size can be reduced by a factor of more than 2 if the more specific prefixes could be integrated in the already existing covering routing entries [1], [5]. Therefore, by announcing these more specific prefixes, the ASes are contributing to the explosive inflation of the GRT. The resulting additional cost generated by this type of behaviour is described as a *negative externality*. Generally, a negative externality is the additional cost that the behaviour of a single agent may bring to the other agents, without any voluntary agreement between the two that would allow for a negotiation of the distribution of these costs.

The size of the routing table is a negative externality because when a network is deaggregating it obtains a benefit which is far greater than the cost this operation incurs and it does not consider the additional cost it brings to the other networks. In other words, ASes deaggregate on the expense of all the members of the Default-Free Zone.

This problem has been described as a *tragedy of the commons* [7] in [3], [6]. In this paper we propose a game theoretic model of the Internet that aims to study the dynamics of the interaction between ASes in the Internet and to evaluate to which extent the Internet public resources generate tragedy.

In Section II we consider a *commons model* in which the ASes sharing the same BGP routing space have to make the choice of deaggregating or not the assigned address blocks. One important result of our analysis is that the economic incentive for the ASes in the interdomain is to engage a detrimental behaviour of heavily deaggregating their prefixes, thus leading to a *tragedy of the commons*.

In Section III we study the properties of the *game equilibria* and we examine its relation to the *optimal social welfare* point of the considered game setup.

Finally, we try to evaluate one of the possible techniques of avoiding the tragedy of the commons and of bringing the equilibrium point closer to the social optimum in Section IV. We propose a pricing mechanism to internalize the additional costs. We conclude the paper in Section V.

II. THE GAME THEORETIC MODEL

Since the seminal article by Hardin [7], *"The Tragedy of the Commons"* has been used to model the problems of overuse and degradation of resources, with a wide range of applications. According to Hardin [7], a tragedy of the commons occurs when a group of entities abuses a common resource, thus harming the other individuals with whom it shares this resource and themselves. In the paper the author argues that any common natural resource "remorselessly generates tragedy", since the gain an individual user receives from increasing its consumption from the common outweighs its own cost and all the users of the resource will evenly pay for this.

The game theoretic model presented in this paper is based on the previous analysis of the tragedy of the commons made in [8]. In real life settings, the games played are typically quite complex and have large strategy spaces that are not specified beforehand. Here we present a simplified model of the interdomain routing commons problem. We consider a number of N ASes in the interdomain, interconnected to form the Internet as we know it. For simplifying purposes, we assume that each AS is represented by a single router.

We analyze a symmetric one-shot complete-information game. The players are the N ASes that have to simultaneously decide the number of prefixes to announce in the Internet. A strategy for a player i is the number of prefixes it originates in the interdomain, p_i. We assume that the strategy space is $[0, \infty)$ to cover all the possible choices that could be of interest to the AS. We model the hardware constraints imposed by the routing equipment developers by assuming that P_{max} is the maximum number of prefixes that can be fitted in the memory of the largest capacity state-of-the-art router on the market. Although this highlights the technological limitations, it does not impose any restriction on the strategy space. Considering the game setup presented above, we propose the following expression for the payoff each player i receives from announcing p_i prefixes, given that the other players are announcing $(p_1, p_2, ...p_{i-1}, p_{i+1}, ...p_N)$ prefixes is:

$$u_i(p_i, p_{-i}) = p_i v(P) - c \min\{P_{max}, P\}, \qquad (1)$$

where p_{-i} is the vector of strategies chosen by all the other players but player i, $P = p_1+p_2+...+p_{i-1}+p_i+p_{i+1}+...+p_N$ is the total number of announced prefixes in the Internet, P_{max} is the maximum number of prefixes that can be stored in a router in the interdomain, c denotes the cost incurred by an AS storing one prefix and, finally, $v(P)$ denotes the value each AS receives each prefix announced. We explain all these concepts in more detail next.

The utility function is the difference between the total gain that an AS receives from announcing p_i prefixes ($p_i v(P)$) in the interdomain and the cost for storing all the announced routing information up to the maximum permitted limit ($c \min\{P_{max}, P\}$).

In this model, we consider that the *Global Routing Table* is a *finite common resource*. There is a direct dependency between the size of the GRT and the *router memory size*. Assuming that each routing entry needs the same amount of memory in order to be stored in the routing table, we consider that every prefix has assigned an individual memory slot in the routing equipment. The cost each AS has to pay for storing a prefix is the price of this memory slot, c.

We assume that every AS stores all the routes and upgrades its routing equipment until the maximum capacity of the routers is reached. The limitation in router memory capacity is reflected in the payoff function for each AS i by the term $c \min\{P, P_{max}\}$, i.e. the total routing cost. We assume that when the total number of announced prefixes is higher than the maximum number of possible entries in the GRT, the ASes start randomly discarding prefixes.

By $v(P)$ we denote the value each AS receives from announcing one prefix in the interdomain. The total benefit each AS receives is equal to $p_i v(P)$. The value function $v(P)$ is chosen so that it captures the incentives that players have to deaggreagate and also the consequences of choosing an inefficient strategy (the number p_i of prefixes is too high and some of the announced prefixes cannot be stored in the GRT).

Formally, for $P < P_{max}$, $v(P) = const.$ and for $P > P_{max}, v'(P) < 0$ and $v''(P) < 0$. An example of such a function is depicted in fig. 1.

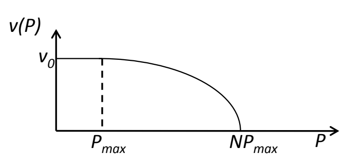

Fig. 1. The generic shape of the value function

As we can see in fig. 1, when the total number of routing entries P is lower than P_{max}, the value per prefix is constant, every router receiving the same benefit from announcing one more prefix in the Internet (v_0). Therefore, while below this threshold, announcing one more prefix in the Internet does not affect the received per prefix value, imposing only the additional cost of storing that new routing entry.

When the number of the entries in the GRT grows to more than the maximum supported by the existent memory capacity then the ASes are randomly discarding prefixes from their routing tables. Thus, certain destinations are not reachable by some of the ASes, thus modifying the value that the agents expected to receive. This physical limitation is reflected in the value function $v(P)$: when $P > P_{max}$, the decrease in value is notable. We assume that this is the only factor that is influencing the benefit received per announced prefix.

When the number of prefixes announced by each of the N ASes in the Internet is equal P_{max} (thus, the total number of prefixes in the Internet being $P = NP_{max}$), the value received per prefix is zero, as the ASes will use their entire capacity only to store their own announced prefixes and, consequently, no network would be able to reach any other one in the Internet.

III. Game Equilibria and Overall Optimality

In this section we analyze the equilibria properties of the interdomain routing game. We focus on the relation between the *Nash Equilibrium* of the game and the *Optimal Social Welfare* point.

A. Game Equilibria

We consider $(p_1^*, p_2^*, ...p_i^*, ...p_N^*)$ to be the Nash Equilibrium strategy profile of the routing game. Thus, every p_i^* is maximizing the individual payoff $u_i(p_i, p_{-i})$ for each player i in the game, given that the other players choose $p_{-i}^* = (p_1^*, p_2^*, ...p_{i-1}^*, p_{i+1}^*...p_N^*)$:

$$\max_{p_i} u_i(p_i, p_{-i}^*) = \max_{p_i} \{p_i v(P) - c \min\{P_{max}, P\}\} \quad (2)$$

In order to find the p_i value that solves the above-mentioned equation, we first consider the strategy profile of the game so that the total number of prefixes in the Internet is below the maximum router capacity. When $P < P_{max}$, the cost for the routing equipment is depending of the total number of prefixes announced in the Internet. The maximum available capacity of the routers is not reached, so announcing one more prefix will not have any negative impact on the per prefix value and it will only incur the extra cost of upgrading the routing equipment. Moreover, the value function is constant: $v(P) = v_0$. Therefore, the payoff function has the following form:

$$u_i(p_i, p_{-i}) = p_i v_0 - cP, \quad (3)$$

The first order condition for the optimization problem is:

$$v_0 - c = 0. \quad (4)$$

Thus, we have to consider now the relation between the cost of memorizing a prefix and the value per announced prefix. If the cost of a memory slot c is higher than the value received per announced prefix v_0, then the ASes have no economic incentive for announcing prefixes in the Internet. Hence, we practically have no routing operation in the interdomain. Therefore, this case does not present interest for our analysis.

However, when the cost of a memory slot c is below the value received per announced prefix v_0, the ASes have no incentive to stop announcing more specific prefixes. Therefore, they will keep deaggregating the assigned address blocks, as they will always receive a positive benefit ($v_0 - c > 0$). The lack of incentives for the ASes to reduce their deaggregating behaviour eventually leads to using the entire available capacity of the routers. Therefore, assuming that the ASes are greedy economic entities whose only purpose is to increase their benefits, we can easily conclude that the equilibrium point of the considered game is not a strategy profile that verifies $P < P_{max}$. Hence, we search next for the equilibrium profile strategy when $P \geq P_{max}$.

We are relying our analysis on the assumption that every AS is willing to pay for upgrading its routing equipment up to the maximum limit. All the ASes are paying for the highest capacity router, thus the equipment expenditure is the same for all of the players in the game. This is reflected in the payoff function by the presence of the cP_{max} factor.

The inefficient exploitation of the router memory is captured in the value each network receives from announcing a prefix in the Internet. When the total number of prefixes P exceeds the maximum admitted number of memory cards in the router P_{max}, the value per announced prefix is not constant anymore, as the ASes start randomly discarding prefixes from the routing table. As a result, the benefit for those particular networks decreases. Therefore, the value function considered when $P \geq P_{max}$ is a fast decreasing function, as shown in fig. 1. Consequently, the payoff function has the following particular expression:

$$u_i(p_i, p_{-i}) = p_i v(P) - cP_{max}. \quad (5)$$

In this case, the first order condition for the optimization problem corresponding to the Nash equilibrium, when all the other players choose the equilibrium strategies $p_{-i}^* = (p_1^*, p_2^*, ...p_{i-1}^*, p_{i+1}^*...p_N^*)$ is:

$$\frac{du_i(p_i, p_{-i}^*)}{dp_i} = 0 \Rightarrow v(p_i + P_{-i}^*) + p_i v'(p_i + P_{-i}^*) = 0, \quad (6)$$

where $P_{-i}^* = \sum_{j \neq i} p_j^*$. Substituting p_i^* into (6), summing over all the N ASes and dividing by N outputs

$$v(P^*) + \frac{P^*}{N} v'(P^*) = 0. \quad (7)$$

Due to the symmetry of the game, we can conclude that the Nash equilibrium number of prefixes each AS i is originating in the Internet is the same for all the players, i.e. $p_i^* = \frac{P^*}{N}, \forall i$. Therefore, the equilibrium point of the game will be reached when the total number of announced prefixes is equal to the value P^* that satisfies equation (7). In other words, an AS will stop announcing prefixes in the interdomain (and, thus, reach an equilibrium point) when the value received from originating one prefix would be equal to the harm done only to its own already stored prefixes, i.e. $p_i^* v'(P^*)$.

B. Social Optimality

In this section we analyze the properties of the social welfare strategy profile and its relation with the equilibrium strategy profile. In contrast with the Nash Equilibrium, the Optimal Social Welfare strategy profile, denoted by $(p_1^{**}, p_2^{**}, ...p_i^{**}, ...p_N^{**})$, maximizes the sum of payoffs. When the number of announced prefixes in the Internet is lower than the maximum limit ($P < P_{max}$), substituting the expression for $u_i(p_i, p_{-i})$ with the expression from (3) outputs:

$$\max_{P \geq 0} \{Pv(P) - NPc\}. \tag{8}$$

As the value function is constant for $P < P_{max}$, similar to case of determining the Nash equilibrium, the strategy chosen by the players depends on the ratio between the per prefix value and the cost implied by storing a new routing entry in all the routers in the Internet. If the benefit received for announcing one more prefix is lower than the cost incurred ($v_0 < NC$), then the ASes have no incentive to announce prefixes in the Internet. Otherwise, the players will announce all that they can, thus reaching the maximum capacity of the routing equipments. Therefore, we can easily conclude that the overall optimum is not reached when the total number of announced prefixes is strictly below the maximum limit.

When the number of announced prefixes exceeds the maximum router capacity ($P \geq P_{max}$), the first order condition for the optimization problem corresponding to determining the Social Welfare strategy profile has the following expression:

$$\frac{d}{dp}\{Pv(P) - NP_{max}c\} = 0 \Rightarrow v(P) + Pv'(P) = 0. \tag{9}$$

Substituting the Optimal Social Welfare strategies in (9) we obtain

$$v(P^{**}) + P^{**}v'(P^{**}) = 0, \tag{10}$$

where $P^{**} = \sum_i p_i^{**}$. Therefore, in (10) we can see that an AS will stop announcing more prefixes when the value per prefix is equal to the harm done to *all* the prefixes announced in the Internet by all the ASes, i.e. $-P^{**}v'(P^{**})$.

Due to the fact that ASes are modeled as rational agents, it is not in their benefit to consider the harm that their strategies are doing to the other players in the game. For this reason, the strategies chosen by the players in the equilibrium point lead to an inefficient equilibrium, that do not coincide with the social optimum strategy profile.

C. Evaluation of the Model

The main concept of rational behaviour, the Nash equilibria, is known not to always optimize the social outcome. It should be noted that the payoff each player receives in the Nash equilibrium is *lower* than the social optimum payoff, underlying the inefficient consumption of the common resource. Given the game setup presented in section II, we evaluate which is the ratio between the the overall optimum and the Nash equilibrium of the game.

As reflected in the first order condition from (6), the incentive for an AS in the Nash equilibrium point is to announce one more prefix considering only the harm caused to its own already announced routing information. The common resource, i.e. the router memory, is over-utilized because each player is rational and is only considering its own benefits and costs. Hence, in (7) we have the value of $\frac{P^*}{N}v'(P^*)$ in opposition with $P^{**}v'(P^{**})$ in (10).

Moreover, comparing (7) with (10) we can easily prove[1] that the number of prefixes announced in the Nash equilibrium is strictly higher than the total number of prefixes announced in the social optimum:

$$P^* > P^{**}. \tag{11}$$

Next, for the particular case of a value function $v(P) = a - P^2$, where $a = const.$, we analyze the ratio between the values for the total number of prefixes at the equilibrium point and at the social optimum when $P \geq P_{max}$. It can be easily checked that this particular expression of value function complies with the set of rules imposed on the value function defined in the game setup. Thus, since the particular expression of the value function must verify $v(NP_{max}) = 0$, we can express parameter a as $a = N^2P_{max}^2$.

Following the Nash equilibrium analysis in III-A and the optimal social welfare analysis in III-B, we obtain the undermentioned values for the total number of prefixes in each case:

$$(P^*)^2 = \frac{aN}{N+2}; \quad (P^{**})^2 = \frac{a}{3}. \tag{12}$$

Therefore, the ratio between the total number of prefixes in the social optimum (P^{**}) and in the equilibrium (P^*) is

$$\left(\frac{P^{**}}{P^*}\right)^2 = \frac{1}{3}\left(1 + \frac{2}{N}\right) \Rightarrow \frac{P^{**}}{P^*} \approx \sqrt{\frac{1}{3}}. \tag{13}$$

Both the Nash equilibrium and the overall optimum strategy profiles result in a total number of prefixes which exceeds the maximum limit. Consequently, all the ASes are paying the same routing cost, cP_{max}.

As a measure of the global routing system efficiency, we evaluate in this section the price of uncoordinated utility-maximizing decision between the players (or the lack of a central authority who could impose a fair cooperative solution), also known as *the price of anarchy* [9]. The *price of anarchy* (PoA) is defined as the ratio between the optimal "centralized solution" value of the total benefit ($p_i^{**}v(P^{**})$) and the worse equilibria value of the total benefit for a single player ($p_i^*v(P^*)$) [10]. Therefore, given the game setup in section II, the Nash equilibrium strategy profile studied in III-A, the social optimum studied in III-B and using the results from (7) and (10), the price of anarchy has the following expression:

$$PoA = \frac{p_i^{**}v(P^{**})}{p_i^*v(P^*)} \Rightarrow PoA = N\left(\frac{P^{**}}{P^*}\right)^2 \frac{v'(P^{**})}{v'(P^*)}. \tag{14}$$

[1]Extending the proof in [8] for our model, let us assume, by the contrary, that $P^* \leq P^{**}$. Since $v'(P) < 0$, then $v(P^*) \geq v(P^{**})$, and since $v''(P) < 0$, then $0 \geq v'(P^*) \geq v'(P^{**})$. Finally, since $\frac{P^*}{N} < P^{**}$, the left term of equation (7) strictly exceeds the left term of equation (10), which is impossible since both are equal to zero.

where, for each AS i, p_i^{**} denotes the social optimum strategy and p_i^* denotes the Nash equilibrium strategy. For the value function with the above-mentioned particular expression, $v(P) = a - P^2$, where $a = const.$, the PoA is

$$PoA = N\left(\frac{N+2}{3N}\right)^{\frac{3}{2}}. \quad (15)$$

Therefore, when $N \to \infty$ then $PoA \to \infty$. This means that when the number of ASes grows, the Nash equilibrium moves further away from the social optimum. Both results in (11) and (14) prove that the self-interested behaviour of the agents in the Internet leads to a suboptimal outcome, with an inefficient exploitation of the common resource.

IV. A Payment Mechanism

In this section, we propose a solution for avoiding the tragedy of the Internet routing commons. One classic approach is to internalize the costs incurred by the commons problem using monetary exchange in order to obtain a certain outcome. We consider the implementation of a payment mechanism in the current Internet so that the optimal outcome is achieved.

Given the optimal strategy profile $(p_1^{**}, p_2^{**}, ...p_i^{**}, ...p_N^{**})$ studied in III-B, we set the payment to exactly reflect the harm one AS causes to all the other ASes when announcing one more prefix in the Internet. The payment is a per prefix monetary amount introduced into the payoff function so that the outcome of the new game coincides with the previous social optimum. Using the payoff function that has the expression in (5) and the overall optimum strategy profile, the per prefix payment introduced by the mechanism is:

$$x_i = -\sum_{j \neq i} p_j \frac{dv(P)}{dp_i} \Rightarrow x_i = -(P^{**} - p_i^{**})v'(P^{**}). \quad (16)$$

The new strategy profile of the ASes has to maximize the individual payoff function, taking into account the additional cost payed by each AS for each announced prefix:

$$\max_{p_i}\{u_i(p_i, p_{-i}) - p_i x_i\}. \quad (17)$$

Now we prove that the strategy profile corresponding to the optimal social welfare is a solution for the previous equation. Consequently, by including this payment mechanism into the payoff function, the ASes have the incentives to play the strategy corresponding to the social optimum of the original game setup. The first-order condition for this optimization problem is:

$$\frac{du_i(p_i, p_{-i})}{dp_i} - x_i = 0. \quad (18)$$

We show next that the overall optimum strategy profile is a solution for (18). Using (16) and (5) in equation (18) yields:

$$v(P) + p_i v'(P) + (P^{**} - p_i^{**})v'(P^{**}) = 0 \quad (19)$$

Therefore, substituting p_i^{**} in the equation above outputs:

$$v(P^{**}) = -P^{**}v'(P^{**}). \quad (20)$$

We can easily see that the previous result coincides with the social optimum value in (10). Hence, we can conclude that the social optimum is solving equation (18) and thus maximizing the payoff function for all the agents in the game.

Even if by introducing this payment mechanism we bring the game equilibria in the social optimum point, the real-life implementation of such a system is not without controversy, as it would imply that the ASes would engage in monetary exchange that can influence their strategy choice.

The monetary incentives can be included in the game setup as an enforced tax or by creating a market with flexible prices and many traders. If the payment is included in the game as a fixed per prefix tax, the difficulty of the implementation would be calculating its exact value.

However, if implemented as a pricing mechanism in a market with multiple traders, the above-mentioned inconvenience of introducing payments is avoided. The economic equilibrium of the market would be easily reached through the pricing mechanism. In such a scenario, the networks would have to pay to their providers for announcing more specific prefixes.

V. Conclusions

In this paper we have proposed a simplified economic model of the interdomain routing commons problem. Considering the GRT to be a public resource, we have modeled the ASes as rational agents who have to make a strategy choice of how many prefixes to announce in the Internet so that they maximize their own benefit. We found that the game reaches an inefficient outcome because the common resource is over utilized when the total number of prefixes exceeds the maximum limit, facing a case of *the tragedy of the commons*. Finally, for avoiding the tragedy of the commons, we introduce a taxing mechanism where each AS has to pay a cost proportional with the number of prefixes it announces.

References

[1] T. Bu, L. Gao, and D. Towsley, "On characterizing BGP routing table growth," *Computer Networks*, vol. 45, no. 1, pp. 45–54, 2004.

[2] X. Meng, Z. Xu, B. Zhang, G. Huston, S. Lu, and L. Zhang, "IPv4 address allocation and the BGP routing table evolution," *SIGCOMM Comput. Commun. Rev.*, vol. 35, no. 1, pp. 71–80, 2005.

[3] G. Huston, "Analyzing the Internet BGP Routing Table," *The Internet Protocol Journal*, vol. 4, no. 1, 2001.

[4] K. Fall and P. B. Godfrey, "Routing Tables: Is Smaller Really Much Better?" in *HotNets-VIII*, October 2009.

[5] L. Cittadini, W. Mhlbauer, and S. Uhlig, "Evolution of Internet Address Space Deaggregation: Myths and Reality," *IEEE Journal on Selected Areas in Communications, special issue on Internet Routing Scalability*, 2010.

[6] Y. Rekhter, P. Resnick, and S. Bellovin, "Financial Incentives for Route Aggregation and Efficient Address Utilization in the Internet," in *Coordinating the Internet*. MIT Press., 1996.

[7] G. Hardin, "The Tragedy of the Commons," *Science*, vol. 162, pp. 1243–1248, December 1968.

[8] R. Gibbons, *A Primer in Game Theory*. Pearson Education, 2001.

[9] C. Papadimitriou, "Algorithms, games, and the internet," in *STOC '01: Proceedings of the thirty-third annual ACM symposium on Theory of computing*, 2001, pp. 749–753.

[10] T. Roughgarden, "Intrinsic robustness of the price of anarchy," in *STOC '09: Proceedings of the 41st annual ACM symposium on Theory of computing*, 2009, pp. 513–522.