Inter-domain Routing Incentive Model Based on Cooperative Game

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***Abstract*—An incentive mechanism should be incorporated into the current inter-domain routing architecture because it can motivate Internet Service Providers (ISPs) to provide efficient and lasting routing services such as multipath routing and routing customization. In this paper, we model the cooperation and competition behavior of ISPs in the special inter-domain routing system (i.e., UMIR: user-customizing multi-path inter-domain routing), and then propose a novel incentive model based on cooperative-game. We abstract and give some basic concepts such as a routing coalition, sub-coalition and their characteristic function, and then design and develop a fair and feasible revenue allocation algorithm called shapely value algorithm. The theoretical analysis and experimental results show that this incentive model benefits the deployment of UMIR protocol and the formation and stability of a UMIR routing coalition. Therefore, it will push the UMIR network to evolve healthily and orderly.**

Keywords—Internet routing; user-customized multi-path inter-domain routing; inter-domain routing incentive model; cooperative game

I. INTRODUCTION

Currently the Internet hardly provides a routing service that assures the quality of service of various network applications, mainly because the Internet has not an efficient account & pricing function [1]. In the early days of the Internet, the U. S. government was uniformly responsible for the development and management of the ARPANET/NSFNET networks, at that time it was unnecessary for those networks to add the account & pricing function because this would decrease the technical or economic efficiency of the entire network [2]. Hence those initial networks are intrinsically shortage of the account & pricing function. Unfortunately, this function is hardly introduced to the current inter-domain routing architecture [3]. The shortage of the account & pricing function has brought up many challenges of the inter-domain routing, such as path expanding and performance degradation, and has also reduced the enthusiasm and initiative of the Internet Service Provider (ISP) for deploying newly routing protocols or service.

Generally, Internet traffic transmits multiple Autonomous Systems (AS) (for convenient expression, this paper alternates to use between AS and ISP) to arrive at a target network, where each AS is an independent and rational economic entity [4]. ASs with limited network resources must collaboratively transit their traffic with other peers, thereby accomplishing a globe-wide routing service. On the other hand, these independent and rational ASs would compete for their maximizing self-interests each other. In this paper, we consider the Internet routing as the routing game of all ASs, and then suppose that an AS would provide a special routing service and can obtain some economic revenue from stub networks or end users. For this goal, the AS needs other peer ASs to collaboratively provide the high quality of routing service. Therefore, how to model this inter-domain routing game and how to design the revenue allocation method among the Internet ASs will become two important challenges [5].

Our previous researches [6][7] have proposed a customizing inter-domain routing system called the User-customizing Multi-path Inter-domain Routing (UMIR), whose key principle is constructing a special Internet-wide AS-level topology to compute the Internet-wide one or multiple routes meeting user-customizing requirements. For some network users, the UMIR network not only improves their route-selecting flexibility but also meets their individualized routing requirements such as the multi-path routing and quality-of-service routing. However, the UMIR faces several challenges as following: First, since Internet paths available must be strategy-compatible, those paths with incompatible AS strategies will be of no avail even though they may have better performance. Second, although ASs deploy the UMIR protocol to improve their competitiveness, ISP would be not willing to do this without efficient incentive. Therefore, we in this paper propose a routing incentive mechanism for the UMIR network. The basic principle of this mechanism is as following: in the UMIR network, ISPs provide the multi-path routing or quality of routing services for network users that would pay extra fee; meanwhile, ISPs must allocate some revenue to other cooperative ISPs. Finally, this mechanism will motivate ISP to actively deploy the UMIR protocol.

The rest of this paper is organized as follows: Section 2 introduces the background of the UMIR network and the cooperative game; In Section 3, we provide a formal statement of the cooperative-game model of UMIR routing and have an analysis about the UMIR routing game and in Section 4 derive the revenue allocation method. In Section 5, we have carried on the experiment and given some performance evaluation. We conclude in Section 6 with a brief discussion of open problems and future works.

II. BACKGROUND

This section mostly introduces the basic principles of UMIR networks and the relative concepts of the cooperative game.

A. UMIR networks

We have proposed a User-customizing Multi-path Inter-domain Routing (UMIR) [6, 7] whose main target includes (i) implementing the multi-path routing instead of the BGP single-path routing; (ii) meeting the routing requirements of network users about the route-selection flexibility and route-personalized characteristics. The UMIR-enabled networks are composed of multiple ISP agents deployed the UMIR system. In this network, AS nodes accepting users to customize the routing service are called as control node (CN), AS nodes including destination host or network are called as goal node (GN) and other AS nodes are called as cooperative nodes (CPs).

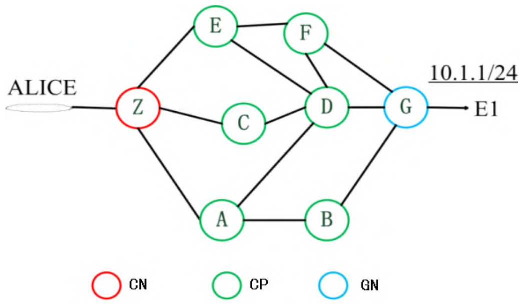

Figure 1. The simplified network (UMIR)

Figure 1 gives a simple example of UMIR networks. Alice is a network user (e.g., a stub network), and it hopes to customize a best-performance route destination to the network E1 from its ISP. This network is made up of UMIR-enabled agent sets {Z, A, B, C, D, E, F, G}, where Z is a control node, G is goal node and others are cooperative nodes. The control node (Z) creates a special network topology by collecting routing information from others cooperative nodes, and then compute and choose the best routes to the destination network E1 (10.1.1/24). In this network, the control node (Z) must request some route information from other cooperative nodes; correspondingly, the cooperative nodes can send their routing information to the control node. The routing information is called as the route-let which lists several important fields as following.

- PID—an identifier of the route-let information which is composed of two neighboring AS numbers.
- Prefix—a target network which is customized by a network user.
- Metrics—link performance vectors (e.g., bandwidth, delay, etc.) of the route-let.
- Type—an incentive model used in the UMIR network.
- Cost—some fee that the network user pays to the individual ISP.

In the UMIR network, users can customize the routing service to the target network from the UMIR-enabled ISP, and its control node initiates the UMIR computing process which constructs an Internet-wide AS-level topology to compute one or more best routes for the customizing user. Specifically, the UMIR process carries four steps as following:

- Customize the personalized routing service. Network users that need some special routing characteristics (e.g., low delay, high bandwidth) can pay their ISPs to purchase the customizing routing services. The ISP's control node will transform these characteristics of the user-customizing requirements into route profile parameters.
- Construct topology and compute the appropriate routes. According to the route profile parameters, the control node can construct an Internet-wide AS-level topology by requiring the route-let from other cooperative nodes, and then compute and choose best routes.
- Install the chosen routes. The control node will advertise every cooperative node to configure her individual data plane along the chosen path.
- Finish the settlement among relative ISPs. Since the control node (i.e., ISP) provides the customizing routing service for network users, these users must pay their ISPs with certain extra fee, in turn, which is allocated by the control node to other cooperative ISPs.

B. Cooperative game and its solutions

The cooperative game is a mathematical model used to describe the cooperation and competition behavior of rational entities, and study how to rationally make decisions in this environment [8, 9]. We utilize the cooperative game to describe the AS relationship in the UMIR network, and model the UMIR routing process as an AS cooperative game model. Each AS plays the UMIR cooperative-game by announcing the route information, and then all participating ASs will obtain certain economic revenue from this routing game.

The game solution is another challenge related to the cooperative game. Many experts of game theory have proposed a number of methods as for how to allocate coalition revenues. In the cooperative game, the allocation methods of coalition revenues are mainly classified into two categories [8]: dominant methods and valuation methods. Valuation methods have a unique allocation method for each cooperative game, which can balance some conflicting claims from various players and which can reflect the allocation equity and justice. The widely used valuation method is shapely-value method, because it has clearly economic implication and the simple calculation. Assume that there is a cooperative game CG=[N, v(S)], N=[1,…,n] and v(S) is the characteristic function of coalition S, which satisfies the axioms of symmetry, efficiency and additivity, the CG has one unique Shapely-Value as following:

$$\Phi(v) = (\varphi_1(v), \varphi_2(v), \ldots, \varphi_n(v))$$

$$\varphi_i(v) = \sum_{S \subseteq N} \frac{(n-|S|)!(|S|-1)!}{n!} [v(S) - v(S \setminus \{i\})] \quad (1)$$

Note that in (1), $v(S)$ - $v(S\setminus\{i\})$ shows the marginal contribution of the player i on the coalition S, if i does not

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belong to S, $v(S) - v(S\backslash\{i\})$ is zero, that is, the player does not have the marginal contribution toward the coalition S.

III. INTER-DOMAINS ROUTING UMIR GAME MODEL

This section firstly analyzes AS behavioral characteristics in the UMIR network by using the cooperative game, and then describes the AS survival scenario. Also, we discuss the rational basis to form a coalition and its stable conditions, and finally build a routing game model for UMIR networks.

A. UMIR game

Each AS of the UMIR network is a rational entity and can control its routing behavior to maximize its own revenue. Under the incentive routing scenarios, an AS declares the own routing information to participate in the routing game, and gets the corresponding revenue. In the UMIR network, an AS may be the control node or cooperative node, or both. On the one hand, ASs need their mutual cooperation to forward the Internet traffic and obtain some economic revenues; on the other hand, different ASs compete with one another to maximize their economic revenues. Thus AS survival scenarios are consistent with the player's of the cooperative game. Therefore, the inter-domain routing for the UMIR networks can be modeled by using the cooperative game, and the equilibrium outcome of the routing game is also gotten by the solution method of the cooperative game theory.

The cooperation game model of the UMIR routing network can be described as following: assume that exist the players set N= {1 ... n}, which is composed of n ASs and each AS is a rational player. The routing system will select a path (i.e., a routing coalition made up of the path's all ASs), and the coalition has also many sub-coalitions and each sub-coalition can define a characteristic function.

By using some terminology from cooperative game [8-10], we give some relative definitions in the routing game model.

Definition 1: Assume that for a routing game G = [N, *v*(S)], its players set N= {1, ..., n} consists of n ASs. If S = {i, | i is a certain AS along the selected path of a customizing user}, S is called as the routing coalition.

In the UMIR network, the member number of coalition S is far smaller than all player number N of this network, that is, $|S| << |N|$. If the UMIR have selected a certain path, all ASs along this selected path will make up of a routing coalition.

Definition 2: Given a routing coalition S = {1,…, k}, for any set $M \subseteq S$, M is called as the sub-coalition of coalition S.

If M is allowed to take a null value and M = S is a routing coalition, and the number of sub-coalition M is $C_{k0} + C_{k1} + \ldots + C_{kk} = 2^k$.

According to the UMIR network in Figure 2, given the path L = z-c-d, there is a routing coalition S = {z, c, d}, whose sub-coalitions have {z}, {c}, {d}, {z, c}, {z, d}, {c, d}, {z, c, d}.

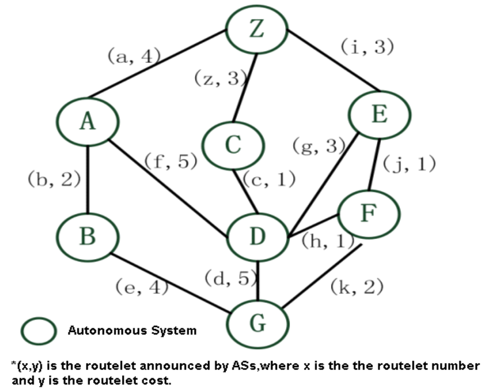

Figure 2. The example of the coalition revenue allocation

Definition 3: Given the routing coalition and its sub-coalitions, the characteristic function v(M) of any sub-coalition M is a mapping from the sub-coalition to the real number $v : M \subseteq S \rightarrow R$.

Definition 4: Call the game CG = [N, *v*(S)] as a UMIR routing game only if this game has following characteristics: (1) The players set consists of all ASs of UMIR network, namely, N = {1,…, k}; (2) For a routing coalition S, its sub-coalition M has the characteristic function *v*(M).

B. Analysis of the UMIR routing game

In the UMIR routing game, each cooperative ISP responses to the information request from the control node, and expects to be selected by the UMIR routing system (i.e., forming a routing coalition), which is a computing result of the routing system on the basis of the user route requirements and the current network resources. This coalition formation mechanism is determined by the internal and external demands of each participating ISP. An ISP's internal demand refers to its customer's personalized routing requirements, which urge it to deploy the UMIR-enabled system. If an ISP does not provide the customizing routing services such as multi-path or QoS routing, likely there rises the customer loss because of ISP's lower performance and competitiveness. An ISP' s external demand means that it must consider its own economic interests as an independent and rational economic entity, thus an ISP must obtain certain benefits by providing extra and high quality routing services.

Once an ISP customizes the personalized path for a network user by participating in the UMIR-enabled network, that is, there will form a stabilizing routing coalition because there has an economic incentive. The main reasons are as following: (i) ISPs almost have large network resources so that their marginal cost of providing collaborative routing is very low and there easily form multiple various coalitions; (ii) As long as their participating coalitions are available, ISPs will obtain the economic benefit from these routing coalitions. These reasons will essentially strengthen the ISP's cooperation willingness, thus making the coalition more stabilizing.

The above analysis shows that, in order to motivate ISPs to provide stabilizing and lasting routing services, we

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must develop some mechanisms for the UMIR network to regulate and restrain AS behavior, including revenue allocation and coalition formation mechanisms. A routing coalition's formation is dependent on the user route requirements and existing network resources, which ensures that collaborative ASs have equally chance of being selected to provide the Internet routing service, i.e., it requires that the routing algorithm is fair and equitable. On the other hand, how to allocate the coalition revenue is a key problem solved for the coalition cooperative games. For UMIR networks, a revenue allocation mechanism is the basis of formation and stability of a routing coalition. In cooperative games, the revenue allocation is the solution of cooperative games, namely, how to allocate coalition revenue to each participating AS member fairly. For example, ASs can declare their routing-link information to the UMIR control node to participate into the routing game, if one AS is selected as the member of a routing coalition, it will obtain some expected revenue, and otherwise the expected revenue is zero. The AS expected revenue is a specific solution of routing cooperative games, such that the AS cannot change the link information to affect its due revenue. Only if all ASs obtain appropriate and reasonable revenue, the whole routing game will achieve an equilibrium solution, which is the Nash bargaining solution of cooperative games: if the UMIR networks exist Nash bargaining solution, no AS can obtain greater benefits by its self-declared strategy.

IV. REVENUE ALLOCATION METHOD

For the solution structure of the cooperation game, the Shapley value method has been widely used for its good economic meaning and simple computing [9]. This section describes how to design the coalition revenue allocation algorithm by using the basic principle of the shapely values method.

A. Sub- coalition and its characteristic function

The key elements of the shapely value method are the coalition definitions and the computing method of the characteristic function. In order to design an effective revenue allocation method, we must give the definitions of coalition and its characteristic function. According to Definition 1, the UMIR network forms a routing coalition by computing and selecting a concrete path, which this coalition is the result of multiple ASs routing game. The coalition members include all ASs along the selected path; moreover these ASs can further form a number of sub-coalitions.

By using a cost-plus pricing method [9] of the economics field, we give the definitions and computing expressions of characteristic function of the sub-coalition.

Definition 5: The characteristic function of the sub-coalition M is defined as sum of coalition cost and profit, and the computing expression is as follows:

$$v(M) = \sum_{i \in M} c_i + (q_0 - \sum_{j \in S-M} c_j) \tag{2}$$

Where c_i is the cost of the member i, q_0 is the expected profits of a routing coalition, c_j is the cost of non-coalition member j. In Equation (2), the coalition revenue consists of two parts: the first item is the cost of all members in the coalition M, and the second item is the expected profit of coalition M.

By Definition 5, the sub-coalition revenue v(M) is the maximum benefit obtained from the coalition, and equals to the total cost of the coalition $\sum_{i \in S} c_i$ plus the difference between the revenues of coalition (q_0) and the cost $\sum_{j \in N-S} c_j$ of no- coalition members.

Below gives an example introducing the computing of coalition revenue. As shown in Figure 2, for the UMIR network, given the coalition S = {z, c, d}, need compute the revenue of two sub-coalition M_1 = {z, c} and M_2 = {z, c, d}. Assume the coalition revenue q_0 is the cost sum of the shortest path, namely q_0= 6, the sub-coalition revenue v (M_1) = 4 + 6 - 5 = 5, other sub-coalition revenue v (M_2) = 9 + 6 - 0 = 15.

B. A simple example

Section III has introduced the relative definition of a routing coalition and sub-coalition and the computing method of characteristic functions. We are going to discuss the revenue allocation method of SPA (Sha-Pley Apportionment). Assume the UMIR network uses one specific routing algorithm (e.g., BGP) to select a particular path according to user requirements, i.e., forming the routing coalition. The computing steps (see Figure 3) of the coalition revenue are as follows:

- **Initialization** that, given the coalition S, the expected revenue of its all members c_i ($1 \le i \le k$, k is a member number) and some initial system parameters.
- **ComputeSubcoalition** that determines the sub-coalitions in the coalition S, and the total number of sub-coalitions.
- **RevenueOfSubcoalition** that computes the revenue value of the sub-coalition M: for any sub-coalitions M, compute the revenue value of the sub-coalition by Equation (2).
- **RevenueOfeachAS** that uses Equation (1) to compute each AS revenue value in the coalition S.

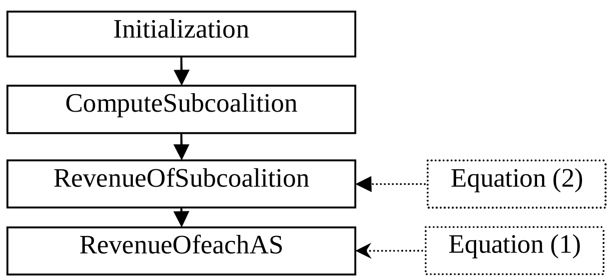

Figure 3. Flow chart of computing coalition revenue

Below we take Figure 2 as an example to show the computing process using the SPA algorithm. Assume a user want to customize the route from Z to G, and the control node selects the path {z-c-d} after running its path computing process, each AS revenue in the coalition S = {z, c, d} can be computed as following steps:

a) Given the coalition S = {z, c, d}, S has eight sub-coalition M such as Φ, {z}, {c}, {d}, {z, c}, {z, d}, {c, d}, {z, c, d}.

b) Compute the revenue of the sub-coalition M by the Equation (2), their result is showed in Table 1.

TABLE I. REVENUES OF SUB- COALITIONS

Sub-coalitions	Revenue
Φ	0
{z}	3
{c}	1
{d}	5
{z, c}	5
{z, d}	13
{c, d}	9
{z, c, d}	15

c) Compute the AS revenue of the coalition S by Equation (1):

$$v(z) = \sum_{\{i\}\subseteq S} \frac{(n-|S|)!(|S|-1)!}{n!} \quad [v(S)-v(S\setminus\{i\})]$$

$$= \frac{1}{3}(3-0)+\frac{1}{6}(4-1)+\frac{1}{6}(12-5)+\frac{1}{3}(14-8) = 4.67$$

Similarly,

$$v(c) = 1.67, v(d) = 7.67$$

d) All AS's revenues of the coalition S are: Φ(v) = (4.67, 1.67, 7.67)

Note: the AS's revenue of the UMIR network only depends on its contribution of coalition revenue. The further simulations will give the validation and comparison of the SPA algorithm. Moreover, AS revenues are independent of their places or positions in the coalition, because this characteristic is guaranteed from the symmetry axiom of the shapely value method [10].

V. EXPERIMENT AND EVALUATION

In order to testify the feasibility of our solution on the routing incentive model, we will do some experiments and have some analysis on the experimental results.

A. *Simulation experiment*

To evaluate the feasibility and effectiveness of several revenue allocation algorithms, we have developed a UMIR simulator [7] to carry out lots of experiments. The ASs are willing to participate in UMIR network with the incentive mechanism, so the experiments do not consider their business strategy and its impact on the routing selection results. Assume that the cost of AS inter-domain links complies with the uniform distribution of [10, 20], which refers to the spending cost that ISP forward or route user traffics (namely, it refers to the contribution under the cooperative routing).

We choose two allocation algorithms named the original average apportionment (OAA) and the cost weighted average apportionment (CWA) as two comparison algorithms. OAA is a simple average revenue allocation algorithm. And CWA is an improvement on the OAA algorithm, which considers the cost value of each coalition member during the routing game and which is based on the weighted cost size. Both algorithms do not consider the contribution of various members to the coalition. For the rational AS, OAA and CWA algorithms are unstable allocation algorithms, so they cannot guarantee to produce a stable and lasting routing coalition. However, the SPA algorithm is essentially a revenue allocation based on the contribution of coalition members, and therefore, it makes the routing coalition become more stabilizing and lasting.

The simulation experiment selects 1000 random AS node pairs (s, t) and runs the UMIR simulator where the selected routing algorithm is used to calculate the routing path of each AS node pair (s, t). And we evaluate the performance of SPA, OAA and CWA algorithms.

B. *The result and theoretical analysis*

Figure 4 shows the revenue allocation results of SPA, OAA and CWA algorithms respectively according to the participating AS with largest coalition contribution. For these AS nodes with big contribution of the routing coalition, SPA distributes the most revenue to them, CWA is the secondary and OAA is the minimum. For example, the data of No. 6 sample can be shown that for the greatest contribution in the coalition, SPA distributes the revenue of 41, CWA distributes the revenue of 36, and OAA distributes the revenue of 32.

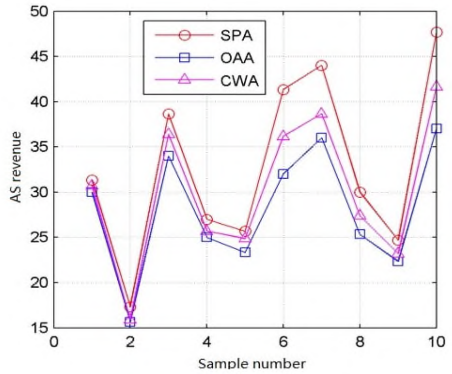

Figure 4. Comparisons of AS node with the most contribution degree

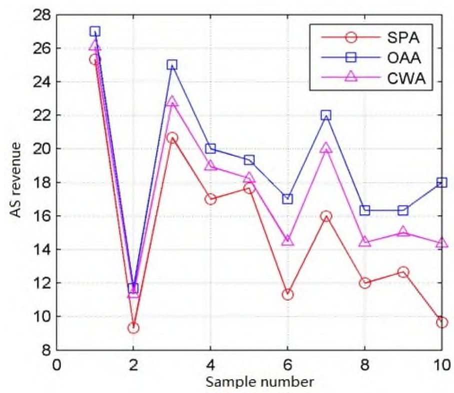

Figure 5. Comparisons of AS node with the less contribution degree

Figure 5 shows the revenue allocation according to the participating AS with the smallest coalition contribution. For AS nodes with smallest contribution, OAA distributes the most revenue, CWA is the secondary and SPA is the minimum. Therefore, compared with the OAA and CWA algorithms, SPA is one allocation algorithm based on the contribution, which benefits to the formation and stability of a routing coalitions.

Figure 6 shows the member revenue changes with total coalition revenue under the SPA allocation algorithm. With the total coalition revenue increases, the member revenue increases too. This is because the member contribution to the whole coalition has not changed, such that the member revenue will linearly increase with the coalition total revenue.

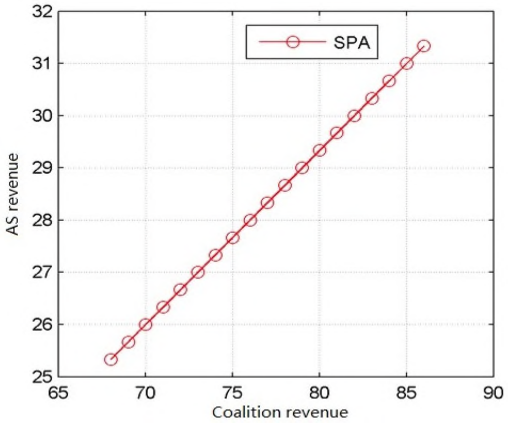

Figure 6. Influences of member revenue by coalition revenue change

As can be seen from experiments, the revenue allocation algorithm (SPA) is based on the contribution to the whole coalition routing, which provides a fair and equitable allocation for the coalition members. Therefore, our designed incentive algorithm can motivate ISP to improve the willingness for deploying the new UMIR protocol, and is helpful to produce a stabilizing and lasting routing coalition, thereby accelerating the healthy and orderly development of the UMIR network.

VI. CONCLUSION

The routing incentive is necessary to motivate ISPs to provide the efficient routing service in the globe–wide Internet, and then a fair and reasonable incentive scheme can benefit the cooperation between ISPs and maintain the Internet routing stability. In fact, there will be theoretical and practical significance as for how to use incentives to encourage ISP to deploy some efficient and valued-routing service or products. Based on the previous studies (i.e., UMIR), we had done the following studies in that paper: (1) analyze in detail the rational basis and stable conditions of a routing coalition formation in the UMIR network; (2) propose a routing cooperative game model for inter-domain routing; (3) design an efficient revenue allocation algorithm for the routing coalition. In the future work, we will verify the consistent ability of the ISP routing services, based on the routing performance from some monitoring facilities; and further, we will build the routing trust evaluation model to solve the deceptive announcements problem in the routing cooperative game.

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