Traffic Scheduling and Revenue Distribution among Providers in the Internet: Trade-offs and Impacts

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***Abstract*—The Internet consists of economically selfish players in terms of access/transit connection, content distribution. Such selfish behaviors often lead to techno-economic inefficiencies such as unstable peering and revenue imbalance. Recent research results suggest that cooperation-based fair revenue sharing, i.e., multi-level ISP (Internet Service Provider) settlements, can be a candidate solution to avoid unfair revenue share. However, it has been under-explored whether selfish ISPs actually cooperate or not (often referred to as the stability of coalition), because they may partially cooperate or even do not cooperate, depending on how much revenue is distributed to each individual ISP. In this paper, we study this stability of coalition in the Internet, where our aim is to investigate the conditions under which ISPs cooperate under different regimes on the traffic demand and network bandwidth. We first consider the under-demanded regime, i.e., network bandwidth exceeds traffic demand, where revenue sharing based on Shapley value leads ISPs to entirely cooperate, i.e., stability of the grand coalition. Next, we consider the over-demanded regime, i.e., traffic demand exceeds network bandwidth, where there may exist some ISPs who deviate from the grand coalition. In particular, this deviation depends on how users' traffic is handled inside the network, for which we consider three traffic scheduling policies having various degrees of content-value preference. We analytically compare those three scheduling policies in terms of network neutrality, and stability of cooperation that provides useful implications on when and how multi-level ISP settlements help and how the Internet should be operated for stable peering and revenue balance among ISPs.**

I. Introduction

A. Motivation

The Internet is a system where the entities such as EUs (End Users) and content/eyeball/transit ISPs (Internet Service Providers)[1], having different economic perspectives, compete and cooperate in a highly complex manner. Eyeball/transit ISPs connect EUs to the Internet, and content ISPs inject and deliver contents into the Internet [2], e.g., videos, web pages, and files. The major interest of such providers, which is often selfish, is to maximize their profits, sometimes incurring techno-economic inefficiencies in the Internet. For example, ISPs' selective peering with other ISPs may have negative impact on Internet's connectivity. It is reported that some providers express economic complaints on revenue imbalance among them, see e.g., [3], [4]. One of the central issues regarding such complaints is how to fairly distribute the revenue from the users to the providers.

There have been recent research efforts on fair and efficient revenue sharing among providers, using the notion of Shapley value (SV) [5] from cooperative game theory. The SV is a fair payoff distribution scheme and presumes that the *grand coalition* (i.e., the coalition containing all players) is agreed by the players. The SV based revenue sharing hypothesizes that the profit distribution is achieved at a multilateral, global level, rather than a bilateral, local level, thus leading to the nice features in terms of fairness, efficiency, and interconnection incentives, see e.g., [6] and [7].

However, it is questionable that the providers would actually form the grand coalition, referred to as *stability* of the grand coalition. This stability issue in the Internet ecosystem is of critical importance, because, if unstable, in spite of its nice properties and benefits, multi-lateral settlements would not be realized in practice. This motivates us to study how stable the grand coalition is under what conditions such as how overloaded the network is. We can consider two regimes, (i) *under-demanded* and (ii) *over-demanded,* depending on how large network bandwidth is offered compared to users' traffic demand. The case of over-demanded network may occur due to fast technical advances of edge devices, e.g., smart phones/pads and smart TVs, but slow upgrade of network infrastructures. Note that an over-demanded network may significantly change how we should technically treat the issue of stability. Roughly, the stability of the grand coalition with SV can be studied by checking the existence of sub-coalitions in which all players in that coalition can be better off with SV. In the over-demanded case, the individual share depends on how the edge networks *sift out* a part of user demands to meet the capacity.

B. Related Work

In the 1990s, Bailey [8] explored the economic factors with providers' settlements based on Internet interconnection architecture and Huston [9] described the challenges of ISPs' business models against the telecommunications market. In the current debate on revenue sharing alignment in future Internet cooperations, Ghezzhi et al. [10] and Zwichkl et al. [11] depicted the interconnections value network for the future Internet ecosystems, especially they developed the technical guideline for providers to increase revenue opportunities in the marketplace. Moreover, Faratin et al. [12] paid attention to the asymmetry of content ISPs and eyeball ISPs thus they

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[1]ISP is sometimes called just 'provider' throughout this paper.

observed the appearance of paid peering among ISPs. All these studies imply possibility of unstable peering and revenue imbalance among the Internet providers.

To tackle the possible unstable peering and revenue imbalance in the Internet, people have studied multi-lateral settlements among providers, where cooperative fair revenue sharing is the key idea. Examples include the researches on the revenue sharing mechanisms based on proportional fairness and NBS (Nash Bargaining Solution) [13]–[16]. Ma et al. [6] studied the revenue sharing based on the Shapley value, and presented its nice properties that yield globally optimal routing and interconnecting decisions. They also derived closed-form SVs for structured ISP topology composed of content, transit, and eyeball ISPs. In addition to SV's application to providers' settlements, SV has also been applied to many other network-economic problems, e.g., peer-assisted services [17], viral marketing [18], and virtual infrastructure sharing [19].

Despite the interesting results on the fair revenue sharing as presented above, it has been under-explored whether the providers are actually willing to agree to multi-lateral settlements, i.e., stability of the grand coalition. The grand coalition's stability has been extensively studied in cooperative game theory, e.g., [20]–[22]. Ma et al. [6] have only conjectured that the ISPs' grand coalition with SV based revenue sharing is stable.

C. Summary

In this paper, we consider various traffic scheduling policies at the edge, each of which presents different degrees of content-value preference and network neutrality, and compare them in terms of coalition worth and stability of the grand coalition. To that end, we define a coalition game, called *Revenue Sharing Game (RSG)*, where the players are eyeball, transit, and *virtual* content ISPs. The notion of virtual content ISP, which is a triple of content ISP, content, and region, is introduced with the goal of accurately modeling the cooperation decision of a content ISP.

Following the defined coalition game, we first prove that in under-demanded networks, the coalition worth is maximized at the grand coalition, which is always stable with SV based revenue sharing. This formalizes the result conjectured in [6]. Second, in over-demanded networks, where traffic scheduling is an important factor, we prove that the scheduling absolutely prioritizing higher-value contents (called PP: Priority Policy) maximizes the worth over all possible scheduling policies. Also, we prove that the scheduling which (relatively) assigns higher weights to more profitable contents (called RPP: Revenue Proportional Policy) always generates more worth than the content-agnostic scheduling (called TPP: Traffic Proportional Policy). However, in terms of the stability of the grand coalition, even under PP, which is a worth-maximizing policy, the grand coalition may not be stable. We provide sufficient conditions where a scheduling is better than another scheduling in terms of stability. Under the conditions, more content-oriented scheduling tends to be "more stable" than content-agnostic one. Interesting trade-offs are observed here; PP or RPP requires much more complex operations, such as priority scheduling or weighted fair queuing, whereas TPP can be realized by a simple FIFO scheduling.

TABLE I
SUMMARY OF MAJOR NOTATION

Variable	Definition
$\mathcal{C}$, and $\mathcal{B}, T$	Set of content ISPs, content ISPs, and transit ISP
$\mathcal{R}$	Set of all regions
$\mathcal{Q}$	Set of all contents
$\mathcal{Q}^i$	Set of contents serviced by the content ISP C^i
$\mathcal{Q}_r$	Set of contents demanded by the users in the region r
$\mathcal{C}_q$	Set of content ISPs that serve the content q
$\mathcal{C}_r$	Set of content ISPs that serve at least one content in $\mathcal{Q}_r$
C^i	i-th content ISP
$C^i_{r,q}$	Virtual content ISP of i-th content ISP, serving content q to region r
B_r	Eyeball ISP which covers the region r
X_r	Fixed average user population of the region r
$X_{r,q}$	Average user population in the region r that has demand for content q
β_q	Average revenue of the content q
s_q	Average traffic volume of the content q
n_r	Link capacity between B_r and the transit ISP
y_r	Total potential traffic volume in the region r

Our work is highly motivated by [6] in the sense that Shapley value based revenue sharing is beneficial in the economic and engineering sense, but the followings are the key differences: First, in [6], the authors assumed that the network is only *under-demanded*, i.e., traffic demand is small enough, and only conjectured that with Shapley value based revenue sharing the grand coalition would be stable. In this paper, we formally prove its stability. We further studied the case when the network is *over-demanded*, i.e., traffic demand exceeds the network bandwidth, in which case the way the traffic is handled has significant impact on the stability. To this end, we consider three traffic scheduling algorithms (TPP, RPP, and PP) and analyze how stable the grand coalition is with the Shapley value based revenue sharing, under what conditions. We highlight that scheduling policies and stability of the grand coalition is highly inter-coupled, whose analysis was challenging. We have theoretically clarified the stability degree of those three scheduling algorithms. In our preliminary work [1], [23], only a small set of examples is provided hinting that some of traffic scheduling policies can impact the stability. Also, we considered only a single region network, but now we extend it to a multi-region network, thus more general and practical setting, with full proofs of analytic results.

II. MODEL

A. Network Model

We consider a network consisting of a transit ISP T, a set $\mathcal{C}$ of content ISPs, and a set $\mathcal{B}$ of eyeball (or access) ISPs, where we denote by $\mathcal{N} = \mathcal{C} \cup \{T\} \cup \mathcal{B}$ the set of all "providers." The transit ISP offers connectivity between eyeball ISPs and content ISPs. For simplicity and tractable analysis, we assume that there is just a single transit ISP and all eyeball ISPs and content ISPs are connected to the transit ISP, and no direct connection between any content ISP and eyeball ISP exists. Eyeball ISPs connect residential users to the transit ISP. Denote $\mathcal{R}$ as the set of all regions served by the set of eyeball ISPs $\mathcal{B}$. We also denote by B_r the eyeball ISP which covers the region $r \in \mathcal{R}$, where we assume that there does not exist a region covered by multiple eyeball ISPs. Let n_r be the link capacity between B_r and the transit ISP. The content could be delivered from a content ISP to the requesting destination region r via the transit ISP and the eyeball ISP B_r.

Let $\mathcal{Q}$ be the set of all contents in the network. Note that a content can be served by multiple content ISPs. Each region may have a different set of contents to download, for which we let $X_{r,q}$ be the average user population in region r that has demand for content $q \in \mathcal{Q}$. We assume that users are oblivious to content ISPs in downloading contents, i.e., when downloading a content q, users do not differentiate content ISPs (that serve q). We denote $\mathcal{C}_q$ as the set of content ISPs that serve the content q. Let $\mathcal{Q}_r \subseteq \mathcal{Q}$ be the set of contents demanded by the users in region r, and $\mathcal{C}_r$ be the set of content ISPs that serve at least one content in $\mathcal{Q}_r$. In other words, the set $\mathcal{C}_r$ is the union of the sets of content ISPs that serve the contents in $\mathcal{Q}_r$, thus $\mathcal{C}_r = \cup_{q \in \mathcal{Q}_r} \mathcal{C}_q$. We let s_q be the average traffic volume (in bytes) of the content q, and β_q be the average revenue of the content q, i.e., the per-content revenue earned by the content ISPs serving q.

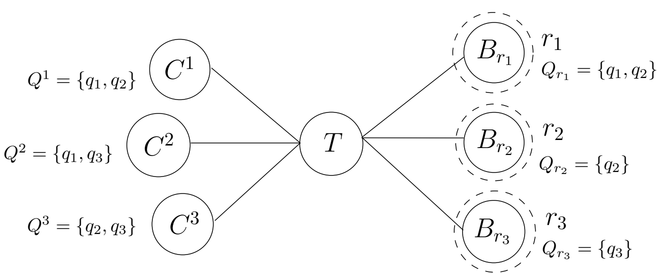


Fig. 1. An example network with three content/eyeball ISP and one transit ISP.

Example. Fig. 1 exemplifies our model, where there exists three content and eyeball ISPs with one transit ISP. Content ISPs C^1, C^2, and C^3 serve the content sets $\{q_1, q_2\}$,$\{q_1, q_3\}$, and $\{q_2, q_3\}$, respectively. Regions r_1, r_2, and r_3 are covered by eyeball ISPs B_{r_1}, B_{r_2}, and B_{r_3}, where the regions r_1, r_2, and r_3 request the cotent sets $\{q_1, q_2\}$, $\{q_2\}$, and $\{q_3\}$, respectively. The request for q_3 in region r_3 can be served by either of C^3 or C^2.

Notation. We use the lower-case i, r, and q to index a content ISP, a region, and a content, respectively. For consistency, we place r and q in subscript and i in superscript. Thus, we often use C^i and $\mathcal{Q}^i$to refer to the i-th content ISP and the set of contents served by C^i.

For any coalition (i.e., a set of ISPs) $S \subset \mathcal{N}$, we denote by $a[S]$ the restriction of a by S, e.g., $\mathcal{R}[S]$ is the set of regions served only in S.

B. Demand and Traffic Scheduling

Let y_r be the "original" traffic demand in region r, representing the total traffic volume requested by the users in region r, i.e., $y_r = \sum_{q \in \mathcal{Q}_r} s_q X_{r,q}$, where $s_q X_{r,q}$ corresponds to the traffic volume from the region r to access the content q. We say that the region r is *over-demanded* if $y_r > n_r$, i.e., the total traffic demand in region r exceeds the link capacity between the eyeball ISP B_r and the transit ISP, and that a network is over-demanded if there exists at least one over-demanded region in the network, otherwise a region or the network is said to be *under-demanded.* [2]

An eyeball ISP will take some traffic shaping action, called *traffic scheduling*, if its serving region is over-demanded, so that its actually-served traffic volume does not exceed the link capacity. We consider a family of traffic scheduling policies abstracted by a function f subject to the following natural condition:

$$\sum_{q \in \mathcal{Q}_r} s_q X_{r,q} \cdot f(s_q, \beta_q, n_r, X_{r,q}) \leq n_r \tag{1}$$

where $0 \leq f(\cdot) \leq 1$. A scheduling policy can be regarded as a traffic shaper which reduces the original per-content user population $X_{r,q}$, thus the value of $f(\cdot)$ corresponds to the portion of user population that "survives" under a given traffic scheduling policy. We study the following three policies: **TPP** (Traffic Proportional Policy), **RPP** (Revenue Proportional Policy) and **PP** (Priority Policy), as formally stated in Table II [3]. These three policies have diversified degrees of implementation complexity, required information, and content-value preference. For example, PP assigns absolute priority to higher-value contents, whereas TPP is indifferent to the content values, and RPP gives higher weights proportional to the profits generated by contents.

We can (arguably) say that TPP is more network-neutral than RPP (similarly, RPP is more network-neutral than PP) due to their different, restricted handling of network traffic, depending on content values. Moreover, TPP can be implemented by droptail queue, which is the simplest one among three scheduling policies whereas PP or RPP requires more complex implementation such as priority queue or weighted-fair queue.

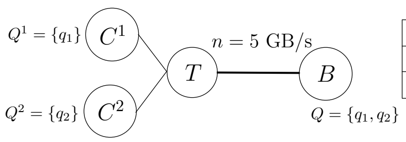
Example. An illustration for three traffic scheduling policies is given in Fig. 2 with two content ISPs, one eyeball and one transit ISP, where two contents (music and video, denoted by q_1 and q_2, respectively) are served by each content ISP (the region index r is dropped here to simplify exposition). The region is clearly over-demanded, because the total demand (5MB/s $\times$ 1000 + 200MB/s $\times$ 100 = 25GB/s) exceeds the capacity (5GB/s). The music's total traffic volume ($s \cdot X$) and the per-content revenue (β) are smaller than each of those of the movie, but more populations want to download the music.

[2]These two regimes are defined on the average of the time-scale when eyeball and transit ISPs' infrastrctures and content distributions are regarded as quasi-static. Also, these different regimes may be defined by considering only when the Internet access is actively made, e.g., daytime, because at nighttime the system will be mostly under-demanded.

[3]In the description of traffic scheduling policies, we often use the notion of normalized content value for a content q, β_q / s_q.

TABLE II
TRAFFIC SCHEDULING POLICIES: TPP (TRAFFIC PROPORTIONAL POLICY), RPP (REVENUE PROPORTIONAL POLICY), AND PP (PRIORITY POLICY)

	$f(\cdot)$	Operation
TPP	$\min\left(1, \frac{n_r}{\sum_{q' \in \mathcal{Q}_r} s_{q'} X_{r,q'}}\right)$	All traffic is treated neutrally, and $X_{r,q}$ is reduced in proportion to the traffic volume of q, s_q.
RPP	$\min\left(1, \frac{\beta_q n_r}{s_q \sum_{q' \in \mathcal{Q}_r} \beta_{q'} X_{r,q'}}\right)$	$X_{r,q}$ is reduced in proportion to the amount of revenue of q, β_q.
PP	$\min\left(1, \left[\frac{n_r - \sum_{q' \in \mathcal{H}_{r,q}} s_{q'} X_{r,q'}}{s_q X_{r,q}}\right]^+\right)$	A content with higher β_q/s_q is absolutely prioritized. ($\mathcal{H}_{r,q}$ is the set of all $q'' \in \mathcal{Q}_r$ s.t. $\beta_{q''}/s_{q''} > \beta_q/s_q$)



	s(MB/s)	β($)	X
q_1(music)	5	1	1000
q_2(video)	200	10	100

Policy	variable	q_1	q_2	Capacity Sharing (total 5 GB/s)
TPP	sX	5 GB/s	20 GB/s	q_1 1 | q_2 4
RPP	βX	1000 $	1000 $	q_1 1 | q_2 1
PP	β/s	$\frac{1}{5}$ $/MB	$\frac{1}{20}$ $/MB	q_1 1

Fig. 2. Example of traffic scheduling policy.

In TPP, the capacity is allocated according to the total traffic volume, i.e., 5 : 20, whereas in RPP the total revenue is used to split the traffic, i.e., 1$ $\times$ 1000 : 10$ $\times$ 100 = 1 : 1.

Finally, in PP, the absolute priority is given to the content with higher normalized value, which is the music. In our example, the music's traffic volume is as same as the capacity n, and thus the video cannot be served at all in PP.

III. REVENUE SHARING GAME (RSG)

In this section, we define a coalition game [24] from cooperative game theory, called Revenue Sharing Game (RSG), followed by necessary preliminaries.

A. Game Formulation

We denote a coalition game with a coalition structure, by $(\mathcal{N}, v, \mathcal{P})$, where $\mathcal{N}$ is a set of players and the game has a transferable[4] utility characterized by a worth function v, which is $v : 2^{\mathcal{N}} \to \mathcal{R}$ and $v(\emptyset) = 0$. The worth function associates with any coalition $S \subseteq \mathcal{N}$ the value generated by cooperation. A coalition structure $\mathcal{P}$ is a partition of $\mathcal{N}$. For example, $\mathcal{P} = \{\{B, T, C^1\}, \{C^2\}\}$ is a partition of $\mathcal{N} = \{B, T, C^1, C^2\}$. The case when $\mathcal{P} = \{\{B, T, C^1, C^2\}\} = \{\mathcal{N}\}$ is called *grand coalition,* for which we use just $(\mathcal{N}, v)$ for simplicity, unless confusion arises.

Players in our RSG should be the providers. Transit and eyeball ISPs are naturally included in the player set. For content ISPs, we introduce a notion of *virtual* content ISP, identified by (i) a content ISP, (ii) a region, and (iii) a content. Denote by $C^i_{r,q}$ the virtual content ISP of i-th content ISP, serving content q to region r. The main objective of introducing virtual content ISPs is to assign finer granularity to the coalition structures for the purpose of reflecting the practice more accurately. Examples include (i) a content ISP such as Google decides to stop serving some contents to South Korea, or (ii) two content ISPs (excluding the rest of content ISPs in the Internet) form a coalition with just localized contents to serve the population in specific regions.

We define the worth of a coalition S as the total revenue earned by the players included in the coalition S. As is done in [7], for a given S, we decompose S into *atomic* coalitions $S_{r,q}$, so that an atomic coalition includes just one eyeball ISP B_r in some region r, a transit ISP T, and a set of virtual content ISPs $C^i_{r,q}$ that serve $q \in \mathcal{Q}_r$ (that are only requested by region r). Then, the coalition worth of S turns out to be simply the summation of the worths of the decomposed atomic coalitions, i.e.,

$$v(S) = \sum_{r \in \mathcal{R}[S]} \sum_{q \in \mathcal{Q}_r[S]} v(S_{r,q}), \tag{2}$$

where the worth of each atomic coalition $S_{r,q}$ is defined as the total fee for accessing content q, paid by the users in region r, $v(S_{r,q}) = \beta_q X_{r,q} f(\cdot)$.

Remark. There are two reasons why we include only content access fee as a revenue source, despite the existence of other revenue sources in the current Internet market, e.g., advertisement fee to content ISPs and network access/transport fee to eyeball/transit ISPs. First, the revenue sharing framework considered in this paper presumes a scheme based on the multi-level settlement among ISPs, i.e., the total revenue is first determined to the group of ISPs, and then redistributed to each individual ISP following a revenue sharing rule. Thus, in this framework, other revenue sources can be modeled as being included in content access fee. For example, network access fee (charged to users by transit and eyeball ISPs) can be as small as just the costs of maintenance, operation, and installation of the physical infrastructures to survive competition [26], [27]. Note that even in such a case, eyeball and transit ISPs will still get their *additional* share in our framework according to their contributions. Other revenue sources largely corresponding to each content, e.g., advertisement fee, can be modeled in the value of each content.

Finally, we present the concept of *super-additivity* of a coalition game $(\mathcal{N}, v)$, which means that a coalition achieves larger coalition worth than what is achieved by its arbitrary partition.

Definition III.1 (Super-additivity) *For any coalition $S, T \subseteq \mathcal{N}$ such that $S \cap T = \emptyset$, $v(S \cup T) \geq v(S) + v(T)$.*

[4]Utility is transferable if players have a common currency that is valued equally by all, thus a part of a player's utility can be losslessly transferred to another player [25].

B. Shapley Value and Stability

Associated with a coalition game $(\mathcal{N}, v, \mathcal{P})$, the coalition structure value is an operator φ which assigns values (or payoffs) to every player in the game $(\mathcal{N}, v, \mathcal{P})$. We denote by $\varphi^i(\mathcal{N}, v, \mathcal{P})$ a coalition structure value for player i. Shapley provides an axiomatic approach to determine a coalition structure value φ, which reflects the following desirable properties (as axioms): efficiency, symmetry, additivity, and dummy, see [5] for details. It has been proved that the value satisfying the four axioms is *uniquely* determined for every coalitional game in the premise of grand coalition $(\mathcal{N}, v)$ (i.e., $\mathcal{P} = \{\mathcal{N}\}$). This special coalition structure value is referred to as *Shapley value (or simply SV),* which is also our focus.

Shapley value is characterized as: for any player i,

$$\varphi^i(\mathcal{N}, v) \quad = \quad \frac{1}{|\mathcal{N}|!} \sum_{\pi \in \Pi} \Delta_i(v, S(\pi, i)), \qquad (3)$$

where Π is the set of $|\mathcal{N}|!$ orderings of $\mathcal{N}$ and $S(\pi, i)$ is the set of players preceding i in the ordering π, and $\Delta_i(v, S)$ is the marginal contribution of player i for a coalition $S \subseteq \mathcal{N} \backslash \{i\}$, i.e., $\Delta_i(v, S) = v(S \cup \{i\}) - v(S)$. Simply speaking, SV is interpreted by the average marginal contribution over all orderings of players. The axiomatic coalition structure value for any coalition structure $\mathcal{P}$ (not just the grand coalition) is called the Aumann-Drèze value (A-D value) [24]. Then, A-D value for a player $i \in S \in \mathcal{P}$ is also denoted by $\varphi^i(S)$ in this paper. For simplicity, we use the term of "Shapley value" for both Shapley and A-D values, because their axiomatic structures are the same except that A-D values are computed for arbitrary coalitions.

In RSG, the worth of S is represented as the summation of the worths of the decomposed atomic coalitions, as (2). Since the providers in each atomic coalition $S_{r,q}$ share the worth of $S_{r,q}$ with SV, thus the total SV of provider i is also the summation of the SVs of provider i in $S_{r,q}$, i.e.,

$$\varphi^i(S) = \sum_{r \in \mathcal{R}[S]} \sum_{q \in \mathcal{Q}_r[S]} \varphi^i(S_{r,q}). \qquad (4)$$

Note that each decomposed atomic coalition $S_{r,q}$ is *simple* [28] in the sense that each player's marginal contribution is 0 or the entire worth of $S_{r,q}$, i.e., $\Delta_i(v, S(\pi, i)) = 0$ or $v(S_{r,q})$. Then, it is easily derived by the definition of SV in (3): for any coalition S,

$$\begin{aligned} \varphi^i(S) \quad = \quad & \sum_{r \in \mathcal{R}[S]} \sum_{q \in \mathcal{Q}_r[S]} \frac{1}{|S_{r,q}|!} \times \\ & \sum_{\pi \in \Pi_{S_{r,q}}} v(S_{r,q}) \cdot \mathbf{1}_{\{\Delta_i(v, S(\pi, i)) > 0\}}, \end{aligned}$$

or,

$$\varphi^i(S) = \sum_{r \in \mathcal{R}[S]} \sum_{q \in \mathcal{Q}_r[S]} \phi^i(S_{r,q}) \cdot v(S_{r,q}), \qquad (5)$$

where $\phi^i(S_{r,q})$ is called the *Shapley portion* of the player i for coalition $S_{r,q}$, defined by:

$$\phi^i(S_{r,q}) = \frac{1}{|S_{r,q}|!} \sum_{\pi \in \Pi_{S_{r,q}}} \mathbf{1}_{\{\Delta_i(v, S(\pi, i)) > 0\}}, \qquad (6)$$

where $\mathbf{1}_{\{.\}}$ is the indicator function. Provider i's Shapley portion in coalition $S_{r,q}$ states the ratio of its quota to the coalition $S_{r,q}$'s worth. A provider i's SV in coalition $S_{r,q}$ depends only on its Shapley portion and the worth of coalition $S_{r,q}$. Note that it is not affected by neither the worth nor the Shapley portion of the other coalitions. This observation has also been used in the prior work [6], which facilitates the analysis of this paper.

We now introduce the concept of stability of the grand coalition under the SV-based value distribution.

Definition III.2 (Stability of Grand Coalition [20], [21]) *The grand coalition is said to be* stable *for a game* $(\mathcal{N}, v)$ *with respect to the Shapley value* φ*, if for all* $S \subset \mathcal{N}$ *there is a player* $i \in S$ *such that* $\varphi^i(\mathcal{N}, v, \mathcal{N}) \geq \varphi^i(\mathcal{N}, v, \{S, \mathcal{N} \setminus S\})$.

Intuitively, the grand coalition is stable under Shapley value, if for any coalition S, there exists at least one player $i = i(S)$ (which may depend on the considered coalition S) that becomes happier in the grand coalition than in S, thus there is no reason to stay out of the grand coalition. We call such a player $i(S)$ *Shapley-advocating player* for a given S.

We now study various impacts of traffic scheduling policies on the revenue of the providers that work in a cooperative manner and the stability of such cooperative behaviors. To that end, we start by studying the coalition worth in Section IV, followed by the stability analysis in Section V.

IV. Coalition Worth

It is immediately clear that in under-demanded networks, the worth function of RSG is super-additive, and thus, the coalition worth is naturally maximized by the grand coalition regardless of the employed traffic scheduling policy. However, in over-demanded networks, the worth function of RSG is no more super-additive since the actually-served content traffic amount is affected by the traffic scheduling policy. Thus, we focus on the over-demanded network. To differentiate the worth for each traffic scheduling policy, we use the notation $v_T(S), v_R(S)$, and $v_P(S)$ to refer to the worth functions of TPP, RPP and PP, respectively, for a given coalition S. We first state our main result on the coalition worth.

Theorem IV.1 (Coalition Worth: Over-demanded) *Consider an over-demanded network and the corresponding RSG.*

- *(i) The RSG under PP is super-additive. Thus, under PP, the worth of the grand coalition is maximized with respect to the worth of other subcoalitions.*
- *(ii) For any given coalition S, the following inequality holds:* $v_P(S) \geq v_R(S) \geq v_T(S)$ *for all* $S \subseteq \mathcal{N}$*. Moreover, PP is an optimal policy that maximizes the worth over all possible traffic scheduling policies.*

Interpretations. First, in *(i),* it is shown that there exists a scheduling policy, which is PP, ensuring that the worth increases as the coalition becomes larger (i.e., super-additivity), thus the grand coalition is preferred under PP. This result is not highly surprising because PP always assigns higher priority to the traffic with higher content values. Second, in *(ii),* this value-oriented feature in PP leads to the result that for any given coalition S, PP is an optimal policy in terms of the worth for S among all other policies.

Similar tendency can be seen between RPP and TPP, as stated in Theorem IV.1*(ii)*. To be more precise, consider two contents q_i, q_j in a given coalition (with region r), where assume that q_i has a larger normalized content value than q_j, i.e., $\beta_i/s_i \geq \beta_j/s_j$. Note that due to this difference in terms of content value, a scheduling policy that assigns more capacities to the contents with higher β/s will eventually generate more worth than other policies which do not. From Table II, we can check that the ratio of the assigned capacities to each content is given by:

$$\text{RPP: } \frac{\beta_i X_{r,i}}{\beta_j X_{r,j}} \quad \text{and} \quad \text{TPP: } \frac{s_i X_{r,i}}{s_j X_{r.j}}.$$

Also, from $\beta_i/s_i \geq \beta_j/s_j$, we have $\beta_i/\beta_j \geq s_i/s_j$. This means that, for example, supposing that a unit capacity is assigned to q_j, then in RPP, q_i, is allocated more capacity than in TPP. This value-based inter-content preference in RPP allows us to have more total worth than in TPP.

Proof: (i): Consider any two coalitions S and S', $S \subset S'$. Then, from the worth decomposition in (2), we get:

$$\begin{aligned} v_P(S') &= \sum_{r\in\mathcal{R}[S']} \sum_{q\in\mathcal{Q}_r[S']} v_P(S'_{r,q}) \\ &= \sum_{r\in\mathcal{R}[S]} \sum_{q\in\mathcal{Q}_r[S]} v_P(S_{r,q}) \\ &+ \sum_{r\in\mathcal{R}[S'\setminus S]} \sum_{q\in\mathcal{Q}_r[S'\setminus S]} v_P(S'_{r,q}) \\ &= v_P(S) + \sum_{r\in\mathcal{R}[S'\setminus S]} \sum_{q\in\mathcal{Q}_r[S'\setminus S]} v_P(S'_{r,q}) \\ &\geq v_P(S). \end{aligned}$$

(ii): All the proofs are based on the description of traffic scheduling policies in Table II and the worth decomposition in (2). Again, due to the revenue decomposition, it suffices to prove for a per-region coalition $S_r \subset S$, $r \in \mathcal{R}$.

First, we prove that for any (possibly over-demanded) coalition S_r $v_R(S_r) \geq v_T(S_r)$. For notational simplicity, we sometimes use s_i rather than s_{q_i} (similarly, β_i and X_i instead of β_{q_i} and X_{q_i}, respectively), unless confusion arises.

From (2) and Table II, we get:

$$\begin{aligned} v_R(S_r) &= \sum_{q\in\mathcal{Q}_r[S]} v_R(S_{r,q}) \\ &= \sum_{q\in\mathcal{Q}_r[S]} \frac{\beta_q n_r}{s_q} \cdot \frac{\beta_q X_{r,q}}{\sum_{q\in\mathcal{Q}_r[S]} \beta_q X_{r,q}}, \end{aligned}$$

and

$$\begin{aligned} v_T(S_r) &= \sum_{q\in\mathcal{Q}_r[S]} v_T(S_{r,q}) \\ &= \sum_{q\in\mathcal{Q}_r[S]} \frac{\beta_q n_r}{s_q} \cdot \frac{s_q X_{r,q}}{\sum_{q\in\mathcal{Q}_r[S]} s_q X_{r,q}}. \end{aligned}$$

Thus, we have:

$$\begin{aligned} & v_R(S_r) - v_T(S_r) && (7) \\ =\; & \frac{n_r}{\sum_{q\in\mathcal{Q}_r[S]} s_q X_{r,q} \sum_{q\in\mathcal{Q}_r[S]} \beta_q X_{r,q}} && (8) \\ \times\; & \left(\sum_{q\in\mathcal{Q}_r[S]} \frac{\beta_q^2 X_{r,q}^2}{s_q X_{r,q}} \sum_{q\in\mathcal{Q}_r[S]} s_q X_{r,q} - \big(\sum_{q\in\mathcal{Q}_r[S]} \beta_q X_{r,q} \big)^2 \right) \\ =\; & \frac{n_r}{\sum_{q\in\mathcal{Q}_r[S]} s_q X_{r,q} \sum_{q\in\mathcal{Q}_r[S]} \beta_q X_{r,q}} \\ \times\; & \sum_{q_i,q_j\in\mathcal{Q}_r[S], i<j} s_i X_{r,i} s_j X_{r,j} \left(\frac{\beta_i}{s_i} - \frac{\beta_j}{s_j} \right)^2 \geq 0. && (9) \end{aligned}$$

Next, to prove that PP is an optimal policy, consider the set of m contents, accessed by the region r in the given coalition S. Let $Q_r[S] = \{1, \cdots, m\}$. Let $\tilde{\beta}_q = \beta_q/s_q$. Without loss of generality, we assume that $\tilde{\beta}_1 \geq \cdots \geq \tilde{\beta}_m$. For any traffic scheduling policy (characterized by its function $f(\cdot)$ as in (1)), let the portion of capacity n_r that is actually used for serving content q be p_q, i.e., $n_r p_q = s_q X_{r,q} f(\cdot)$. Then a traffic scheduling policy in the considered region r can be characterized as a vector $\boldsymbol{p}' \in \mathcal{A}$, where

$$\begin{aligned} \mathcal{A} = \Big\{ & \boldsymbol{p} = (p_q : q = 1, \cdots, m) \mid \\ & \sum_{q\in Q_r[S]} p_q = 1,\ \forall q, 0 \leq p_q \leq \bar{p}_q, \bar{p}_q = s_q X_{r,q}/n_r \Big\}. \quad (10) \end{aligned}$$

Note that $v(S_r) = n_r \sum_{q\in\mathcal{Q}_r[S]} p_q \tilde{\beta}_q$. This worth is maximized over the constraint set $\mathcal{P}$ by assigning the largest possible p_q in the sequence of $\tilde{\beta}_q$, which is realized by PP. This completes the proof. ∎

V. Stability of Grand Coalition

A. Under-demanded Network

In under-demanded networks, RSG was super-additive, as discussed in Section IV, and thus the worth is maximized at the grand coalition for any scheduling policy, and the grand coalition tends to be preferred. However, it is not straightforward that the grand coalition is stable in the sense of Definition III.2, because there may be a smaller coalition in which the players in that coalition can obtain larger individual shares than in the grand coalition. Examples that a (coalition) game is super-additive but unstable include the famous n-person symmetric majority game [22]. However, in RSG, as stated in Theorem V.1, the grand coalition is provably stable with SV, which is only conjectured in [6], [12]. To explain why, recall that the Shapley value in (3) quantifies the average marginal contribution, meaning that a player with higher contribution will be given a higher share. In n-person symmetric majority game, all players' contributions on the coalition worth are the same, thus they equally share the coalition worth with SV. The majority coalition's worth is always one, thus an arbitrary player's Shapley value under the grand coalition is always smaller than that under the other majority coalition.

However, in RSG, the transit ISP is always included in all the coalition with positive worth, since without the transit

ISP the traffic is not transported between users and content ISPs. It implies that the transit ISP's contribution on the grand coalition's worth is larger than or equal to that on other coalitions', i.e. $\varphi^T(\mathcal{N}) \geq \varphi^T(S)$, for any $S \subset \mathcal{N}$. Then, the transit ISP becomes a Shapley-advocating player for any coalition S. Hence, by Definition III.2, the grand coalition is stable in under-demanded network. Theorem V.1 formally states that no ISP will stay out of the grand coalition if the network does not suffer from congestion.

Theorem V.1 (Stability of GC: Under-demanded) *In RSG, the grand coalition is stable with SV for under-demanded networks.*

Proof: If the coalition S' does not contain the transit ISP T, then $v(S') = 0$. Thus, every ISP in the S' is Shapley-advocating ISP for the S'. We claim that the Shapley-advocating ISP in the coalition S containing T is the transit ISP T. Note that the grand coalition $\mathcal{N}$ is decomposed into atomic coalitions, $\mathcal{N}_{r,q}$. For any coalition $S \subseteq \mathcal{N}$, the decomposed atomic coalition of S, which is $S_{r,q}$, is a subset of $\mathcal{N}_{r,q}$, i.e., $S_{r,q} \subseteq \mathcal{N}_{r,q}$. Thus, it is trivial that $v(\mathcal{N}_{r,q}) \geq v(S_{r,q})$. From (6), the transit ISP's Shapley portion in $S_{r,q}$ is given by

$$\phi^T(S_{r,q}) = \frac{1}{2} - \frac{1}{(|\mathcal{C}_q[S_{r,q}]|+1)(|\mathcal{C}_q[S_{r,q}]|+2)},$$

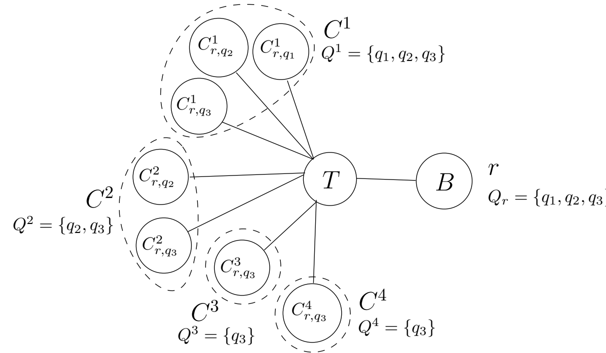
where $|\mathcal{C}_q[S_{r,q}]|$ is the number of content ISPs serving content q contained in the coalition $S_{r,q}$. Then, the Shapley portion of transit ISP in $\mathcal{N}_{r,q}$ is greater than or equal to that in $S_{r,q}$, i.e., $\phi^T(\mathcal{N}_{r,q}) \geq \phi^T(S_{r,q})$, since $|\mathcal{C}_q[\mathcal{N}_{r,q}]| \geq |\mathcal{C}_q[S_{r,q}]|$. Thus, from (5), $\varphi^T(\mathcal{N}_{r,q}) \geq \varphi^T(S_{r,q})$. Then, from (4), we can conclude that $\varphi^T(\mathcal{N}) \geq \varphi^T(S)$, for any $S \subset \mathcal{N}$. It implies that the transit ISP is the Shapley-advocating ISP for any $S \subset \mathcal{N}$. From the Definition of stability III.2, the grand coalition is stable. ■

B. Over-demanded Network: Stability Dominance

However, if the network is over-demanded, it is challenging to describe a "clean" condition under which the grand coalition is always stable for a given traffic scheduling policy. The challenge of stability analysis for over-demanded networks lies in the fact that a player's actual SV is computed in close connection with a traffic scheduling policy, which changes the total worth differently according to the policy's philosophy. This complex coupling makes the analysis almost impossible in general network with multiple transit ISPs and eyeball ISPs. Thus, we take a *comparative* approach that when the grand coalition is stable under some traffic scheduling policy, we study the conditions that the grand coalition is also stable under other policies. For that analysis, we first define the notion of *stability-dominance*:

Definition V.1 (Stability-dominance) *A policy* Π *is said to* stability-dominate *another policy* Π' *(for simplicity, we denote as* $\Pi \geq_S \Pi'$*), if for a given (over-demanded) network, the stability of the grand coalition under* Π' *implies that under* Π.

Next, for tractable analysis, we consider a simplified system that has only one eyeball ISP (i.e., a single region over-demanded network [5]) under the *heavy content regime*. By heavy content regime, we mean that for a given over-demanded network, we assume that removing one content in the network lets the network be under-demanded, i.e., only the grand coalition is over-demanded and any other smaller coalitions are all under-demanded. This restriction is not just for tractable analysis, but also reflects that "light contents", whose total traffic volume is not significant, is unlikely to significantly impact the stability. If needed, we use the subscript T, R, or P, to explicitly express SV's dependence on each scheduling policy, e.g., $\varphi^i_P(\mathcal{N})$ or $\varphi^i_R(\mathcal{N})$. Also, we henceforth omit the subscript r, since we consider a single region network.



n	X	X_q	s_q	β_q
100	5	1, 3, 2	30, 65/3, 17	360, 650/3, 153

s_qX_q	β_qX_q	β_q/s_q
30, 65, 34	360, 650, 306	12, 10, 9

Fig. 3. Example topology: The grand coalition is stable under some policies, but unstable under other policies. Three values in the table refers to ones for three contents q_1, q_2, and q_3.

We first present Lemma V.1 implying that it suffices to check the Shapley value of either transit or eyeball ISP to check the stability of the grand coalition.

Lemma V.1 *A policy* Π *stability-dominates another policy* Π'*, if the player* i*, which is either the transit ISP* T *or the eyeball ISP* B*, satisfies*

$$\varphi^i_{\Pi}(\mathcal{N}) \;\geq\; \varphi^i_{\Pi'}(\mathcal{N}). \tag{11}$$

Proof: Similarly to the proof of Theorem V.1, if a coalition $S' \subset \mathcal{N}$ does not contain either the eyeball ISP B or the transit ISP T, then $v(S') = 0$. Thus, we only consider the coalitions $S \subset \mathcal{N}$ containing both T and B. From Definition III.2, a policy Π stability-dominates another policy Π' if $\varphi^T_{\Pi'}(\mathcal{N}) \geq \varphi^T_{\Pi'}(S)$ implies $\varphi^T_{\Pi}(\mathcal{N}) \geq \varphi^T_{\Pi}(S)$, for all $S \subset \mathcal{N}$. Note that we assume heavy-content regime, thus for all $S \subset \mathcal{N}$, S is under-demanded. Therefore, the SVs under different traffic scheduling policies are the same for all coalitions $S \subset \mathcal{N}$, i.e., $\varphi^i_{\Pi}(S) = \varphi^i_{\Pi'}(S), \forall S \subset \mathcal{N}$. Consequently, if $\varphi^i_{\Pi}(\mathcal{N}) \geq \varphi^i_{\Pi'}(\mathcal{N})$, then $\varphi^T_{\Pi'}(\mathcal{N}) \geq \varphi^T_{\Pi'}(S)$ implies $\varphi^T_{\Pi}(\mathcal{N}) \geq \varphi^T_{\Pi}(S)$. This completes the proof. ■

In Lemma V.1, we have proved that the stability dominance among traffic scheduling policies is determined by SV of either transit or eyeball ISP at the grand coalition. In the following

[5]As an extension, we will consider the stability of multi-region network in Section V-D.

section, we will compare the traffic scheduling policies in the context of the stability-dominance for a given network.

C. Impact of Traffic Scheduling Policies on Stability

Example: GC is not always stable even under PP. It is tempting to conjecture that the grand coalition is stable under PP, because of the nice properties of PP such as worth maximization at the grand coalition and worth optimality across all possible scheduling policies (see Theorem IV.1). Counter-intuitively, it is not always true, which is exemplified in Fig. 3. In this example, the grand coalition is not stable because the Shapley value of the transit ISP in a smaller coalition can be larger than that of the grand coalition, i.e., $\varphi^T(\mathcal{N}) = 411.83$, and $\varphi^T(\mathcal{N} \setminus \{C^1_{r,q_1}\}) = 413.63$. This instability even in PP can arise from the characteristic of the Shapley value (or the Shapley portion): Note that $\beta_1/s_1 > \beta_2/s_2 > \beta_3/s_3$ from Fig. 3, but $\phi^T(\mathcal{N}_{q_1}) < \phi^T(\mathcal{N}_{q_2}) < \phi^T(\mathcal{N}_{q_3})$. It implies that the grand coalition is not stable since the content q_1 has too small Shapley portion, i.e., q_1 is serviced by small number of content ISPs, even though it is a valuable content.

We now present our main result which compares traffic scheduling policies in terms of stability. Theorem V.2 states that a scheduling policy with value-preference is better than other policies that are more agnostic to content values, under some mild conditions.

Theorem V.2 (Stability of GC: Over-demanded) *When ISPs share their revenue with Shapley value, for an over-demanded network under the heavy content regime,*

$$PP \ \geq_S \ RPP \ \geq_S \ TPP, \tag{12}$$

if the following condition is met:

$$\begin{aligned}\textbf{C1:} \sum_{q_i,q_j \in Q, i>j} &(s_i s_j X_i X_j) \\ \times \quad \left(\frac{\phi^T(\mathcal{N}_{q_i})\beta_i}{s_i} - \frac{\phi^T(\mathcal{N}_{q_j})\beta_j}{s_j}\right)&\left(\frac{\beta_i}{s_i} - \frac{\beta_j}{s_j}\right) \geq 0.\end{aligned} \tag{13}$$

Proof: The proof is based on the description of traffic scheduling policies in Table II and the worth decomposition in (2). Using the assumptions of one transit and one eyeball ISP under the heavy content regime, from a simple algebra it is not hard to see that the Shapley value of the transit ISP at the grand coalition is given by:

$$\begin{aligned}\varphi^T_R(\mathcal{N}) &= \sum_{q\in\mathcal{Q}} \phi^T(\mathcal{N}_q) \cdot v_R(\mathcal{N}_q) \\ &= \sum_{q\in\mathcal{Q}} \phi^T(\mathcal{N}_q) \cdot \frac{\beta_q n}{s_q} \cdot \frac{\beta_q X_q}{\sum_{q\in\mathcal{Q}} \beta_q X_q}, \quad (14) \\ \varphi^T_T(\mathcal{N}) &= \sum_{q\in\mathcal{Q}} \phi^T(\mathcal{N}_q) \cdot v_T(\mathcal{N}_q) \\ &= \sum_{q\in\mathcal{Q}} \phi^T(\mathcal{N}_q) \cdot \frac{\beta_q n}{s_q} \cdot \frac{s_q X_q}{\sum_{q\in\mathcal{Q}} s_q X_q}. \quad (15)\end{aligned}$$

Thus, using (14) and (15),

$$\begin{aligned}&\frac{1}{\kappa}\left(\varphi^T_R(\mathcal{N}) - \varphi^T_T(\mathcal{N})\right) = \\ &\sum_{q\in\mathcal{Q}} \frac{\phi^T(\mathcal{N}_q)\beta_q^2 X_q^2}{s_q X_q} \cdot \sum_{q\in\mathcal{Q}} s_q X_q - \sum_{q\in\mathcal{Q}} \phi^T(\mathcal{N}_q)\beta_q X_q \cdot \sum_{q\in\mathcal{Q}} \beta_q X_q \\ &= \sum_{\substack{q_i,q_j \\ \in\mathcal{Q}, i>j}} s_i X_i s_j X_j \left(\frac{\phi^T(\mathcal{N}_{q_i})\beta_i}{s_i} - \frac{\phi^T(\mathcal{N}_{q_j})\beta_j}{s_j}\right)\left(\frac{\beta_i}{s_i} - \frac{\beta_j}{s_j}\right),\end{aligned}$$

where the constant $\kappa > 0$ is:

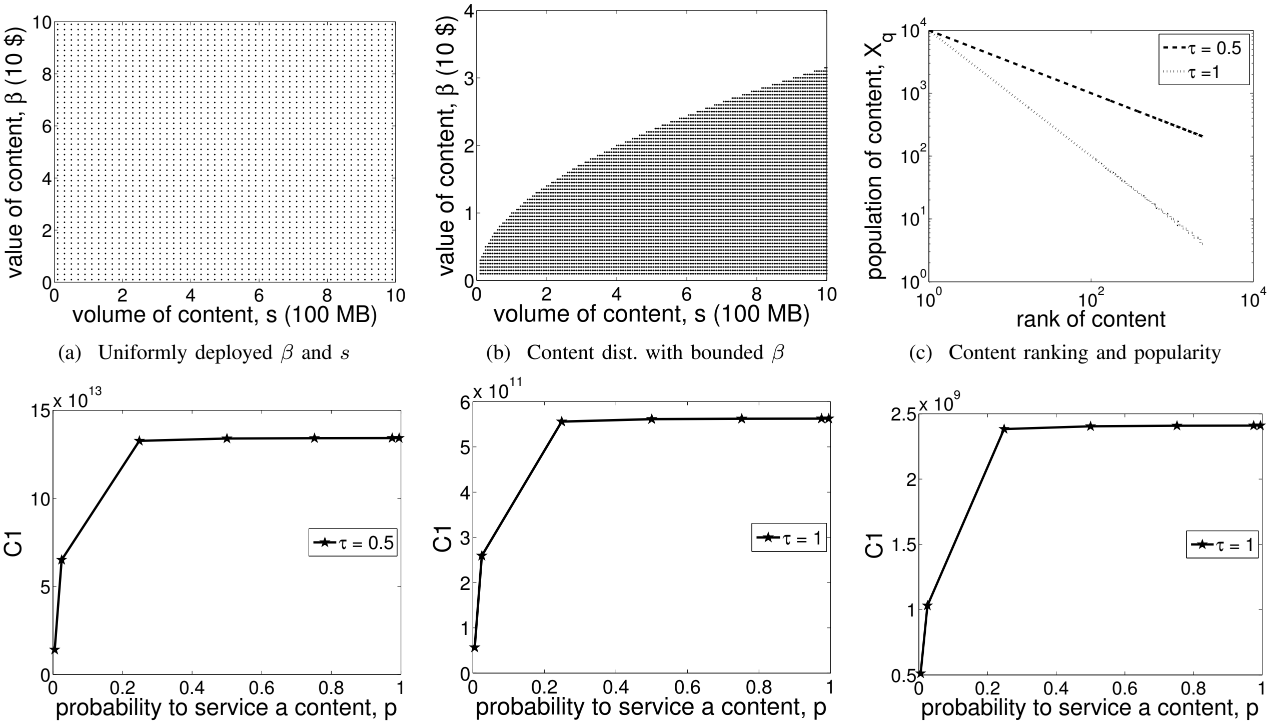
$$\kappa = \frac{n}{\sum_{q\in\mathcal{Q}} s_q X_q \cdot \sum_{q\in\mathcal{Q}} \beta_q X_q}.$$

Noting that κ is a positive constant, we have: $\varphi^T_R(\mathcal{N}) - \varphi^T_T(\mathcal{N}) \geq 0$ if and only if $\mathbf{C1} \geq 0$. Then from Lemma V.1, if $\mathbf{C1} \geq 0$, RPP stability-dominates TPP, i.e., RPP $\geq_S$ TPP.

Next, to prove that PP stability-dominates any other policies, similarly to the proof of Theorem IV.1, consider a set $Q = \{1, \cdots, m\}$ of m contents accessed by the region in the grand coalition $\mathcal{N}$. Let $\tilde{\beta}_q = \beta_q/s_q$. Again, without loss of generality, we assume that $\tilde{\beta}_1 \geq \cdots \geq \tilde{\beta}_m$. For any traffic scheduling policy, let the portion of capacity n that is actually used for serving content q be p_q (note that we consider a single region here), i.e., $np_q = s_q X_q f(\cdot)$. Then a traffic scheduling policy in the grand coalition can be characterized as a vector $\boldsymbol{p} \in \mathcal{A}$, where $\mathcal{A}$ is from (10). Note that $v(\mathcal{N}) = n\sum_{q\in\mathcal{Q}} p_q \tilde{\beta}_q$, and thus the Shapley value of the transit ISP is $\varphi^T(\mathcal{N}) = n \cdot \sum_{q\in\mathcal{Q}} \phi^T(\mathcal{N}_q) p_q \tilde{\beta}_q$. If the condition $\mathbf{C1} \geq 0$ is met, it implies that prioritizing higher-value contents guarantees higher Shapley value of the transit ISP. Then, this Shapley value is maximized over the constraint set $\mathcal{P}$ by assigning the largest possible p_q in the sequence of $\tilde{\beta}_q$, which is done by PP. This completes the proof. ■

As showed in the example of Fig. 3, a more profitable traffic scheduling policy such as PP does not always guarantee the stability of ISPs' grand coalition. Instead, Theorem V.2 presents the *stability degree* of three policies for an over-demanded network with Shapley value based revenue sharing. It implies that more profitable traffic scheduling policies tend to have higher degree of stability when ISPs share their revenue with Shapley value, which is a balanced and fair revenue sharing algorithm. In other words, under **C1**, an over-demanded network under either RPP or PP is stable (i.e., all ISPs have stable peerings) with Shapley value whenever the network is stable under TPP.

When does the condition C1 hold? We cannot theoretically guarantee that **C1** always holds, but the following numerical example, as shown in Fig. 4, tells us that the condition **C1** is mild. We consider a network consisting of 50 content ISPs, one transit, and one eyeball ISP. We assign two cases of size-value distributions, as depicted in Fig. 4(a) and Fig. 4(b), respectively. Fig. 4(a) is the case that β and s are uniformly at random over 2500 contents, whereas in Fig. 4(b), the contents satisfying $\beta < \sqrt{s}$ (excluding the contents with small volume but high values) are selected. This choice seems somewhat artificial, but comes from the trend that the content value does grow in less proportion to the size [29]. Moreover, we assume



(a) Uniformly deployed β and s

(b) Content dist. with bounded β

(c) Content ranking and popularity

(d) **C1** under (a) when $\tau = 0.5$

(e) **C1** under (a) when $\tau = 1$

(f) **C1** under (b) when $\tau = 1$

Fig. 4. Numerical results showing the mildness of the condition **C1**.

that the total population in the network is 100,000 and we consider two cases of content popularity by using Zipf-like distribution with parameter $\tau = 0.5$ and 1, shown as Fig. 4(c) (both axis are log-scaled).

We vary "content availability" by introducing a content selection probability p that corresponds to the probability that a content ISP selects any content (thus, the mean number of contents owned by one content ISP is $2500 \times p$). Then, $|\mathcal{C}_{q_i}| \sim \text{Binomial}(2500, p)$, for all contents q_i. Figs. 4(d), 4(e), and 4(f) show how **C1** varies for $p = 0.005, 0.025, 0.25, 0.5, 0.75, 0.9975, 0.995$. Figs. 4(d) ($\tau = 0.5$) and 4(e) ($\tau = 1$) are the results with the size-value distribution in Fig. 4(a). Fig. 4(f) uses the size-value distribution in Fig. 4(b) with $\tau = 1$. We see that for all cases, the condition **C1** holds.

To better understand what Theorem V.2 implies, we introduce *value-preferential* C-ISP, which prefers the higher-valued contents, i.e., the C-ISP serves content q_i rather than q_j, if $\beta_i/s_i > \beta_j/s_j$. Naturally, it reflects C-ISPs' inherent desire to maximize their revenues, since C-ISP can get more revenue by serving higher-valued contents. Stability of GC is affected by the value-preferential behavior of C-ISP as described in following proposition.

Proposition V.1 (Stability with value-preferential C-ISP) *When ISPs share their revenue with Shapley value, for an over-demanded network under the heavy content regime,*

$$PP \geq_S RPP \geq_S TPP, \tag{16}$$

when C-ISPs are value-preferential ones.

Proof: From (13), let $c_{ij} = (s_i s_j X_i X_j) \times \left(\frac{\phi^T(\mathcal{N}_{q_i})\beta_i}{s_i} - \frac{\phi^T(\mathcal{N}_{q_j})\beta_j}{s_j}\right)\left(\frac{\beta_i}{s_i} - \frac{\beta_j}{s_j}\right)$. It suffices to show that if $\frac{\beta_i}{s_i} - \frac{\beta_j}{s_j} > 0$, then $\frac{\phi^T(\mathcal{N}_{q_i})\beta_i}{s_i} - \frac{\phi^T(\mathcal{N}_{q_j})\beta_j}{s_j} > 0$. Without loss of generality, we assume that $\beta_i/s_i > \beta_j/s_j$. Then, when all C-ISPs are value-preferential, it is always true that $|\mathcal{C}_{q_i}| > |\mathcal{C}_{q_j}|$. Then, $\phi^T(\mathcal{N}_{q_i}) > \phi^T(\mathcal{N}_{q_j})$ since the Shapley portion of the transit ISP in the decomposed coalition containing q_i is given by:

$$\phi^T(\mathcal{N}_{q_i}) = \frac{1}{2} - \frac{1}{(|\mathcal{C}_{q_i}|+1)(|\mathcal{C}_{q_i}|+2)}.$$

This completes the proof. ■

D. Extension to Multi-region Networks

For tractability, our work for stability in Section V is limited in the sense of network topology since we only consider single region networks where single eyeball ISP exists. Even though we assume the limited topology, the rigorous analysis of stability was still challenging caused by interactions of traffic scheduling policy and computational complexity of Shapley value.

In this section, we extend the stability analysis to *multi-region* network. The main ideas of extension are (i) the independence on traffic scheduling policy of each region and (ii) the independence on coalition worth of each region. Recall that the traffic scheduling policy f is defined as (1):

$$\sum_{q \in \mathcal{Q}_r} s_q X_{r,q} \cdot f(s_q, \beta_q, n_r, X_{r,q}) \leq n_r$$

where $0 \leq f(\cdot) \leq 1$. In above equation, the traffic scheduling policy $f(\cdot)$ only depends on traffic from a single region r, thus scheduling policies of multi-region are independent. Moreover, the coalition worth of grand coalition (2) can be decomposed into the worths of single-regional subcoalitions:

$$v(S) = \sum_{r\in\mathcal{R}[S]} \sum_{q\in\mathcal{Q}_r[S]} v(S_{r,q}) = \sum_{r\in\mathcal{R}[S]} \left\{ \sum_{q\in\mathcal{Q}_r[S]} v(S_{r,q}) \right\}. \quad (17)$$

Thus, the coalition worth of each region is also independent on that of others. Consequently, the stability of multi-region networks can be expressed by the stability of single-regional subcoalitions.

Proposition V.2 (Stability of multi-region network) *The grand coalition of over-demanded multi-region network is stable for a game $(\mathcal{N}, v)$ with Shapley value, if for all $r \in \mathcal{R}$, subcoalition $\mathcal{N}_r = \cup_{q\in\mathcal{Q}_r}\mathcal{N}_{r,q}$ is stable for a game $(\mathcal{N}_r, v)$ with Shapley value.*

Proof: From the definition of the grand coalition in Definition III.2, the grand coalition $\mathcal{N}$ is stable if $\forall S \subset \mathcal{N}$, $\exists i \in S$ such that $\varphi^i(\mathcal{N}, v, \mathcal{N}) \geq \varphi^i(\mathcal{N}, v, \{S, \mathcal{N} \setminus S\})$. The SVs of player i in $\mathcal{N}$ and in $S \subset \mathcal{N}$ are defined by:

$$\varphi^i(\mathcal{N}, v, \mathcal{N}) = \sum_{r\in\mathcal{R}} \sum_{q\in\mathcal{Q}_r} \phi^i(\mathcal{N}_{r,q}) \cdot v(\mathcal{N}_{r,q}),$$

and

$$\varphi^i(\mathcal{N}, v, \{S, \mathcal{N} \setminus S\}) = \sum_{r\in\mathcal{R}[S]} \sum_{q\in\mathcal{Q}_r[S]} \phi^i(\mathcal{S}_{r,q}) \cdot v(\mathcal{S}_{r,q}),$$

respectively. Moreover, from the definition of SV,

$$\varphi^i(\mathcal{N}_r, v, \mathcal{N}_r) = \sum_{q\in\mathcal{Q}_r} \phi^i(\mathcal{N}_{r,q}) \cdot v(\mathcal{N}_{r,q}),$$

$$\varphi^i(\mathcal{N}_r, v, \{S_r, \mathcal{N}_r \setminus S_r\}) = \sum_{q\in\mathcal{Q}_r[S_r]} \phi^i(\mathcal{S}_{r,q}) \cdot v(\mathcal{S}_{r,q}),$$

where $\mathcal{N}_r = \cup_{q\in\mathcal{Q}_r}\mathcal{N}_{r,q}$ and $S_r = \cup_{q\in\mathcal{Q}_r[S_r]} S_{r,q}$.

We already know that $\forall r \in \mathcal{R}$, subcoalition $\mathcal{N}_r$ is stable, thus $\forall S_r \subset \mathcal{N}_r, \exists i \in S_r$ such that

$$\varphi^i(\mathcal{N}_r, v, \mathcal{N}_r) \geq \varphi^i(\mathcal{N}_r, v, \{S_r, \mathcal{N}_r \setminus S_r\}).$$

Consequently, we can get this inequality below:

$$\varphi^i(\mathcal{N}, v, \mathcal{N}) = \sum_{r\in\mathcal{R}} \varphi^i(\mathcal{N}_r, v, \mathcal{N}_r) \geq$$

$$\sum_{r\in\mathcal{R}[S]} \varphi^i(\mathcal{N}_r, v, \{S_r, \mathcal{N}_r \setminus S_r\}) = \varphi^i(\mathcal{N}, v, \{S, \mathcal{N} \setminus S\}).$$

This completes the proof. ■

This extension thoroughly shows that our stability analysis is enough to adopt in practical networks. Still, our study looks like that it has a level of simplification since we assume that there exists an eyeball ISP in a region. However, even there exist multiple eyeball ISPs in a single region, each of eyeball ISP has its own link capacity connected to transit ISP. Therefore, an eyeball ISP in the region can consider as an eyeball ISP who has its own link and own region in which its customers are. Consequently, the only remaining assumption is a single transit ISP, the extension to multi-transit ISP would be future direction of our research.

VI. Conclusion and Discussion

A. Summary

In this paper, we have studied the coalition worth and the stability of the grand coalition under Shapley value based revenue sharing. We especially focus on the impact of traffic scheduling policies on them, where we have considered both under-demanded and over-demanded networks. The main challenges for over-demanded networks stem from the complex inter-plays on how the individual players are assigned their own share from the worth generated by cooperation, controlled by the employed scheduling policy. The main messages of our analysis are: traffic scheduling polices with higher value preference tend to achieve larger coalition worth and have better stability features.

People have been worried about the unfair sharing of the revenue in the Internet [3], [4], and some of the recent works [6], [13]–[16] have claimed that the cooperation of ISPs helps with fair sharing and is beneficial to both ISPs and users. However, it has still been questionable whether providers are willing to cooperate. Our work provides an answer but to such a question of *stability* of the ISPs' cooperation. We consider two cases when the network is congested and uncongested, and conclude that when the network is uncongested, ISPs have strong tendency to cooperate, whereas when congested, ISPs' cooperation highly depends on how the traffic from content providers is differentiated by the network service providers.

The implications to providers include: (a) In case when network capacity is enough to handle the Internet traffic, ISPs have enough incentive to form a coalition, but (b) in case when capacity increase does not follow traffic increase and the network is congestion often, the network ISPs (i.e., transit and eyeball ISPs) should give more priority to the content traffic with more values to stabilize their cooperation. These implications may provide a clue to why cooperation is very difficult in practice, because content-aware traffic management adds high complexity in network operation, and network neutrality is still a burden to them.

B. Limitation and Future Work

We consider a network that has only one transit ISP and in the section that discusses stability of the coalition of over-demanded networks, we further assume that there exists only one region with only one eyeball ISP. We have relaxed the assumption on only one region in Section V-D, however, we still need an assumption of a single transit ISP for tractability. Thus, naturally, future work includes the study of the cases when there exists multiple transit ISPs, where some kind of approximation techniques such as fluid-model approximation or large-scale asymptotic may be necessary.

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