Profit Optimization for Wireless Video Broadcasting Systems Based on Polymatroidal Analysis

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***Abstract*—This study addresses the problem of profit maximization between wireless service providers (WSPs) and content providers (CPs) in wireless broadcasting systems, while simultaneously providing high quality of experience for end-users (EUs). We first study the profit model in wireless broadcasting networks with a particular attention to the heterogeneous requirements of EUs, e.g., different display sizes and variable channel conditions. Then, we propose a profit formulation that describes the requirements of wireless service providers and content providers, as well as the satisfaction of EUs that essentially depends on video quality and service charges. We propose a new polymatroidal theoretic framework for maximizing the resulting three-side achievable profit through proper bandwidth allocation. Our framework exploits two particular structures, namely the underlying polymatroidal structure of the profit region and the contra-polymatroidal structure of the rate region. We then propose a profit maximization solution by finding a rate allocation vector on the sum-rate facet that satisfies the maximal achievable profit among the WSP, CPs, and EUs. Experiments on different broadcasting scenarios demonstrate the effectiveness of the proposed method. The WSP is capable of generating more revenues by applying the proposed approach to their marketing strategies while satisfying the demands from CPs and EUs.**

***Index Terms*—Heterogeneous, optimization, polymatroid, pricing, video broadcasting.**

I. Introduction

VIDEO traffic over wireless networks is becoming a dominant traffic type in mobile applications [1], which is regarded as the most influential factor driving the need for increasing network capacity.[1] At the same time, mobile devices become more heterogeneous in capabilities ranging from smartphones with small screens to tablets with high-resolution displays. Wireless service providers (WSPs) have to develop new strategies along with adaptable pricing structures that can support heterogeneous users' requirements to meet the rapid growing demand for video services. Pricing video-services becomes more attractive to WSPs than the conventional Quality-of-Service (QoS) management because it is well accepted by end-users (EUs) and content providers (CPs). In wireless broadcasting systems, the pricing is characterized as a framework where WSPs can impose price strategies of services or specific QoS provisions to users. WSPs make profits by offering network connectivity and bandwidth, which allow content providers to provide videos for end-users [2]. EUs then access the content of interest and select what they are willing to pay for. This results in a complex interplay between different parts of wireless video broadcasting systems. Therefore, there is a need for an effective design of new pricing strategies and resource allocation that can maximize the profit, which is a pretty challenging task.

Current pricing schemes in wireless networks could be roughly classified into two types, i.e., fixed pricing and dynamic pricing, depending on usage flexibility, wireless condition adaptability, and scalability requirements from WSPs and EUs [3], [4]. Based on different requirements of pricing strategies from WSPs, those two categories can be further divided into three pricing schemes: Usage-based [5], service-based [6], and time-dependent [7] pricing schemes. One common objective of these pricing schemes is to allocate wireless resources to current and future EUs, such that the overall resource utilization can be maximized. The resource utilization could be revenues [8], capacity usage, EUs' satisfaction [9], transmitted power [10], or spectrum reuse [11], [12] for example.

Generally, as the capacity of a wireless network reaches its maximum, WSPs can control the amount of delivered content over the network and maximize profits by selecting a proper pricing strategy. Most current pricing schemes consider high-bandwidth data applications and unfortunately neglect the true nature of the traffic. For example, unlike most generic data applications, audio and video streaming services usually present nonconvex utility properties, and such properties cannot be delineated by stepwise or sigmoid functions [13] that are typically used for characterization of consumed bandwidth in data services. The pricing problem therefore becomes more complex in streaming services as bandwidth presents the tradeoff between the quality of services and constraints of the streaming applications.

At present, the problem of video broadcasting under pricing-driven models has not been well studied, despite the fact that

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[1][Online]. Available: http://www.allot.com/Allot_MobileTrends_Report_Shows_Significant_Growth.html

many methods have been proposed to improve video quality in wireless networks.

From the viewpoint of video broadcasting, most video broadcasting solutions assumed only simplistic underlying wireless network models, and they did not consider the relationship between WSPs, CPs, and heterogeneous EUs. Contrarily, as the demand for large-bandwidth video services becomes higher, the requirement to drive high-resolution video streams varies with the tradeoff between the quality and the type of resources. For example, wireless video streaming is the most energy-consumption service in user terminals due to the large proportion of video data in transmission. Thus, many studies emphasized improvement in the QoE and energy efficiency for heterogeneous wireless receivers, such as [14]. Recent research maximized the net video quality through auction [15] or game theoretic approaches [16], rather than profit maximization. More recently, Zhou *et al.* [17] developed a new idea to optimally allocate the resource by jointly considering the uncertainties of QoE models and video playback time. One remarkable advantage of their solutions was low complexity. Note that one of the major purposes for a broadcasting system is to improve the QoE. However, how to define and model the QoE is a difficult problem. Most recent research solved this problem from different aspects, such as extended PSNRs [18] and video summary metrics [19]. Since scalable video broadcast/multicast services employ a single transmission rate to cover all EUs [20], SVC streaming-based models become a tendency compared with most existing solutions in wireless broadcasting networks. The recent model in [21] and its extension version "Q-STAR" [22] showed efficiency in QoE measure, particularly in wireless multimedia broadcasting systems [14]. However, it is still difficult for profit analysis on how to satisfy the requirements of current wireless video broadcasting, where the WSP is not only interested in its own profit but also guarantees the QoE of EUs and the profit of CPs.

From the perspective of pricing-driven transmission, despite recent intensive studies on revenue-based solutions, there is still no effective approach for video service-based resource allocation, except for [23]. Moreover, it is unclear how the relationship between WSPs, CPs, and heterogeneous EUs influences a wireless video broadcasting system. For example, the work in [8] presented a rate-allocation model for traditional content (instead of using multimodals) by considering a three-way interaction among EUs, ISPs, and CPs. The work [2] studied the revenue maximization for Internet Service Providers (ISPs) with time-constrained pricing in broadband access networks, and the research in [24] examined the profit maximization for a cognitive virtual network operator in a dynamic wireless network. However, these works did not exploit detailed knowledge of the video content nor the requirements for CPs and EUs to offer pricing-driven video services. Going one step further, the study in [10] formulated a resource-allocation problem for voice users, where the willingness of the user was modeled as a step function with respect to "Signal-to-Interference plus Noise Ratios (SINRs)." Through forward-link transmit-power allocation, their proposed system could maximize either the sum-satisfaction of all broadcasting EUs or the total revenue generated from the EUs. Interestingly, none of the above works proposed a joint resource optimization framework where all the components of the system as well as video clients with heterogeneous capabilities are considered together. It is therefore a challenge to design an effective pricing structure in consideration of the profits of WSPs and CPs along with the satisfaction of heterogeneous EUs.

This paper studies the pricing problem[2] for wireless broadcasting services by considering jointly the different actors in the system. It proposes a new polymatroidal theoretic framework, which is effective and powerful to address three-side markets in profit maximization problems. More particularly, we draw upon the polymatroidal pricing structure and show how the profit can be maximized for WSPs and CPs, while the satisfaction of EUs is preserved. The merit of our framework is that this study provides a precise mathematical characterization of the optimization solutions and their properties, with a unified framework where three-side profit maximization can be sought for.

We first account for heterogeneous EU demands, for instance, video spatial resolutions, time-varying channel states, and transmission prices, which all affect the Quality of Experience (QoE) of wireless users. Second, we effectively exploit the special polymatroidal structure of the profit regions for EUs, CPs, and WSPs, whose three-side subsets respectively form three polymatroidal structures. By exploiting the particular properties of polymatroidal representation, we can maximize the system profit by solving the rate-allocation problem with the use of a two-tier structure: 1) an outer loop aims at the profit maximization of the WSP and 2) an inner loop focuses on the maximal achievable profit and satisfaction of CPs and EUs, respectively. This two-tier optimization problem can be efficiently solved by using greedy methods adapted to the proposed polymatroidal representation. We then propose extensive experiments to analyze the performance of our proposed profit optimization framework for various broadcasting scenarios. The results show that our method can improve performance with respect to the optimization of the utility of each component independently. In particular, our algorithm leads to almost full utilization of network resources, subsequently bringing satisfactory QoE for multiple heterogeneous EUs. Meanwhile, the WSP and CPs can simultaneously obtain maximal profits, which confirms the benefit of our joint optimization method. With the pricing strategies solved by proposed polymatroidal structures, the WSP is capable of computing the optimal source rates and channel rates for each video requested by heterogeneous users.

In summary, the contributions of this study are listed as follows.

- We propose a new formulation of the profit maximization problem based on a three-side system that combines WSPs, CPs, and EUs. Its objective is to find an optimal solution for maximizing the user satisfaction and the overall profits during broadcasting.
- This study presents a new decomposition of the profit maximization problem by converting it into a special rate-splitting problem. We prove that such a problem is a special

[2]This work focuses on the optimization of endogenous variables $\{r_s, \gamma_s\}$ (i.e., the rate vector and the error protection vector) based on observed exogenous variables (i.e., the charges between WSPs, CPs, and EUs). Notably, the exogenous variables are set by the market of WSPs and CPs, but not by the proposed method. This study adapts the endogenous variables to exogenous variables, so that WSPs can select the optimal rate vector and the optimal error protection vector to guarantee the QoE of EUs.

covering problem that allocates both video-layer rates and the corresponding error-protection rates to all EUs.
- We propose a novel polymatroidal representation to model the three-side profit regions and introduce a contra-polymatroidal model for the rate regions. We further prove that the polymatroidal surface represents the maximal profit output, and that the contra-polymatroidal surface implies the minimal required rate based on a given system profit.
- We show that the resource optimization problem is equivalent to that of finding a point at the intersection of sum-rate facets, which satisfies the profits among the active EUs, CPs, and WSP. We devise a fast algorithm for the computation of the general splitting-rate points on the sum-profit facet.
- We propose a progressive performance analysis where the simulations are carried out over typical wireless broadcasting scenarios with the proposed solution consistently maximizing the final profit of the total system.

The rest of the paper is organized as follows. In Section II, we describe the general framework along with the pricing model considered in this paper. In Section III, we present the new polymatroidal along with contra-polymatroidal structures and show that the optimal rate allocation can be obtained by solving a family of polymatroidal optimization problems. In Section IV, we give the detailed optimization solution. Experimental results are provided in Section V. Finally, the conclusion and future work are presented in Section VI.

II. Pricing Model

In this section, we consider a wireless video broadcasting network, where a WSP transmits video content provided by CPs to heterogeneous EUs. The following description firstly analyzes the characteristics of EUs in wireless environments and then introduces the network pricing model and the profit region.

A. User Satisfaction Model

Unlike general data traffic, video delivery systems should be capable of providing different levels of quality through adaptive coding and transmission. To cover heterogeneous end-user requirements, they can employ Scalable Video Coding (SVC)[25] to provide layered and scalable video streams. We use SVC to generate spatial scalable layers to serve multiple EU groups simultaneously with different display capabilities. Video streams are usually transmitted progressively and layer by layer, and each set of layers corresponds to a group of users with the same display quality. To handle channel losses, Forward Error Correction (FEC) is a frequently used mechanism for the flexible protection during video transmission as it can adapt to variable channel conditions. When bandwidth is limited, the proper design of FEC mechanisms is critical to the three-side maximization problem considered in this paper as it dominates the QoE of users. Before we discuss the profit maximization problem, the following description first concentrates on how to quantify layered transmissions by devising a metric that permits to have multiple sessions with different QoE.

Inspired by the model in [13], [26] and [27], we develop a rate-utility function for multiuser broadcasting based on spatial scalability and FEC protection. This function is primarily based on a perceptual quality metric called "model for normalized quality v.s. normalized spatial resolution (MNQS)" [22]. It can measure the perceptual quality of each video content. The uniqueness of this metric is that it considers the impact of the spatial, temporal, and amplitude resolution of a compressed video. The function of the MNQS is

$$MNQS(l) = \frac{1 - e^{-\theta(\tau)(\frac{l}{L})^{0.74}}}{1 - e^{-\theta(\tau)}} \tag{1}$$

where $\theta(\tau)$ is a model parameter with the quantization stepsize τ, and $l = \{1, \ldots, L\}$ is the index of the spatial layer of the video content. In this work, τ and $\theta(\tau)$ are fixed, and the quality metric is simplified as a function of the spatial-layer index l. It is straightforward to prove that $MNQS(l)$ is an increasing function. The output of the MNQS function is related to the video rate of the lth layer.

Let us now consider a single-cell network, which broadcasts layered video contents to a group of heterogeneous users. Assume that there are N users that are requesting S video contents. The quality of services for an EU is a function of the effective rate of the video that this client is served with. Then, in a scalable broadcasting system, the quality $MNQS(l)$ of each user is achieved only when the data of the current layer and the previous layers can be successfully received. Based on such an assumption, the error protection mechanism should also be adopted accordingly to the requirements of channel conditions. Overall, the heterogeneity of clients and channel conditions lead to the following characteristics. 1) The system should be capable of serving heterogeneous devices with different display sizes. For example, the $(l-1)$th, lth, and $(l+1)$th layers can respectively satisfy the requirements from smartphones, tablets, and laptops. 2) For the each layer l, various error protection rates $\gamma_{s,l}$ may be required for different clients even for the same video source rate $r_{s,l}$. The quality $MNQS(l)$ of each user evolves accordingly.

We can now analyze the utility function $u_{s,n}(\cdot)$ for user n and service s, where $u_{s,n}$ is a function of the source rate r_s requested by the EU (an example is shown in Fig. 1). We define the total broadcasting rate as $\varsigma_s = r_s + \gamma_s = \sum_{k=1}^{l}(r_{s,k} + \gamma_{s,k})$, where $r_{s,k}$ is the original video rate of the kth layer; $\gamma_{s,k}$ is the corresponding error protection rate; r_s is the total source rate, and γ_s is the total FEC rate. Assume ε_n is the channel erasure rate of user n when we use Fountain coding [28], [29] to realize FEC. Then, $\gamma_{s,l}$ can be roughly estimated as $\gamma_{s,k} \geq r_{s,k}(\frac{1+\delta}{1-\varepsilon_n} - 1)$, where δ is the overhead of Fountain coding, and δ is a fixed small positive value. In layered coded bitstreams, the lth layer is valid only when the current layer and all the lower layers $\{1, \ldots, l\}$ are successfully received. We use the following two conditions to demonstrate such dependence. There are

$$u_{s,n}(r_s) = MNQS\left(l_n\right) \tag{2}$$

and

$$\gamma_{s,k,n} \geq r_{s,k}\left(\frac{1+\delta}{1-\varepsilon_n} - 1\right) \qquad \forall k \in \{1, \ldots, l\}. \tag{3}$$

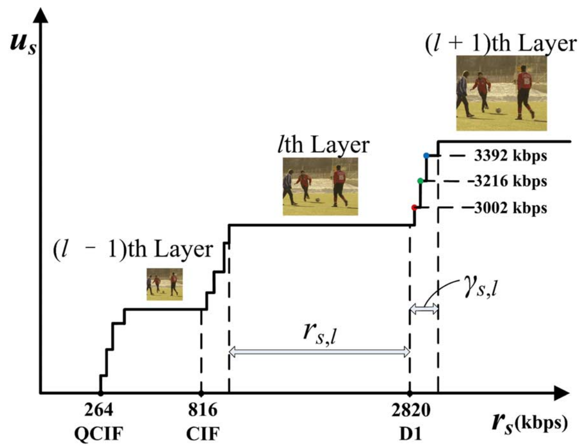


Fig. 1. Example of layered video transmission, where three heterogeneous EUs are serviced. The vertical axis denotes utility rates, whereas the horizontal is video rates. In wireless transmission, an additional $\gamma_{s,l}$ rather than basic lth layered video-rate is required if more EUs are supported.

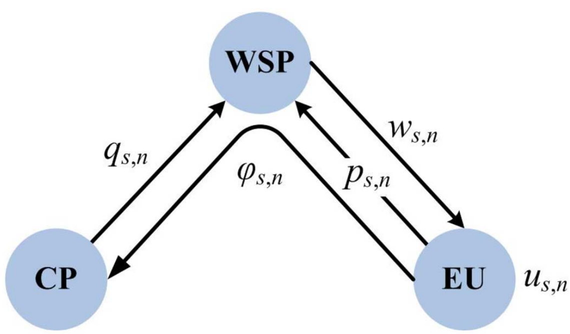


Fig. 2. Basic price relation among the WSP, CPs, and EUs.

B. Network Pricing Model

This subsection introduces the pricing model for wireless videos broadcast to heterogeneous end-users. The basic pricing relationships among the WSP, CPs, and EUs are shown in Fig. 2. The EU requests video content from CPs through the service platform offered by the WSP. The profit function $v_{s,n}(r_s)$ herein describes the benefit of the content provider associated with the content s, which is serviced at quality $u_{s,n}(r_s)$ to EU n. We define $p_{s,n}$ as the price per unit of data that the EU n pays to the WSP for the data traffic. The function $q_{s,n}$ denotes the price per unit of video data that the CP pays to the WSP in order to cover the network cost or the storage expense, for example. Finally, the function $\varphi_{s,n}$ specifies the price per unit of video data that the EU pays to the CP for watching the video content. Both $p_{s,n}$ and $q_{s,n}$ are charged by the WSP. Each transmission link between the EU and the WSP is provided at the cost of $w_{s,n}$ per unit rate. The interactions between the WSP, EUs, and CPs is regulated by controlling the prices—$p_{s,n}$, $q_{s,n}$, and $\varphi_{s,n}$—to decide the network traffic.[3]

Since we consider the transmission of scalable data over lossy channels, we have the following properties. First, the WSP sends additional channel coding bits of rate γ_s to guarantee the reliable transmission of the r_s video source rate. The prices that the WSP charges to CPs and EUs are only related with r_s, while the cost of WSP depends on both r_s and γ_s. Second, in a video delivery system, which employs the layered encoding and transmission model, the satisfaction function shows a stepwise shape [13], and this means bandwidth allocation could be limited to distinct levels. Besides, the satisfaction of EUs increases only when an additional layer can be successfully delivered, which means that the same rate r_s is a stepsize function depending on the number of layers. For example, when the user n requests content s, the quality $u_{s,n}(r_s)$ is obtained by this user. The user should pay $r_s \cdot \varphi_{s,n}$ and $r_s \cdot p_{s,n}$ due to the content service and wireless traffic provision, based on the basic network pricing problem [2]. The users' experience involves not only the video quality but also the return of their payment. The users always want their demands to be cost-effective, and we devise a user profit function accordingly as follows. On the premise that the system could allocate layered video rate r_s for EUs with reliable transmission based on the available capacity R_{Budget}, the problem of maximizing the total profits of EUs can be written as

$$\mathrm{P_{EU}}: \quad \max \sum_s \sum_n (u_{s,n}(r_s) - r_s \cdot p_{s,n} - r_s \cdot \varphi_{s,n})$$
$$\text{s.t.} \sum_s (r_s + \gamma_s) \le R_{\text{Budget}} \qquad \forall \mathbf{r} \succeq 0, \gamma \succeq 0 \tag{4}$$

where $\mathbf{r} = [r_1, \ldots, r_S]$ is the video-rate vector, and $\gamma = [\gamma_1, \ldots, \gamma_S]$ represents the corresponding error-protection rate vector.

The following practical example illustrates the dependency of the CP price functions. The profit function $v_{s,n}$ is often assumed to be increasing and only dependent on the rate r_s. To obtain the exact shape of this utility function, the following procedures are adopted. Since wireless video services have a close relation to data rates, without loss of generality, we assume that the profit $v_{s,n}$ of the CP is an increasing function of the rate r_s. Then, the income becomes $\varphi_{s,n} \cdot r_s$. Moreover, as the services operated by CPs involve the platforms of WSPs, they have a cost denoted as $q_{s,n} \cdot r_s$. For a CP providing the service s, the profit function is defined as

$$v_s(r_s) = \sum_n \varphi_{s,n} \cdot r_s - q_{s,n} \cdot r_s \tag{5}$$

where $\varphi_{s,n}$ is the revenue in term of per unit rate. The following analysis presents the case of profit $v_s(r_s)$. Notably, this analysis is still effective for other functions that share similar properties. Since EUs have the freedom to select contents of interest, the objective of the CP is to maximize the sum of the surpluses of total video contents instead of individual ones. Therefore, the profit for CPs is given by

$$\mathrm{P_{CP}}: \quad \max \sum_s \sum_n (r_s \cdot \varphi_{s,n} - r_s \cdot q_{s,n})$$
$$\text{s.t.} \sum_s r_s \le R_c \qquad \forall \mathbf{r} \succeq 0 \tag{6}$$

where R_c is the storage or the capacity that a WSP should reserve for the video content.

[3]Since the price model between WSPs, CPs, and EUs is still open, we employ the model in [2] to build the price relation.

Finally, the profit maximization of WSPs is on the premise of recovering the cost for such storage or capacity provision for the different scenarios.

$$\begin{aligned}&\mathrm{P}_{\mathrm{WSP}}:\\&\max\sum_s\sum_n((r_s\cdot p_{s,n}-(r_s+\gamma_s)\cdot w_{s,n})+r_s\cdot q_{s,n})\\&\text{s.t.}\sum_s\sum_n((r_s\cdot p_{s,n}-(r_s+\gamma_s)\cdot w_{s,n})+r_s\cdot q_{s,n})\geq 0\\&\sum_s(r_s+\gamma_s)\leq R_{\text{Budget}}\qquad\forall\mathbf{r}\succeq 0,\gamma\succeq 0\end{aligned}\tag{7}$$

where $w_{s,n}$ denotes the cost of traffic provision. This WSP model focuses on minimizing the operational costs when a video rate is requested and allocated. However, the WSP cannot tolerate unlimited requests from CPs and EUs. The same holds for CPs and EUs. Thus, it is impossible to simultaneously meet the optimal requirements from three sides and to separately solve the aforementioned objective functions due to conflicts. To simplify such a problem, firstly we combine the objective functions (4), (6), and (7) into one expression. Then, we maximize such an expression from the perspective of the WSP as the WSP plays a pivotal part in this three-side system.

Therefore, after combining (4), (6), and (7), the three-side system profit maximization problem can be expressed as follows:

$$\mathrm{P}_{\mathrm{SYS}}:\max\left(\mathbf{P}_{\mathrm{EU}},\mathbf{P}_{\mathrm{CP}},\mathbf{P}_{\mathrm{WSP}}\right)^{\mathrm{T}}\tag{8}$$

where T represents the transpose operator.

The following subsection shows how to maximize the three-side profits by focusing on the WSP.

C. Profit Region Under Dynamic Rate Allocation

As mentioned above, we formulate the three-side profits by focusing on the WSP. This means that we have to introduce a common variable that is shared by three actors in this system, so that we can maximize the profit by adjusting this variable. Such a common variable is the video rate. Once an optimal video rate is firstly found for CPs and EUs, we can subsequently explore the profit region of the WSP. This subsection focuses on characterizing such a relation between the allocation rate and the profit region.

Let us denote $\mathcal{R}$ as a rate-allocation policy, which generates a mapping from the rate space to $\mathbb{R}_+^S$. Policy $\mathcal{R}$ selects a video rate, r, from a set of possible solutions, $\mathbf{R}$. Given the characteristics of EUs, $\mathcal{R}_i$ can be interpreted as the video-source rate allocated to EU i. For a given rate-allocation policy $\mathcal{R}$, we can deduce the profit sets of EUs, CPs, and the WSP.

Let $\mathcal{B}^{\mathrm{CP}}$ specify the total profit region of CPs, and let $\mathbf{B}^{\mathrm{CP}}$ denote the profit vector of all CPs. We can use $E=\{1,\ldots,S\}$ to represent the set of CPs and use A to specify a subset in E. Consequently, $\mathbf{B}^{\mathrm{CP}}(A)$ represents the profit sum of all CPs in the set A where the notation $\mathbf{x}(A)$ denotes $\sum_{i\in A}\mathbf{x}(i)$. Then, for the problem of (6), the total profit region for the CPs is characterized by

$$\mathcal{B}^{\mathrm{CP}}(\mathcal{R})=\left\{\mathbf{B}^{\mathrm{CP}}\in\mathbb{R}_+^S|\mathbf{B}^{\mathrm{CP}}(A)\leq\sum_{s=1}^{|A|}\sum_n(\varphi_{s,n}r_s-r_sq_{s,n}),A\subseteq E\right\}.\tag{9}$$

According to (5), each CP earns the revenue from the source-data rate and the content $\varphi_{s,n}$. Let us denote $\Delta(A)=\sum_{s=1}^{|A|}\sum_n(\varphi_{s,n}-q_{s,n})$ and $\mathbf{R}(A)=\sum_{s\in A}r_s$. The profit region of the given profit function in (5) can be rewritten as

$$\mathcal{B}^{\mathrm{CP}}(\mathcal{R})=\left\{\mathbf{B}^{\mathrm{CP}}\in\mathbb{R}_+^S|\mathbf{B}^{\mathrm{CP}}(A)\leq\mathbf{R}(A)\cdot\Delta(A),A\subseteq E\right\}.\tag{10}$$

Like the profit of CPs, the total profit region $\mathcal{B}^{\mathrm{EU}}(\mathcal{R})$ for EUs is given by

$$\mathcal{B}^{\mathrm{EU}}(\mathcal{R})=\left\{\mathbf{B}^{\mathrm{EU}}\in\mathbb{R}_+^S|\mathbf{B}^{\mathrm{EU}}(A)\preceq\sum_{s=1}^{|A|}\sum_n(u_{s,n}(r_s)-r_sp_{s,n}-r_s\varphi_{s,n}),A\subseteq E\right\}.\tag{11}$$

For the WSP, we can similarly deduce the total profit capacity region $\mathcal{B}^{\mathrm{WSP}}(\mathcal{R})$ as shown in (12), at the bottom of the page.

Since the EU pays for the services only when the video content can be successfully received. To guarantee this, as previously mentioned, the WSP adopts the FEC scheme [29] to provide reliable and flexible video broadcasting. From (3), we know that $\gamma_s\geq r_s(\frac{1+\delta}{1-\varepsilon_s}-1)$, where δ is a small positive value that can be omitted. Thus, there is $\gamma_s\geq r_s(\frac{1}{1-\varepsilon_s}-1)$, which indicates that for EU n, who is requesting content s. If the channel erasure rate $\varepsilon_{s,n}\leq\varepsilon_s$, this EU can receive r_s successfully. This is because γ_s is related to ε_s, which is a threshold. As long as $\varepsilon_{s,n}$ of an EU is smaller than this threshold, the system allocates a channel rate to the EU. The minimal rate is obtained when $\varepsilon_{s,n}$ is equivalent to ε_s. Then, (12) can be simplified as

$$r_sp_{s,n}+r_sq_{s,n}-\left(r_s+\gamma_s\right)w_{s,n}=r_s(p_{s,n}+q_{s,n}-\frac{w_{s,n}}{1-\varepsilon_s}\right).\tag{13}$$

Furthermore, the profit region of the WSP, $\mathcal{B}^{\mathrm{WSP}}(\mathcal{R})$, is simplified as

$$\mathcal{B}^{\mathrm{WSP}}(\mathcal{R})=\left\{\mathbf{B}^{\mathrm{WSP}}\in\mathbb{R}_+^S|\mathbf{B}^{\mathrm{WSP}}(A)\leq\sum_{s=1}^{|A|}\sum_n r_s(p_{s,n}+q_{s,n}-\frac{w_{s,n}}{1-\varepsilon_s}),A\subseteq E\right\}.\tag{14}$$

$$\mathcal{B}^{\mathrm{WSP}}(\mathcal{R})=\left\{\mathbf{B}^{\mathrm{WSP}}\in\mathbb{R}_+^S|\mathbf{B}^{\mathrm{WSP}}(A)\leq\sum_{s=1}^{|A|}\sum_n(r_s\cdot p_{s,n}+r_s\cdot q_{s,n}-(r_s+\gamma_s)\cdot w_{s,n}),A\subseteq E\right\}\tag{12}$$

Notably, $\mathcal{B}^{\mathrm{CP}}(\mathcal{R})$, $\mathcal{B}^{\mathrm{EU}}(\mathcal{R})$, and $\mathcal{B}^{\mathrm{WSP}}(\mathcal{R})$ are the sets of achievable profits when the rates are dynamically allocated according to a rate-allocation policy $\mathcal{R}$.

III. Profit Structure

As mentioned earlier in Section II-C, the three-side optimization subproblems cannot be separately resolved. To tackle the problem, a commonly shared variable, video rates for allocation, is introduced to form new objective functions.

In the following discussion, we show that these new objective functions satisfy the properties of polymatroids and contra-polymatroids. Consequently, a global optimal solution for the three-side system can be found with the use of polymatroids and contra-polymatroids. More specifically, the rate regions of the three actors form contra-polymatroidal structures, the surfaces of which suggest the minimal required rate. Besides, the profit regions of these actors form polymatroidal structures, where the surfaces represent the maximal profit output based on a minimal required rate.

The motivation of using polymatroidal and contra-polymatroidal structures herein is the benefit of the duality between them. The profit region maximization problem that is modeled by a polymatroidal structure can be effectively solved by converting itself into an optimal rate-allocation problem, which can also be subsequently resolved by using the contra-polymatroidal structure. In this study, we explore such a dual structure and show that it can be used to solve three-side optimization problem of (8).

In short, the proposed solution firstly finds out solution pairs, which are formed by the profits of CPs along with the corresponding allocated videos rates, by using Lemma 3.1. Subsequently, the same procedure repeats for finding solution pairs for EUs. As the possible video rates of allocation are enumerated, we plug these rates into the objective function of the profit region for the WSP, and the maximum profit can be calculated thereby. For clarity, an example is given in Section III-C.

A. Rate Region and Contra-Polymatroidal Structure

In this subsection, we show that the rate regions of CPs and EUs are related to contra-polymatroidal structures. Besides, we also show that the rate regions are associated with their contra-structures, i.e., polymatroids, which are the profit regions of the EUs, CPs, and WSP.

Let s denote the index of CPs and R_s^{CP} represent the rate of the sth CP. For systems of multiple CPs, the sum-rate facet has $S!$ corner points. We use a graph $\mathcal{G}(\mathcal{B},\mathcal{E})$ to delineate the relation between the corner points, where $\mathcal{B}$ denotes the set of vertices, and $\mathcal{E}$ specifies the set of edges. The vertices of $\mathcal{G}$ are precisely the rate vectors of CPs. Obviously, the vertices have $S!$ permutations. Let π be a permutation in the set $\mathcal{B}$. Define the rate vector $\mathbf{r}^{\mathrm{CP}}(\pi) \in \Re^{\mathfrak{S}}$ by $r_{\pi(1)}^{\mathrm{CP}}(\pi) = f(\pi(1))$ and $r_{\pi(i)}^{\mathrm{CP}}(\pi) = f(\{\pi(1),\ldots,\pi(i)\}) - f(\{\pi(1),\ldots,\pi(i-1)\})$ for $i = 2,\ldots,S$. According to [30], the sum-rate facet is exactly the convex hull of these corner points, and such a facet is reflected by the set $\mathcal{E}$.

The inner region of the sum-rate facet composes the rate region of CPs. The results of rate allocation policies $\mathbf{r}^{\mathrm{CP}}(\pi) \in \Re^S$ form a wide range of profits. However, finding the rate vector that results in the maximal profit is usually an NP-hard problem. Alternatively, we first give a feasible profit c_2 and then maximize it. The corresponding rate vector $\overset{\circ}{\mathbf{r}}{}^{\mathrm{CP}}(\pi)$ becomes the optimal solution. To describe our solution, we first need the following lemma.

Lemma 3.1: There exists $c_2 \geq 0$, which satisfies $\sum_s \sum_n (r_s \cdot \varphi_{s,n} - r_s \cdot q_{s,n}) \geq c_2$.

Proof: This lemma shows that, if we find a solution that meets the criterion, this solution is an extreme point. The hint about this proof is that we can focus on the derivation of the lower bound of the inequality. The detailed proof is given in Appendix A. Regarding how to search for a solution that fits Lemma 3.1, we can utilize Theorem 3.2 to locate the extreme point, namely, c_2, of the objective function for CPs. Recall that there are three-side variables in our system modeled by (8). Once c_2 is found, we can simplify the original system and turn it into a problem for the WSP and EUs.

Subsequently, we focus on finding a basic rate vector, which satisfies Lemma 3.1. Let us denote $\mathcal{R}(B^{\mathrm{CP}})$ as the rate region of CPs. Therefore, $\mathbf{R}^{\mathrm{CP}} = (R^{\mathrm{CP}}(1),\ldots,R^{\mathrm{CP}}(S))$ represents the rate vector of the CPs. There are $2^{|E|}$ rate constraints, where $E = \{1,\ldots,S\}$, in any given rate vector. Denote B^{CP} as $\sum_s \sum_n v_{s,n}(r_s)$. Then, at the achievable profit c_2, the feasible rate region is characterized by

$$\mathcal{R}(B^{\mathrm{CP}}) = \left\{\mathbf{R}^{\mathrm{CP}} \in \mathbb{R}_+^S | \mathbf{R}^{\mathrm{CP}}(A) \geq \mathbf{B}^{\mathrm{CP}}(A)/\Delta(A), A \subseteq E\right\} \tag{15}$$

where $\Delta(A) = \sum_{s=1}^{|A|} \sum_n (\varphi_{s,n} - q_{s,n})$ and $\sum_{i=1}^{S} B_{\pi(j)}^{\mathrm{CP}}(i) = c_2$. The parameter π_j is a permutation in the set $E = \{1,\ldots,S\}$ and $1 \leq j \leq S!$.

We now show that a subset of the corresponding rate region, including the corner points and the sum-rate facet, forms a contra-polymatroid. For the proof, we need the following theorem.

Theorem 3.2: The rate region of CPs, $\mathcal{R}(B^{\mathrm{CP}})$, is a contra-polymatroid.

To prove this theorem, we examine whether or not the three fundamental properties of contra-polymatroidal structures hold, namely, normalized, nondecreasing, and supermodular properties. The detailed proof is given in Appendix B. As long as the rate region of CPs is a contra-polymatroid, we can use its duality to find the optimal solution for CPs.

Notably, according to the analysis for the rate region of CPs, it is sufficient to consider a more general CP profit problem stated in (6), in terms of a contra-polymatroid with a generalized symmetric rate vector. The allocated rates of the CPs under a permutation π are described as follows:

$$\begin{cases} R_{\pi(j)}^{\mathrm{CP}}(1) = \dfrac{\sum_{s=1}^{1} B_{\pi(j)}^{\mathrm{CP}}(1)}{\sum_{s=1}^{1}\sum_n (\varphi_{s,n} - q_{s,n})} \\ R_{\pi(j)}^{\mathrm{CP}}(i) = \dfrac{\sum_{s=1}^{i} B_{\pi(j)}^{\mathrm{CP}}(i)}{\sum_{s=1}^{1}\sum_n (\varphi_{s,n} - q_{s,n})} - \dfrac{\sum_{s=1}^{i-1} B_{\pi(j)}^{\mathrm{CP}}(i)}{\sum_{s=1}^{i-1}\sum_n (\varphi_{s,n} - q_{s,n})}. \end{cases} \tag{16}$$

By using the permutation formulated in the above equation, an extreme point can located in the performance region of CPs.

As the extreme point for CPs is located, we subsequently search for the extreme point for EUs.

Denote $\mathcal{R}(B^{\mathrm{EU}})$ as the rate region of EUs. Therefore, $\mathbf{R}^{\mathrm{EU}}$ represents the rate vector of EUs, where $\mathbf{R}^{\mathrm{EU}} = (R^{\mathrm{EU}}(1), \ldots, R^{\mathrm{EU}}(S))$. There are $2^{|E|}$ rate constraints, where $E = \{1, \ldots, S\}$, in any given rate vector. Like Lemma 3.1, we also define c_1 as the achievable profit[4] and denote $\mathbf{c}_1 = \{c_1, \ldots c_1\}$. Then, the feasible rate region is characterized by

$$\mathcal{R}(B^{\mathrm{EU}}) = \{\mathbf{R}^{\mathrm{EU}} \in \mathbb{R}_+^S | \mathbf{B}^{\mathrm{EU}}(\mathbf{R}^{\mathrm{EU}}) \succeq \mathbf{c}_1\} \tag{17}$$

where $\sum_{i=1^S} B^{\mathrm{EU}}_{\pi(j)}(i) = c_1$. The vector π_j is a new permutation in the set $E = \{1, \ldots, S\}$ and $1 \leq j \leq S!$. The following theorem shows that the rate region of EUs is also a contra-polymatroidal structure.

Theorem 3.3: Rate region of EUs, $\mathcal{R}(B^{\mathrm{EU}})$, is a contra-polymatroid.

The idea and the proof are entirely analogous to those of Theorem 3.2. As Theorem 3.2 is used for CPs, we can utilize the contra-polymatroidal properties and the duality to find the extreme point, i.e., c_1, for EUs.

Based on Lemma 3.1, Theorems 3.1 and 3.2, extreme points for EUs and CPs are located at c_1 and c_2, respectively. This implies that (7) can be further simplified as the profit optimization for WSPs because the video rates allocated to CPs and EUs are fixed. The original three-side optimization problem that exhibits a conflict between the WSP, CPs and EUs is converted to one-side problem based on the WSP.

The following subsection then focuses on finding the optimal profit region of the WSP when those of CPs and EUs are fixed.

B. Profit Region and Polymatroidal Structure

When the sets of feasible rate regions, i.e., $\mathcal{R}(B^{\mathrm{CP}})$ and $\mathcal{R}(B^{\mathrm{EU}})$, respectively support given profits c_2 and c_1, which are contra-polymatroidal structures as shown earlier, the achievable profit region of the WSP satisfies the property of a polymatroidal structure under the policy $\mathcal{R}$. The following theorem substantiates such an interpretation.

Theorem 3.4: Under a given policy $\mathcal{R}$, the achievable profit region of the system, $\mathcal{B}^{\mathrm{WSP}}(\mathcal{R})$, is a polymatroid, as shown in (18), at the bottom of the page.

Proof: To prove this theorem, the polymatroidal properties should be firstly verified. Those are the normalized, nondecreasing, and supermodular properties. For brevity, the detailed proof is given in Appendix C.

[4]For consistency, we use the profit function to reflect the QoE of each user. For the single-user case, the objective function is (4).

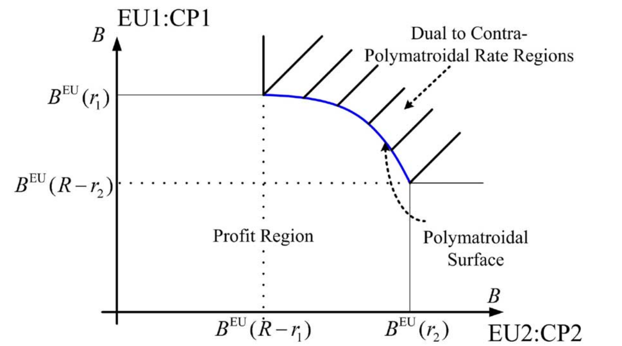


Fig. 3. Two-user example of the polymatroidal profit structure and the contra-polymatroidal rate structure. This figure, along with Fig. 4, demonstrates that an optimal solution exists in the region.

Based on the proof of Theorem 3.4, the profit regions $\mathcal{B}^{\mathrm{CP}}(\mathbf{R})$ and $\mathcal{B}^{\mathrm{EU}}(\mathbf{R})$ are also proved to be polymatroids, respectively.

Theorem 3.4 proves that polymatroids satisfy three properties: Normalized, nondecreasing, and submodular. The work in [31] provided a convenient characteristic of submodular functions. That is, $B^{\mathrm{EU}}(T)$ is a submodular if and only if all $T \subseteq T' \subseteq T''$ and $s \in T''\ T'$ it holds that $B^{\mathrm{EU}}(T \cup \{s\}) - B^{\mathrm{EU}}(T) \geq B^{\mathrm{EU}}(T' \cup \{s\}) - B^{\mathrm{EU}}(T')$. Such a characteristic is also supported in [32]. This characteristic indicates that each of the variance reduction functions $B^{\mathrm{EU}}(s)$ is also submodular. Thus, each maximal independent set is a maximum independent set. Consequently, the proposed polymatroidal solution can be solved in a greedy manner.

The above-mentioned proofs demonstrate that i) profit regions and rate regions form polymatroids and contra-polymatroids; ii) profit regions are achievable when minimum rates are given; iii) profit regions and rate regions have extreme points. However, those proofs do not suggest any feasible approach for locating extreme points. Before we begin with the method of searching extreme points, we give an example below to elaborate the idea in this section.

C. Example of Contra-Polymatroidal Rate Regions and Polymatroidal Profit Regions

We propose a simple example below to demonstrate this relation. As shown in Fig. 3, considering a two-user broadcasting system, where EU1 is requesting content 1 from CP1 by using a rate of r_1, the resulting profit is $B^{\mathrm{EU}}(r_1)$. EU2 is watching content 2 from CP2 with a video rate of r_2, the corresponding profit is $B^{\mathrm{EU}}(r_2)$. Both video services are provided by the platform of the WSP. Although it is not possible to ideally meet all the users' requirements in the general case, we assume that the available capacity constraint R satisfies $R < r_1 + r_2$. As shown in Fig. 3, the vertical and horizontal coordinate respectively represents

$$\mathcal{B}^{\mathrm{WSP}}(\mathcal{R}) = \left\{ \mathbf{B}^{\mathrm{WSP}} \in \mathbb{R}_+^S | \mathbf{B}^{\mathrm{WSP}}(A) \leq \sum_{s=1}^{|A|} \sum_{n} ((r_s + \gamma_s) \cdot p_{s,n} + r_s \cdot q_{s,n} - (r_s + \gamma_s) \cdot w_{s,n}), A \subseteq E \right\} \tag{18}$$

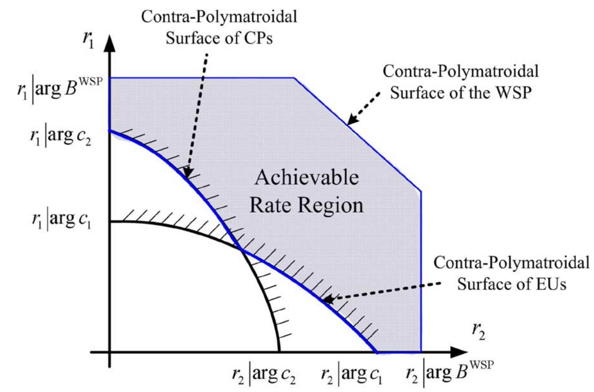


Fig. 4. Contra-polymatroidal rate structure and the achievable rate region based on the two-user example. This figure, along with Fig. 3, demonstrates that an optimal solution exists in the region.

the profit of an EU. The achievable maximal profit region corresponds to the polymatroidal surface, whereas the rate region presents a contra-polymatroid. Both the profit region and the rate region present the duality. Likewise, the achievable profit region of CPs has a similar geometrical structure.

Fig. 4 illustrates the rate relation of the two EUs. The objective of the joint optimization problem in (8) includes three maximal subproblems. Such a problem may have a decomposition-based solution. We first find a possible maximal profit c_2 of CPs, where the corresponding rate region is expressed in (15). Let us denote the rates allocated to the two users by $r_1|\arg c_2$ and $r_2|\arg c_2$, respectively, where the notations mean finding a rate to maximize c_2. Second, denote the rate regions of the maximum EU profits by $r_1|\arg c_1$ and $r_2|\arg c_1$, which are also the results of (17). Third, let us denote the feasible rate region of the WSP by $r_1|\arg B^{\mathrm{WSP}}$ and $r_2|\arg B^{\mathrm{WSP}}$. According to Theorems 3.2 and 3.3, since the rate regions of CPs and EUs are contra-polymatroids, the achievable rate region of the problem presented in (8) is the intersection of three rate-regions. In the following section, we take advantage of the polymatroidal and contra-polymatroidal properties to give a detailed solution to our joint profit optimization problem.

IV. Profit Optimization

In the previous section, we have shown that profit regions and rate regions form polymatroids and contra-polymatroids. Meanwhile, there exists an optimal profit solution if we can locate extreme points in the rate regions first. Despite of the proof for the existence of extreme points, search for extreme points is not fully elaborated. This is the focus of this section.

The brief idea is that we can first locate the extreme points for CPs and EUs. Subsequently, we plug the parameters of the optimal profits for CPs and EUs into the optimization problem of the WSP. The system is finally capable of discovering the best solution for the WSP.

We now exploit the shadows defined above to propose a solution for the joint profit optimization problem. Let $\mathcal{F}$ be the set of all the feasible rate-allocation policies among users, that is, $\mathcal{R} \in \mathcal{F}$ and $\mathcal{F} \equiv \{\mathbf{R} : \sum_s r_s \leq R_{\mathrm{Budget}}\}$. Recall that $\mathcal{R}$ represents the rate-allocation policy. The profit maximization problem is casted as finding the optimal operating vector $\overset{\circ}{\mathbf{R}}$, such that the system profit is maximized. We now use Lagrangian technique to show that the profit optimization can be solved by rate allocation based on a set of polymatroidal structures. Furthermore, the computation of the boundary of the profit region and the associated optimal rate-allocation policy can be reduced to the form of conditional optimization problems. We first show that the following theorem substantiates the above interpretation.

Theorem 4.1: When rates are dynamically allocated according to policy $\mathcal{R} \in \mathcal{F}$, where $\mathcal{F}$ is the set of all feasible rate-allocation policies that satisfy the rate constraint $\mathcal{F} \equiv \{\mathcal{R} : (\mathbf{R}(A) + \Upsilon(A)) \leq R_{\mathrm{Budget}}, \forall s\}$, the profit regions for the CP, the EU, and the WSP are respectively given by

$$\mathrm{EU}: \quad \mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{EU}}(\mathcal{R}) \tag{19}$$

$$\mathrm{CP}: \quad \mathcal{B}^{\mathrm{CP}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{CP}}(\mathcal{R}) \tag{20}$$

$$\mathrm{WSP}: \quad \mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{WSP}}(\mathcal{R}). \tag{21}$$

Proof: Firstly, we show that $\mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{EU}}(\mathcal{R})$. For each rate-allocation policy $\mathcal{F}_k$ that satisfies the limitation of the bandwidth, we have $\overline{\mathcal{B}}^{\mathrm{EU}(k)}(\mathcal{R}) = \{\mathcal{B}^{\mathrm{EU}} \in \mathbb{R}_+^S | \mathcal{B}^{\mathrm{EU}}(S) \leq \sum_{s=1}^{S}\sum_n (u_{s,n}(r_s^k) - r_s^k p_{s,n} - r_s^k \varphi_{s,n})\}$.

Thus, the profit region of EUs becomes $\mathcal{B}^{\mathrm{EU}}(\mathbf{R}) \subset \bigcup_{\mathcal{R}\in\mathcal{F}_k} \mathcal{B}^{\mathrm{EU}(k)}(\mathcal{R})$.

Based on the concept of the achievable marginal profit region, we subsequently obtain the following inner bound and outer bound of $\mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}})$. That is, $\bigcup_{\mathcal{R}\in\mathcal{F}_k} \mathcal{B}^{\mathrm{EU}}(\mathcal{R}) \subset \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{EU}}(\mathcal{R}) \subset \mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}}) \subset \bigcup_{\mathcal{R}\in\mathcal{F}_k} \overline{\mathcal{B}}^{\mathrm{EU}(k)}(\mathcal{R})$.

When $k \to \infty$, $\bigcup_{\mathcal{R}\in\mathcal{F}_k} \mathcal{B}_f^{\mathrm{EU}}(\mathcal{R}) \to \bigcup_{\mathcal{R}\in\mathcal{F}_k} \overline{\mathcal{B}}^{\mathrm{EU}(k)}(\mathcal{R})$. Thus, $\mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{EU}}(\mathcal{R})$. Similarly, we have $\mathcal{B}^{\mathrm{CP}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{CP}}(\mathcal{R})$, and $\mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}}) = \bigcup_{\mathcal{R}\in\mathcal{F}} \mathcal{B}^{\mathrm{WSP}}(\mathcal{R})$. □

The boundary surfaces of $\mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}})$, $\mathcal{B}^{\mathrm{CP}}(\overline{\mathbf{R}})$, and $\mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}})$ are the closures of all points $\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}$, $\overset{\circ}{\mathbf{R}}^{\mathrm{CP}}$, and $\overset{\circ}{\mathbf{R}}^{\mathrm{WSP}}$, respectively, where $\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}$, $\overset{\circ}{\mathbf{R}}^{\mathrm{CP}}$, and $\overset{\circ}{\mathbf{R}}^{\mathrm{WSP}}$ are respectively the solutions to the following problems:

$$\mathrm{EU}: \quad \max_{\mathbf{R}} \mathbf{B}^{\mathrm{EU}}(\mathbf{R}) \quad \text{s.t.} \mathbf{B}^{\mathrm{EU}}(\mathbf{R}) \in \mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}}) \tag{22}$$

$$\mathrm{CP}: \quad \max_{\mathbf{R}} \mathbf{B}^{\mathrm{CP}}(\mathbf{R}) \quad \text{s.t. } \mathbf{B}^{\mathrm{CP}}(\mathbf{R}) \in \mathcal{B}^{\mathrm{CP}}(\overline{\mathbf{R}}) \tag{23}$$

$$\mathrm{WSP}: \quad \max_{\mathbf{R}} \quad \mathbf{B}^{\mathrm{WSP}}(\mathbf{R}) \quad \text{s.t. } \mathbf{B}^{\mathrm{WSP}}(\mathbf{R}) \in \mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}}). \tag{24}$$

The theorem shows that the individual optimal solutions for the three actors lie on the surfaces of the closures. We can use this theorem to search for the optimal solution that simultaneously satisfies the criteria if these surfaces intersect.

Ideally, the optimal solution $\overset{\circ}{\mathbf{R}}$ for the system profit maximization problem in (8) is the intersection in $\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}$, $\overset{\circ}{\mathbf{R}}^{\mathrm{CP}}$, and

$\overset{\circ}{\mathbf{R}}^{\mathrm{WSP}}$. However, there exist conflicts among the EUs, CPs, and WSP. Intuitively, the end-users wish to pay less for the services, whereas the CPs and the WSP lean towards increasing revenues as much as possible. Thus, the boundary surfaces of $\mathcal{B}^{\mathrm{EU}}(\overline{\mathbf{R}})$, $\mathcal{B}^{\mathrm{CP}}(\overline{\mathbf{R}})$, and $\mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}})$ may not have any intersections. Consequently, the achievable solution for the problem in (8) consists in making the EUs and CPs respectively have their maximal profits c_1 and c_2 and in maximizing the profit of the WSP. By plugging c_1 and c_2 into (29), as a result, the whole system can achieve overall profit maximization due to fixed rates for CPs and EUs. We illustrate the process as follows.

According to Lemma 3.1 and the analysis of the rate region for EUs, there exist $\mathbf{c}_1 = [c_1, \dots c_1]$ and $\mathbf{c}_2 = [c_2, \dots c_2] \succeq 0$, which satisfy $\mathbf{c}_1 \preceq \mathcal{B}^{\mathrm{EU}}(\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}) \preceq \mathcal{B}^{\mathrm{EU}}(\overset{\circ}{\mathbf{R}}^{\mathrm{EU}})$ and $\mathbf{c}_2 \preceq \mathcal{B}^{\mathrm{CP}}(\mathbf{R}^{\mathrm{CP}}) \preceq \mathcal{B}^{\mathrm{CP}}(\overset{\circ}{\mathbf{R}}^{\mathrm{CP}})$. Hence, what is shown in (25) and (26), shown at the bottom of the page. Given a set of desired rates $\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}_{c_1}$, $\overset{\circ}{\mathbf{R}}^{\mathrm{CP}}_{c_2}$, and $\overset{\circ}{\mathbf{R}}^{\mathrm{WSP}}$ such that

$$\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}_{c_1} = \{\mathbf{R} | \min \overset{\circ}{\mathbf{R}}^{\mathrm{EU}^{-1}}(c_1)\} \quad (27)$$

$$\mathbf{R}^{\mathrm{CP}}_{c_2} = \{\mathbf{R} | \min \mathbf{B}^{\mathrm{CP}^{-1}}(c_2)\} \quad (28)$$

$$\overset{\circ}{\mathbf{R}}^{\mathrm{WSP}} = \{\mathbf{R} | \arg_{\mathbf{R}} \max \mathbf{B}^{\mathrm{WSP}}(\mathbf{R})\} \quad (29)$$

the achievable optimal solution set $\ddot{\mathbf{R}}(E)$ is

$$\ddot{\mathbf{R}} = \overset{\circ}{\mathbf{R}}^{\mathrm{EU}}_{c_1} \bigcap \overset{\circ}{\mathbf{R}}^{\mathrm{CP}}_{c_2}(E) \bigcap \overset{\circ}{\mathbf{R}}^{\mathrm{WSP}}. \quad (30)$$

The points $\overset{\circ}{\mathbf{R}}^{\mathrm{WSP}}$ on the boundary surface of $\mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}})$ are the optimal operating points because the other points in $\overset{\circ}{\mathbf{R}}^{\mathrm{EU}}_{c_1}$ and $\overset{\circ}{\mathbf{R}}^{\mathrm{CP}}_{c_2}$ are dominated componentwise by parts of the points on the boundary surface. The reason is that the WSP does not accept any negative profit rate while maintaining a practical system in this case. Thus, to solve the system profit problem, the discussion on WSP profit problems is required.

The following theorem shows the computation of the boundary of the WSP profit region and the associated optimal rate-allocation policy.

Theorem 4.2: The boundary surface of $\mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}})$ is the closure of all points $\ddot{\mathbf{R}}$ such that $\ddot{\mathbf{R}}$ is a solution to the problem mentioned in (24) if and only if there exists a $\lambda \in \mathbb{R}^{+}_{S}$, such that $\ddot{\mathbf{R}}$ is a solution to the optimization problem

$$\max_{\mathbf{R}} \mathbf{B}^{\mathrm{WSP}} - \lambda \cdot \mathbf{R} \quad \text{s.t.} \quad \mathbf{B}^{\mathrm{WSP}} \in \mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}}). \quad (31)$$

Proof: Consider the set $T = \{(\mathbf{B}, \mathbf{R}) : \mathbf{R} \in \mathbb{R}^{+}_{S}, \mathbf{B} \in \mathcal{B}^{\mathrm{WSP}}(\overline{\mathbf{R}})\}$. It can be verified that $\sum_n (r_s \cdot p_{s,n} + r_s \cdot q_{s,n} - (r_s + \gamma_s) \cdot w_{s,n}))$ is a convex function. Then, the set T is a convex set. There exist Lagrange multipliers $\lambda \in \mathbb{R}^{+}_{S}$ associated with the rate constraint, such that $\ddot{\mathbf{R}}$ is a solution to the optimization problem

$$\max_{\mathbf{B}, \mathbf{R} \in \Gamma} \mathbf{B}^{\mathrm{WSP}} - \lambda \cdot \mathbf{R}. \quad (32)$$

Therefore

$$\begin{aligned} \mathbf{B}^{\mathrm{WSP}}(\overline{\mathbf{R}}) &= \bigcup_{\mathbf{R}: \sum_s r_s + \gamma_s \le R_{\mathrm{Budget}}} \mathbf{B}^{\mathrm{WSP}}(\mathbf{R}) \\ &= \bigcup_{\mathbf{R}: \sum_s r_s + \gamma_s = R_{\mathrm{Budget}}} \mathbf{B}^{\mathrm{WSP}}(\mathbf{R}). \end{aligned}$$

Let π be a permutation in the set $\mathcal{B}$. Based on the polymatroidal structure of $\mathcal{B}^{\mathrm{WSP}}$ shown in (12), for any given rate-allocation policy $\mathcal{R}$, $\mathbf{B}^{\mathrm{WSP}}$ is maximized at

$$\begin{cases} B_{\pi(1)} = \sum_n (r_{\pi(1)} \cdot p_{\pi(1),n} + r_{\pi(1)} \cdot q_{\pi(1),n} \\ \qquad - (r_{\pi(1)} + \gamma_{\pi(1)}) \cdot w_{\pi(1),n}) \\ B_{\pi(k)} = \sum_n (r_{\pi(k)} \cdot p_{\pi(k),n} + r_{\pi(k)} \cdot q_{\pi(k),n} \\ \qquad - (r_{\pi(k)} + \gamma_{\pi(k)}) \cdot w_{\pi(k),n}), \qquad k = 2, .., S. \end{cases}$$

This completes the proof. □

Such a proof shows that the optimal points of the profit region all fall on the surface of polymatroids. We can solve the problem in (24) to reach the original three-side optimization because the two other sides, i.e., CPs and EUs, are firstly tackled in Algorithm 1. Thus, once the two sides of the three-side problem are solved, the entire global solution can be generated. Define $\Gamma(r_s) = \sum_n (r_s \cdot p_{s,n} + r_s \cdot q_{s,n} - (r_s + \gamma_s) \cdot w_{s,n})$. Consider the simplified form of (14). Its derivative is $\Gamma(r_s)' = \sum_n (p_{s,n} + q_{s,n} - \frac{w_{s,n}}{1-\varepsilon_s})$. Then, (24) becomes

$$\max \sum_s \int_0^{R_{\mathrm{Budget}}} \Gamma(r_s)' dr_s. \quad (33)$$

Define the marginal function $\Gamma(r_s)^* = [\max_s \Gamma'(r_s)]^+$, where $[x]^+ \equiv \max(x, 0)$. Also, denote $\lambda = \{\lambda_1, \dots, \lambda_S\} \in \mathbb{R}^{+}_{S}$. Based on the key properties of polymatroids mentioned in [33] and Lemma 3.2 of [34], the optimal solution for the problem of (33) is precisely the vertices $V(\pi^*)$ of the polyhedron surface of $\mathcal{B}^{\mathrm{EU}}(\mathbf{R})$. Notably, π^* is any permutation such

$$\mathcal{B}^{\mathrm{EU}}_{c_1}(\mathcal{R}) = \{\mathbf{B}^{\mathrm{EU}} \in \mathbb{R}^{S}_{+} | \mathbf{c}_1 \preceq \mathbf{B}^{\mathrm{EU}}(A) \preceq \sum_{s=1}^{|A|} \sum_n (u_{s,n}(r_s) - r_s \cdot p_{s,n} - r_s \cdot \varphi_{s,n}), A \subseteq E\} \quad (25)$$

$$\mathcal{B}^{\mathrm{CP}}_{c_2}(\mathcal{R}) = \{\mathbf{B}^{\mathrm{CP}} \in \mathbb{R}^{S}_{+} | \mathbf{c}_2 \preceq \mathbf{B}^{\mathrm{CP}}(A) \preceq \mathbf{R}(A) \cdot \Delta(A), A \subseteq E\} \quad (26)$$

that $\Gamma'(r_{\pi^*(1)}) > \Gamma'(r_{\pi^*(2)}) > \ldots > \Gamma'(r_{\pi^*(S)})$. The value $\mathbf{B}^{\mathrm{WSP}}$ should be attained at a point that satisfies

$$\begin{cases} B_{\pi(1)} = \sum_n (u_{\pi^*(1)}(r_{\pi^*(1)}) + v_{\pi^*(1)}(r_{\pi^*(1)}) \\ \qquad -(r_{\pi^*(1)} + \gamma_{\pi^*(1)}) \cdot w_{1,n}) \\ B_{\pi(k)} = \sum_n (u_{\pi^*(k)}(r_{\pi^*(k)}) + v_{\pi^*(k)}(r_{\pi^*(k)}) \\ \qquad -(r_{\pi^*(k)} + \gamma_{\pi^*(k)}) \cdot w_{k,n}), \qquad k = 2, \ldots, S. \end{cases} \tag{34}$$

For the problems in (27) and (28), the Lagrangian formulations are

$$\min_{\mathbf{B}^{\mathrm{EU}}} \mathbf{R} - \lambda_1 \cdot \mathbf{B}_{c_1}^{\mathrm{EU}} \quad \text{s.t.} \quad \mathbf{B}^{\mathrm{EU}} \in \mathcal{B}_{c_1}^{\mathrm{EU}}(\overline{\mathbf{R}}) \tag{35}$$

and

$$\min_{\mathbf{B}^{\mathrm{CP}}} \mathbf{R} - \lambda_2 \cdot \mathbf{B}_{c_2}^{\mathrm{CP}} \quad \text{s.t.} \quad \mathbf{B}^{\mathrm{CP}} \in \mathcal{B}_{c_2}^{\mathrm{CP}}(\overline{\mathbf{R}}). \tag{36}$$

Algorithm 1: Rate of the achievable profit region for EUs and CPs

Initialization:
 $E = \{1, \ldots, S\}$, $\mathbf{r} = \{r_s | r_s = 0, 1 \le s \le S\}$.
 The step size is Δr. Compute R_s.
Repeat
 Select s, where $s = \arg\max_{s \in E} \Psi'_{|\mathbf{r}}(r_s)$.
 if $r_s < R_s$
  if $\Psi'_{|\mathbf{r}}(r_s) \neq 0$
   $r_s + \Delta r \Rightarrow r_s$
  else
   Select s, where $s = \arg\min_{s \in E} R_{s,l+1} - r_s$,
   $R_{s,l} \le r_s \le R_{s,l+1}, l + 1 \le L$.
   $r_s + \Delta r \Rightarrow r_s$
  end if
 else
  $E - s \Rightarrow E$.
 end if
Until
 $E = \emptyset$, or achieve c_1 (c_2 for CPs).

Then, we can compute the feasible rate regions of the problems in (35) and (36) through the following algorithms. We illustrate these two algorithms in the same form through a generic function $\Psi(r_s)$. The difference is, for EUs, $\Psi(r_s) = \sum_n u_{s,n}(r_s) - r_s p_{s,n} - r_s q_{s,n}$. However, for CPs, $\Psi(r_s) = r_s \cdot \sum_n (\varphi_{s,n} - q_{s,n})$. The derivative of this generic function is $\Psi'(r_s)$. Let us denote $R_{s,l}$ as the rate of the lth video layer sent from CP s and denote R_s as the rate of CP s when the CP satisfies the demands of all the users.

As mentioned at the beginning of Section IV, Algorithm 1 is used to locate the extreme points for CPs and EUs. Following Algorithm 1, we plug the parameters of these extreme points into Algorithm 2. Thus, we can compute the feasible rate regions of the problem in (29) for the WSP by using the following algorithm.

Algorithm 2: Rate of the maximum profit region for the WSP

Initialization:
 $E = \{1, \ldots, S\}$, $\mathbf{r} = \{r_s|_s = 0, 1 \le s \le S\}$.
 The step size is Δr. Compute R_s.
Repeat
 Select s, where $s = \arg\max_{s \in E} \Gamma'_{|\mathbf{r}}(r_s)$.
 if $r_s < R_s$
  if $\Gamma'_{|\mathbf{r}}(r_s) \neq 0$
   $r_s + \Delta r \Rightarrow r_s$
  else
   Select s, where $s = \arg\min_{s \in E} R_{s,l+1} - r_s$,
   $R_{s,l} \le r_s \le R_{s,l+1}, l + 1 \le L$.
   $r_s + \Delta r \Rightarrow r_s$
  end if
 else
  $E - s \Rightarrow E$.
 end if
Until
 $E = \emptyset$, or $\sum r_s \ge R_{\mathrm{Budget}}$.

Then, we can get the final optimal rate vector by computing (30), which is also the intersection of the results of Algorithms 1 and 2. For Algorithm 1, assume the video rates of contents when the profit region achieves c_1 are $r_1, \ldots, r_s$. Then, the complexity is computed as $O(\sum_{s=1}^{S} \frac{r_s}{\Delta r})$. The complexity of Algorithm 2 is $O(S \cdot \lceil \frac{R_{\mathrm{Budget}}}{\Delta r} \rceil)$. The convergence of Algorithm 2 is related to the granularity of video rates, or rate partitioning. When the marginal revenue of the objective function is constant, rate partitioning is not necessary. Besides, Algorithm 2 can converge and obtain the best solution. On the other hand, if the marginal revenue changes, the system requires fine granularity of video rates.

V. Numerical Simulation Results

This section presents a simple three-side market problem with one WSP, three CPs, and 102 EUs. We show how to obtain optimal transmission and resource allocations by using the model presented in Sections II and III, along with the solution presented in Section IV.

A. Simulation Setup

In our simulation, we consider a single network, where 102 mobile end-users are serviced during video broadcasting, and the video contents are separately provided and copyrighted by three CPs. Furthermore, the video content provided by these three CPs are respectively stored at the three types of cyberspace—servers of the WSP, third-party data clouds, and servers of the CPs. Based on connection and storage costs, these three types of storages directly influence the revenues of the CPs. The price $\{p_{s,n}, q_{s,n}, w_{s,n}\}$ we examine herein are exogenous. This means that $\{p_{s,n}, q_{s,n}, w_{s,n}\}$ are observable, and they are set by the market of CPs and WSPs (i.e., not by the proposed method). In a monopolistic market, the price structure is under the complete control of a WSP or a CP. Contrarily, in a competitive market, a WSP or a CP has no control over the price structure but accepts the prices that are driven by markets [2]. Typically, since the prices are different from WSPs to CPs, this work refers to the price structure in China Mobile Communications Corporation[5] and uses it as a case study in our simulation.

The video traffic and connections of EUs are provided by the WSP, so the traffic and connections are homogeneous to the WSP. Nevertheless, devices on the user side are heterogeneous owing to different display sizes and various channel conditions. Besides, the contents that users request are diverse. In view of those heterogeneous requirements, the simulation uses the H.264 extended SVC video encoder to generate layered video streams. Such an encoder has versatility, for instance, spatial scalability, and multicontent broadcasting capability, which can serve various purposes.

As for the pricing parameters, notably, as mentioned earlier, this study investigates the optimization of endogenous variables $\{r_s, \gamma_s\}$ (i.e., the rate vector and the error protection vector). Recall that r_s stands for the video rate after H.264 encoding, and γ_s represents additional protection rates for r_s when more EUs are serviced. For the sake of clarity, in the following simulations, each CP provides different video contents. Assume three CPs are respectively broadcasting the standard video sequences "city," "soccer," and "harbor." The spatial scalability is in QCIF, CIF, and D1 formats for serving the users with smartphones, tablets, and laptops. The channel state of the 102 users complies with the erasure rate distribution [29]. That means that $\varepsilon_{s,n}$ for each user randomly falls into a predefined range between 0.0 and 0.5. Besides, such an interval is divided into five segments in our setting for brevity. The channel coding that we use in the simulation is Fountain Coding. The system provides three broadcasting contents and serves $n = 102$ mobile users. All the users belong to three groups—Groups 1, 2, and 3. These groups respectively correspond to the users who request videos in QCIF, CIF, and D1 formats. As previously mentioned, the purpose of this work is to explore the transmission scheme under a given price structure. Thus, this work studies the price structure parameters $\{p_{s,n}, q_{s,n}, w_{s,n}, \varphi_{s,n}\}$, and these parameters are exogenous variables but not endogenous ones. Consequently, the maximum profits $\{\mathrm{P}_{\mathrm{WSP}}, \mathrm{P}_{\mathrm{CP}}, \mathrm{P}_{\mathrm{EU}}\}$ are actually generated through adjusting the endogenous allocated rates $\{r_s$ and $\gamma_s\}$ based on observable $\{p_{s,n}, q_{s,n}, w_{s,n}, \varphi_{s,n}\}$.

Since this work studies the transmission problem for a three-side market, this section conducts four sets of conditional experiments for evaluation. The four sets are listed as follows.

1) *Cooperative and reasonable price structure*: This scenario is a general case to illustrate an ideal market.
2) *Variable price structure*: This experiment assesses the effect on profits when one side (i.e., the WSP, CPs, or EUs) changes prices arbitrarily. The corresponding resource-allocation results are also discussed in this experiment.
3) *Unreasonable price structure*: This experiment conducts a test to evaluate the performance of different pricing schemes when the worst case of the variable price scenario occurs.
4) *Typical price structures*: Since pricing plans vary in many countries, we test three well-known broadband pricing schemes and examine the performance of the proposed profit model under these plans.

[5]"China GPRS/EDGE dataplans," http://www.86callchina.com/gprs-cdma-data-cards.htm

In addition to the study of our optimization strategy, called "Matroid-3-Side," this section also investigates the performance of the following typical schemes. The details are described as follows.

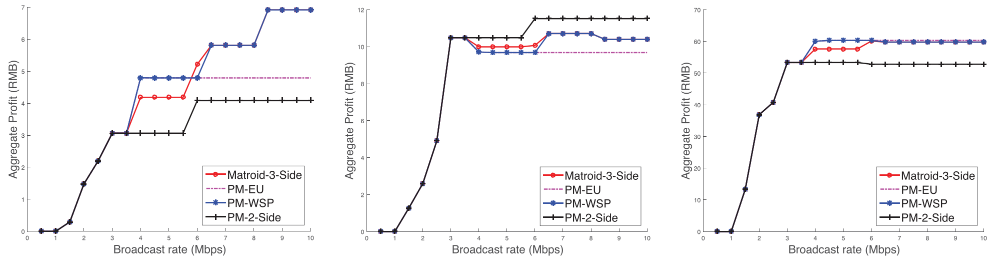
1) *PM-WSP*: This profit-maximizing rate-allocation is rebuilt based on the work by Li *et al.*[35] under a monopolistic WSP condition. This approach allows the WSP to choose the most proper rate allocation according to their desirable financial target.
2) *PM-EU*: Since all the profits of WSPs and CPs are in fact generated from EUs, the final profits of WSPs and CPs increase only when more EUs access the video services. In this scheme, the user-friendly allocation [35] is used by the WSP. Such a scheme uses a user-profit objective to dominantly adjust the rate allocation when both the satisfaction of an EU and the payment from the EU are considered.
3) *PM-2-Side*: This scheme was originally proposed by Hande *et al.*[2], and we modify it to support the computation of a two-side market—monopolistic WSP with multiple CPs.

The following sections describe the experimental results when the above-mentioned schemes are applied to experimental settings (1)–(3). For clarity, we employ line graphs to illustrate the experimental results. The following discussion gives the profit results and the corresponding rate allocation.

B. Profit Performance Analysis

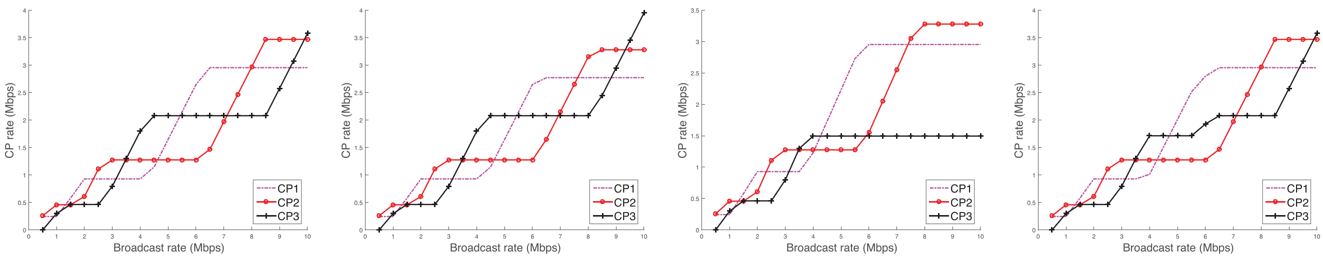
1) Profit Performance Under the Cooperative and Reasonable Price Structure: We begin by considering the ideal case in the broadcasting network, where the price structures among the WSP, CPs, and EUs are perfect. In such a scenario, all the profits increase when more broadcasting rates are supplied. Nevertheless, although all the schemes perform well in this ideal environment, not every scheme except ours yields maximum profits for three sides.

2) Profit Performance Under the Variable Price Structure: In a practical market, it is common for a WSP or a CP to change its price policy. EUs may also change their preferences at any time. The price changes from any side influence the profit of the other sides. The objective of this work is to maximize the profits through transmission control under a given price structure, no matter how cooperative the market price becomes. To verify this idea, we conduct the following experiment. We respectively change the parameters φ, p, q of the price model to examine the outcomes under different schemes, as shown in Figs. 5, 7, and 9. The corresponding rate assignments are illustrated in Figs. 6, 8, and 10. When the CP increases its subscribing price φ for content, we can make the following observations (see Figs. 5 and 6). First, when the available rate-resource is limited, the effective profits of three sides under all the pricing and allocation scheme generate the same results. Nevertheless, the assigned rates have no significant difference. Second, when the availability of resources is at the medium level, the WSP earns higher profits by using the first scheme "PM-WSP," whereas the CPs make the lowest profit, no matter how φ changes. The second scheme "PM-EU" takes much into account the EUs' benefits such that the profits of the EUs reach the maximum, but the profits of the WSP and the CPs become lower. When the third scheme "PM-2-Side" is applied to the system, since it allocates the rates



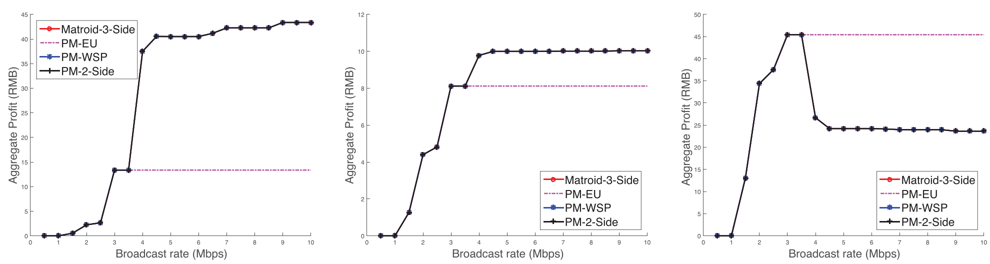
(a) Profit of the WSP (b) Profit of the CPs (c) Profit of the EUs

Fig. 5. Profits of three sides when the content price that is set by the CP φ varies.



(a) Rates under scheme (i): PM-WSP (b) Rates under scheme (ii): PM-EU (c) Rates under scheme (iii): PM-2-Side (d) Rates under the proposed scheme: Matroid-3-Side

Fig. 6. Corresponding allocated rates under four schemes.



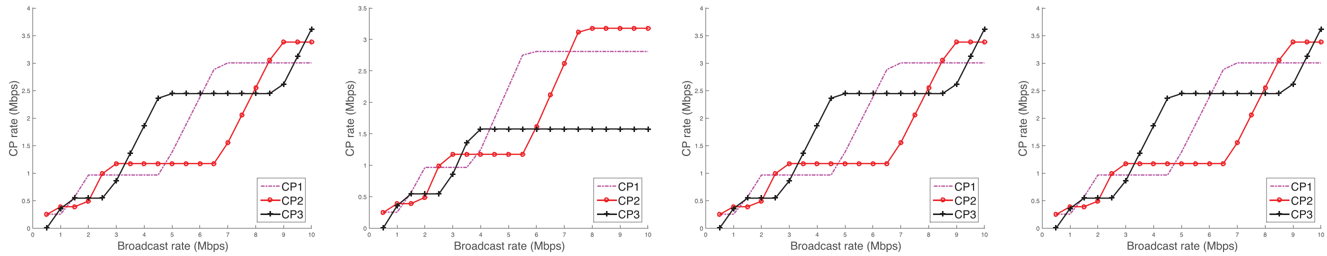
(a) Profit of the WSP (b) Profit of the CPs (c) Profit of the EUs

Fig. 7. Profits of three sides when the price p that the EUs should pay the WSP varies.

in consideration of CP participation, the CP keeps at higher profit level. However, the profits of both the WSP and EUs decrease. Regarding the proposed scheme "Matroid-3-Side," as its design is to avoid the overpriced or underpriced cases, the profit keeps a balance among those three sides. Thirdly, when higher broadcasting rates are adopted in the system, schemes "PM-EU" and "PM-2-Side" do not make higher profits for the WSP. This is unreasonable for the business operation of the WSP. Only the first scheme "PM-WSP" and the proposed scheme "Matroid-3-Side" yield higher revenues for the WSP and EUs compared with schemes "PM-EU" and "PM-2-Side." Overall, we can conclude that schemes "PM-WSP" and "Matroid-3-Side" are effective for WSP deployment and EU access costs. More specifically, the proposed scheme shows the advantage of a balance between three sides, especially when medium resources are present. Thus, the proposed scheme is more effective than scheme "PM-WSP" and outperforms the other two schemes.

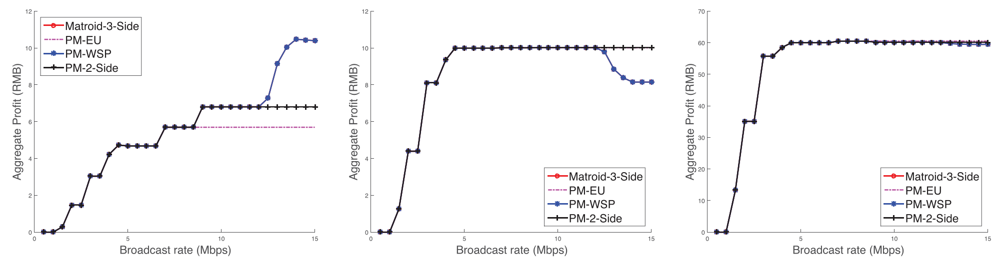
To further test the robustness of each scheme, we conduct another experiment on variable policies. Figs. 7–10 show the results. When the WSP charges p to the EUs, as illustrated in Figs. 7 and 8, the profits of both the WSP and CPs do not increase as the broadcasting rates rise. However, the profit of EUs reduces, as shown in Fig. 7(c). This phenomenon is reasonable because high prices decrease the satisfaction of users and the subscriptions. Scheme "PM-EU" shows better profits only for EUs but generates lower profits for both the WSP and CPs. Closely examining the result of scheme "PM-EU" indicates that when the system provides medium and high broadcasting rates, the profit of the WSP reaches half the amount of revenues as usual, compared with the other three schemes. Fourth, when the charge to CPs is increased to q, as shown in Figs. 9 and 10, such a charge has little impact on the EUs, no matter what type of schemes is used in the system. As a whole, if high broadcasting rates are employed, scheme "PM-WSP" and the proposed scheme "Matroid-3-Side" ensure the profit of the WSP, whereas that of CPs is reduced. Scheme "PM-2-Side" favors CPs over the WSP because it considers the benefit of CPs more.

Finally, the findings of the above three experiments indicate that when one side changes its price strategy, the profits of the other two actors vary accordingly. The final profit of each actor of the system depends on the scheme design. Schemes "PM-WSP" and "PM-2-Side" respectively take the benefits of their own sides into major consideration, with little consideration of the other sides. These two schemes might have a conflict between each other. Scheme "PM-EU" pays more attention to the benefit of EUs although it gradually dwindles the revenues of



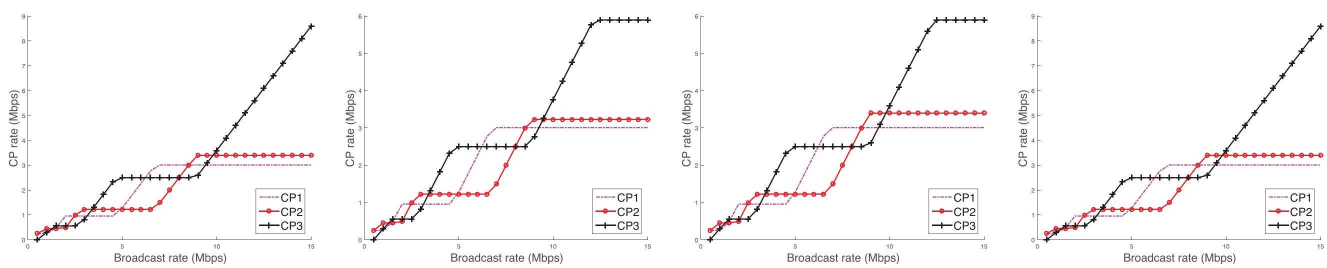
(a) Rates under scheme (i): PM-WSP
(b) Rates under scheme (ii): PM-EU
(c) Rates under scheme (iii): PM-2-Side
(d) Rates under the proposed scheme: Matroid-3-Side

Fig. 8. Corresponding allocated rates under four schemes.



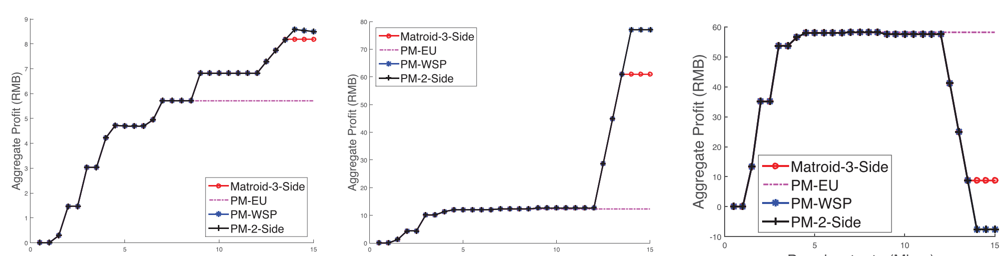
(a) Profit of the WSP
(b) Profit of the CPs
(c) Profit of the EUs

Fig. 9. Profits of three sides when the price q that the WSP charges the CP varies.



(a) Rates under scheme (i): PM-WSP
(b) Rates under scheme (ii): PM-EU
(c) Rates under scheme (iii): PM-2-Side
(d) Rates under the proposed scheme: Matroid-3-Side

Fig. 10. Corresponding allocated rates under four schemes.

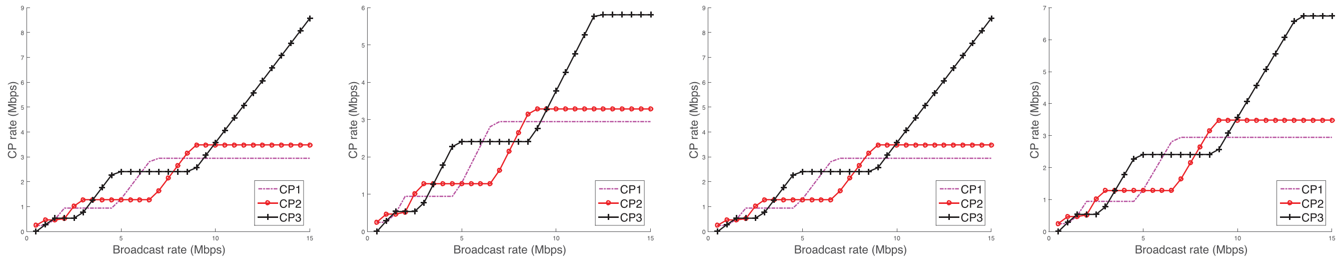


(a) Profit of the WSP
(b) Profit of the CPs
(c) Profit of the EUs

Fig. 11. Profits of three sides when the content price that is set by CPs φ is high.

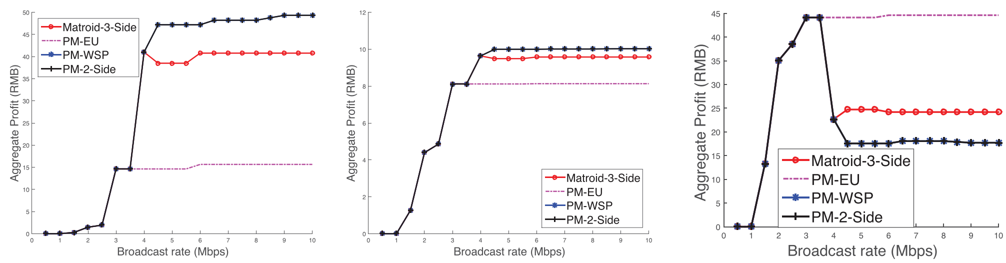
the WSP and CPs. Thus, scheme "PM-EU" might not be applicable to practical systems. Scheme "Matroid-3-Side" ensures the benefits of the WSP and EUs while reserving a balance between three sides. Compared with the other schemes, scheme "Matroid-3-Side" demonstrates better profit performance in a three-side market.

3) Profit Performance Under the Unreasonable Price Structure: This test evaluates the performance of the different rate-allocation schemes under three extreme pricing conditions. That is, each side keeps improving its price or benefit so as to achieve a maximum benefit. This extreme situation might lead to an unbalanced market because excessively high prices eventually decrease the number of subscriptions as well as the corresponding final sum of profits. However, it is still likely to occur in practical markets because each side has the right to make its own choice and adjusts the price at any time. Under the influence of unreasonable price structures, there could be fluctuating turbulence in the market, but in the end a new mechanism would take over and stabilizes the market. We evaluate the profit performance under reasonable price schemes in Figs. 11, 13, and 15. The corre-



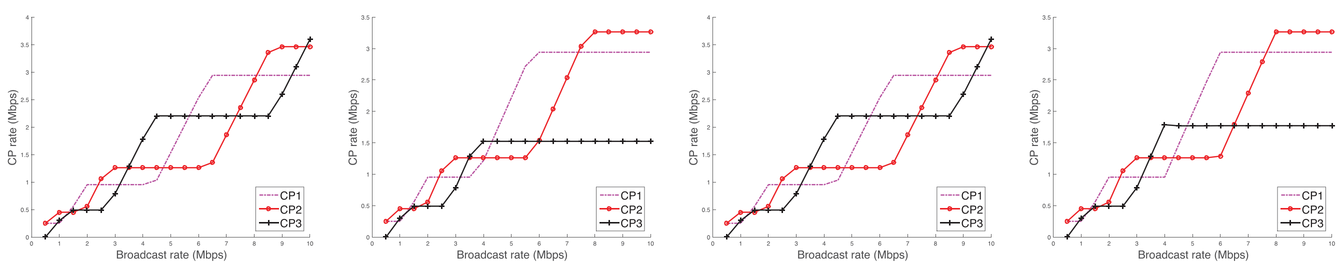
(a) Rates under scheme (i): PM-WSP
(b) Rates under scheme (ii): PM-EU
(c) Rates under scheme (iii): PM-2-Side
(d) Rates under the proposed scheme: Matroid-3-Side

Fig. 12. Corresponding allocated rates under four schemes.



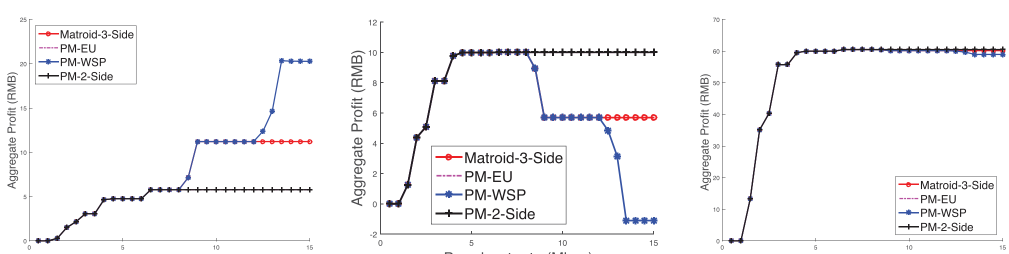
(a) Profit of the WSP
(b) Profit of the CPs
(c) Profit of the EUs

Fig. 13. Profits of three sides when the price p that the EU pays the WSP is high.



(a) Rates under scheme (i): PM-WSP
(b) Rates under scheme (ii): PM-EU
(c) Rates under scheme (iii): PM-2-Side
(d) Rates under the proposed scheme: Matroid-3-Side

Fig. 14. Corresponding allocated rates under four schemes.

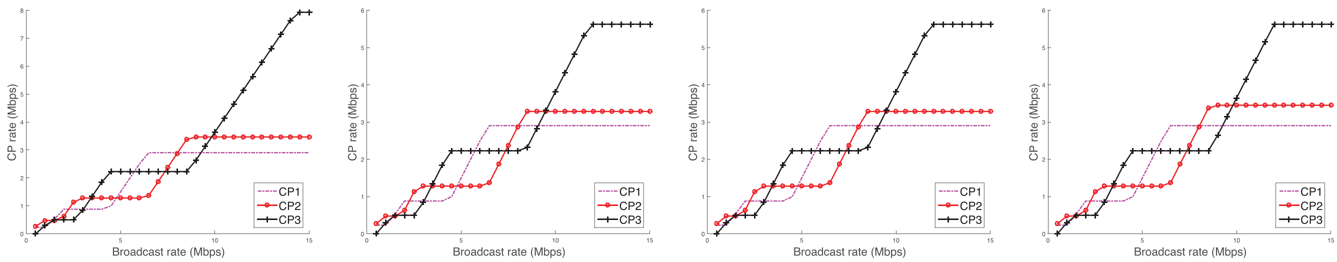


(a) Profit of the WSP
(b) Profit of the CPs
(c) Profit of the EUs

Fig. 15. Profits of three sides when the price q that the WSP charges CPs is high.

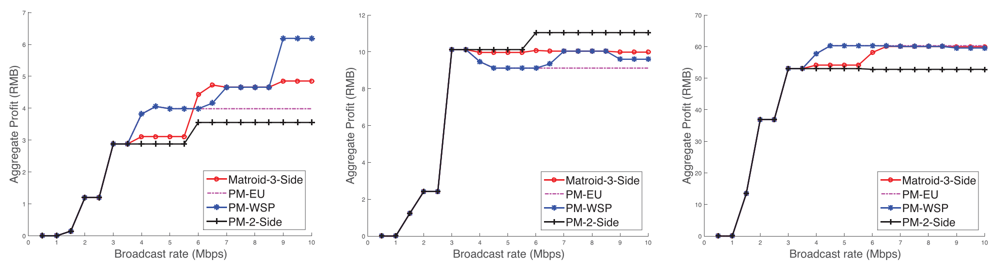
sponding rate assignments are shown in Figs. 12, 14, and 16. As shown in Figs. 11 and 12, when CPs overcharge a subscribing price φ to the EUs, imminent profit gain is available at CPs. However, it causes the decrease of EUs. Scheme "PM-WSP" does not relieve this unbalance. As for Scheme "PM-EU," it reflects the willingness of EU profits, but the number of subscriptions decreases nonetheless. Scheme "PM-2-Side" cares about the profits of CPs and the WSP. When the traffic price p of EUs is excessively high, as shown in Figs. 13 and 14, similar phenomenon occurs, i.e., EU subscriptions diminish. These two tests show that only the proposed scheme manages to tradeoff the profits between CPs and EUs, on the premise of a profit guarantee for the WSP. When the WSP increases the price charged to CPs, as shown in Figs. 15 and 16, the profit of CPs drops quickly even when more broadcasting rates are offered later. Among these four schemes, only the proposed scheme shows favorable balancing abilities to share profits among the different actors of the system.

4) Profit Performance Under Typical Price Structures: Today, WSPs have used sophisticated pricing schemes for broadband data access with the popularity of mobile devices and exponential growth of video services. The above experi-



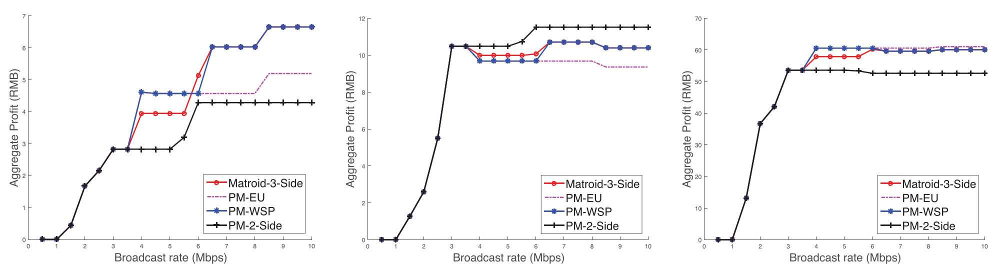
(a) Rates under scheme (i): PM-WSP
(b) Rates under scheme (ii): PM-EU
(c) Rates under scheme (iii): PM-2-Side
(d) Rates under the proposed scheme: Matroid-3-Side

Fig. 16. Corresponding allocated rates under four schemes.



(a) Profit of the WSP
(b) Profit of the CPs
(c) Profit of the EUs

Fig. 17. Profits of three sides under usage-based pricing scheme.



(a) Profit of the WSP
(b) Profit of the CPs
(c) Profit of the EUs

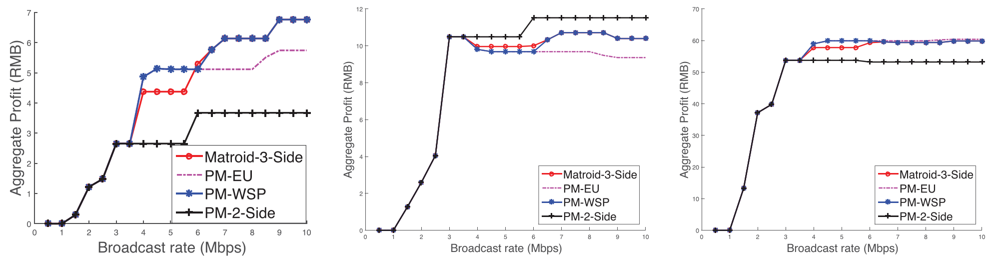
Fig. 18. Profits of three sides under the Paris-Metro pricing scheme.

ments demonstrated that the proposed model could guarantee the three-side profits through transmission control, regardless of the change of given price parameters. Next, we evaluate the performance on typical and practical markets by testing three well-known broadband pricing schemes mentioned in [6], including usage-based pricing, Paris-Metro pricing, and priority pricing.

Usage-based pricing: This pricing plan was implemented by New Zealand, U.S., U.K., etc. Under this pricing structure, the EU is charged in proportion to the actual volume of data usage. In practice, the EU usually pays a flat price merely up to a predetermined volume of traffic. When usage exceeds such a predetermined volume, the EU is charged in proportion to the volume of data consumed. Thus, the WSP can keep high profits at the expense of the lower profit of CPs or EUs, which is shown in Fig. 17(a)–(c). However, if the factor of EUs is over-considered, i.e., prior guarantees of the interest of EUs, it is hard to improve the profit of the WSP even when the available rate increases, shown in Fig. 17(a). The proposed solution marked in "Matroid-3-side" demonstrated favorable resilience on the three-side market.

Paris-Metro pricing: This plan is designed for adaption to differentiated service classes. EUs have the freedom to select desired services. This pricing structure permits the WSP to partition the resources into logical traffic classes, each of which is identical in its treatment of data packets but charges users differently [6]. Consequently, the EU pays more when selecting more expensive services. It is fair for EUs, as shown in Fig. 18(c). However, both the WSP and CPs would not benefit from such a structure, as displayed in Fig. 18(a) and 18(b), because differentiated video streaming services require stepwise bandwidth to achieve the same QoE in consideration of content characteristics. In such a case, an efficient rate-allocation scheme becomes necessary because the rate vectors for multiuser broadcasting form a sum-rate facet. Thus, the proposed "Matroid-3-Side" model is more competent than the other three methods because the achievable profit regions of the three sides are easy to obtain through its contra-polymatroidal structures.

Priority pricing: This pricing scheme enables the WSP to manage its services with priority classes. EUs request different QoS services by packet setting. Higher priority services mean higher payment and better quality. Since the conflict among WSP, CPs and EUs exist, most studies begun to find the rate equilibrium. However, the equilibrium and the associated revenue from services do not hinge upon the prices of the different priority classes. Instead, the prices have a relation with the prob-



(a) Profit of the WSP (b) Profit of the CPs (c) Profit of the EUs

Fig. 19. Profits of three sides under the priority pricing scheme.

ability of packet loss during the transmission [6]. Thus, those schemes with better consideration of both transmission control and rate allocation would show more effectiveness by using this pricing plan. Consequently, the proposed "Matroid-3-Side" model demonstrated better profit performance among the WSP, CPs and EUs, as shown in Fig. 19(a)–(c).

VI. Conclusion and Future Works

In this paper, we propose a framework for profit maximization in wireless video broadcasting systems. We model the profit maximization of WSPs and CPs, together with the integrated QoE maximization of EUs. The relation between the WSP, CPs, and EUs is formulated as a three-side profit problem. For the WSP, EUs, and CPs, we exploit the polymatroidal structures for profit region optimization and the contra-polymatroidal structures for rate region optimization, respectively. This leads to an explicit and rapid solution for profit optimization along with rate allocation. The experimental results demonstrate that the proposed solution effectively maximize the profits of the WSP along with CPs while simultaneously reserving the maximum satisfaction of EUs. In the future, we will expand and combine this method into a more complex broadcasting system with more heterogeneous QoE for EUs.

Appendix A
Proof of Lemma 3.1: Existence of c_2

Let T be a set of elements in E. Since $\varphi_{s,n} \geq q_{s,n}$, there is $\sum_{s=1}^{|T|}\sum_n r_s \cdot (\varphi_{s,n} - q_{s,n}) \geq 0$. Then, $B^{\mathrm{CP}}(T) = \sum_{s=1}^{|T|}\sum_n (r_s\varphi_{s,n} - r_s q_{s,n}) = \sum_{s=1}^{|T|}\sum_n r_s \cdot (\varphi_{s,n} - q_{s,n}) \geq 0$. Hence, there is a positive value c_2 such that $\max \sum_{s=1}^{|T|}\sum_n (r_s\varphi_{s,n} - r_s q_{s,n}) \geq \sum_{s=1}^{|T|}\sum_n (r_s\varphi_{s,n} - r_s q_{s,n}) \geq c_2 \geq 0$ holds.

Appendix B
Proof of Theorem 3.2: Rate Region of CP is a Contra-Polymatroid

(i) It is normalized: Clearly, $R^{\mathrm{CP}}(\emptyset) = 0$.

(ii) It is nondecreasing: Let T and T' be two finite sets of elements in E, and $T' \subseteq T \subseteq E$. Since $B^{\mathrm{CP}}(T') = \sum_{s=1}^{|T'|}\sum_n (r_s \cdot \varphi_{s,n} - r_s \cdot q_{s,n})$, there is $R^{\mathrm{CP}}(T') = \sum_{s=1}^{|T'|}\sum_n \frac{b_s}{\varphi_{s,n} - \cdot q_{s,n}}$. Define $\Delta V = \frac{b_s}{\varphi_{s,n} - \cdot q_{s,n}}$. Then,

$$
\begin{aligned}
R^{\mathrm{CP}}(T) &= \sum_{s=1}^{|T|}\sum_n \Delta V \\
&= \sum_{s=1}^{|T'|}\sum_n \Delta V + \sum_{s=T'+1}^{|T|}\sum_n \Delta V \\
&\geq R^{\mathrm{CP}}(T').
\end{aligned}
$$

(iii) It is supermodular: Let $T' \cap T = T''$. There is $T' \cup T = T' + T - T''$. Then,

$$
\begin{aligned}
R^{\mathrm{CP}}(T' \cup T) + R^{\mathrm{CP}}(T' \cap T) &= \sum_{s=1}^{|T'|}\sum_n (\Delta V) + \sum_{s=1}^{|T|}\sum_n (\Delta V) \\
&\quad - \sum_{s=1}^{|T''|}\sum_n (\Delta V) + \sum_{s=1}^{|T''|}\sum_n (\Delta V) \\
&= \sum_{s=1}^{|T'|}\sum_n (\Delta V) + \sum_{s=1}^{|T|}\sum_n (\Delta V).
\end{aligned}
\tag{37}
$$

$$
R^{\mathrm{CP}}(T') + R^{\mathrm{CP}}(T) = \sum_{s=1}^{|T'|}\sum_n (\Delta V) + \sum_{s=1}^{|T|}\sum_n (\Delta V). \tag{38}
$$

Combining (37) and (38) yields

$$
R^{\mathrm{CP}}(T' \cup T) + R^{\mathrm{CP}}(T' \cap T) = R^{\mathrm{CP}}(T') + R^{\mathrm{CP}}(T).
$$

Thus, R^{CP} satisfies the supermudular property.

By combining (i), (ii), and (iii), $\mathcal{R}(B^{\mathrm{CP}})$ is a contra-polymatroid. This completes the proof. □

Appendix C
Proof of Theorem 3.4: Profit Region of EUs Is a Polymatroid

(i) It is normalized: Clearly, $B^{\mathrm{EU}}(\emptyset) = 0$.

(ii) It is nondecreasing: Let T and T' be two finite sets of elements in E, and $T' \subseteq T \subseteq E = \{1, 2, \ldots, S\}$. Define $\Delta(U) = (u_{s,n}(r_s) - r_s \dot{p}_{s,n} - r_s \cdot \varphi_{s,n})$. Then

$$B^{\mathrm{EU}}(T') = \sum_{s=1}^{|T'|} \sum_{n} \Delta(U)$$

$$B^{\mathrm{EU}}(T) = \sum_{s=1}^{|T|} \sum_{n} \Delta(U) = \sum_{s=1}^{|T'|} \sum_{n} \Delta(U) + \sum_{s=|T'|+1}^{|T|} \sum_{n} \Delta(U) \geq B^{\mathrm{EU}}(T').$$

(iii) It is submodular: Let $T' \cap T = T''$, and there is $T' \cup T = T' + T - T''$. Then,

$$B^{\mathrm{EU}}(T' \cup T) + B^{\mathrm{EU}}(T' \cap T) = \sum_{s=1}^{|T|} \sum_{n} \Delta(U) + \sum_{s=1}^{|T'|} \sum_{n} \Delta(U) + \sum_{s=1}^{|T''|} \sum_{n} \Delta(U) - \sum_{s=1}^{|T''|} \sum_{n} \Delta(U) = \sum_{s=1}^{|T|} \sum_{n} \Delta(U) + \sum_{s=1}^{|T'|} \sum_{n} \Delta(U). \tag{39}$$

$$B^{\mathrm{EU}}(T') + B^{\mathrm{EU}}(T) = \sum_{s=1}^{|T|} \sum_{n} \Delta(U) + \sum_{s=1}^{|T'|} \sum_{n} \Delta(U). \tag{40}$$

Combining (39) and (40), there is

$$B^{\mathrm{EU}}(T' \cup T) + B^{\mathrm{EU}}(T' \cap T) = B^{\mathrm{EU}}(T') + B^{\mathrm{EU}}(T).$$

Thus, B^{EU} satisfies the submodular property.

After combining (i), (ii), and (iii), $\mathcal{B}(B^{\mathrm{EU}})$ is a polymatroid. This completes the proof. □

References

[1] Cisco Syst., Inc.. San Jose, CA, USA, "Global mobile data traffic forecast update, 2011–2016," Feb. 2012 [Online]. Available: http://www.puremobile.com/media/infortis/documents/cisco_mobile_forecast.pdf

[2] P. Hande, C. M., R. Calderbank, and S. Rangan, "Network pricing and rate allocation with content provider participation," in *Proc. INFOCOM*, Mar. 2009, pp. 990–998.

[3] C. Gizelis and D. Vergados, "A survey of pricing schemes in wireless networks," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 1, pp. 126–145, First Quarter 2011.

[4] V. Pandey, D. Ghosal, and B. Mukherjee, "Pricing-based approaches in the design of next-generation wireless networks: A review and a unified proposal," *IEEE Commun. Surveys Tuts.*, vol. 9, no. 2, pp. 88–101, Second Quarter 2007.

[5] Cisco Systems, Inc.. San Jose, CA, USA, "Moving toward usage-based pricing: A connected life market watch perspective," Mar. 2012 [Online]. Available: http://www.cisco.com/web/about/ac79/docs/clmw/Usage-Based-Pricing-Strategies.pdf

[6] S. Sen, C. Joe-Wong, S. Ha, and M. Chiang, "A survey of smart data pricing: Past proposals, current plans, and future trends," in *Proc. ACM Comput. Surveys*, Nov. 2013, vol. 46, no. 2, pp. 1–37.

[7] S. Sen, C. Joe-Wong, S. Ha, and M. Chiang, "Incentivizing time-shifting of data: A survey of time-dependent pricing for internet access," *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 91–99, Nov. 2012.

[8] P. Hande, C. M., R. Calderbank, and J. Zhang, "Pricing under constraints in access networks: Revenue maximization and congestion management," in *Proc. INFOCOM*, Mar. 2010, pp. 938–946.

[9] E. Tsiropoulou, G. Katsinis, and S. Papavassiliou, "Distributed uplink power control in multiservice wireless networks via a game theoretic approach with convex pricing," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 1, pp. 61–68, Jan. 2012.

[10] P. Liu, P. Zhang, S. Jordan, and M. Honig, "Single-cell forward link power allocation using pricing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 3, no. 2, pp. 533–543, Mar. 2004.

[11] J. Jia, Q. Zhang, Q. Zhang, and M. Liu, "Revenue generation for truthful spectrum auction in dynamic spectrum access," in *Proc. ACM MobiHuc*, May 2009, pp. 3–12.

[12] L. Yang, H. Kim, J. Zhang, M. Chiang, and C. Tan, "Pricing-based spectrum access control in cognitive radio networks with random access," in *Proc. INFOCOM*, Mar. 2011, pp. 2228–2236.

[13] W.-H. Wang, M. Palaniswami, and S. H. Low, "Application-oriented flow control: Fundamentals, algorithms and fairness," *IEEE/ACM Trans. Netw.*, vol. 14, no. 6, pp. 1282–1291, Dec. 2006.

[14] C. Singhal, S. De, R. Trestian, and G.-M. Muntean, "Joint optimization of user-experience and energy-efficiency in wireless multimedia broadcast," *IEEE Trans. Mobile Comput.*, vol. 13, no. 7, pp. 1522–1535, Jul. 2014.

[15] S. Parakh and A. Jagannatham, "VCG auction based optimal allocation for scalable video communication in 4G WiMAX," in *Proc. NCC*, Feb. 2012, pp. 1–5.

[16] S. Parakh and A. Jagannatham, "Game theory based dynamic bit-rate adaptation for H.264 scalable video transmission in 4 G wireless systems," in *Proc. SPCOM*, Jul. 2012, pp. 1–5.

[17] L. Zhou, Z. Yang, Y. Wen, H. Wang, and M. Guizani, "Resource allocation with incomplete information for QoE-driven multimedia communications," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 3733–3745, Aug. 2013.

[18] J. Liu, B. Li, H.-R. Shao, W. Zhu, and Y.-Q. Zhang, "A proxy-assisted adaptation framework for object video multicasting," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 15, no. 3, pp. 402–411, Mar. 2005.

[19] J. Huang, Z. Li, M. Chiang, and A. K. Katsaggelos, "Joint source adaptation and resource allocation for multi-user wireless video streaming," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 18, no. 5, pp. 582–595, May 2008.

[20] S. Hua, Y. Guo, Y. Liu, H. Liu, and S. S. Panwar, "Scalable video multicast in hybrid 3G-ad-hoc networks," *IEEE Trans. Multimedia*, vol. 13, no. 2, pp. 402–413, Apr. 2011.

[21] Y. Wang, Z. Ma, and Y.-F. Ou, "Modeling rate and perceptual quality of scalable video as functions of quantization and frame rate and its application in scalable video adaptation," in *Proc. Packet Video*, May 2009, pp. 1–9.

[22] Y.-F. Ou, Y. Xue, and Y. Wang, "Q-STAR: A perceptual video quality model considering impact of spatial, temporal, and amplitude resolutions," *IEEE Trans. Image Process.*, vol. 23, no. 6, pp. 2473–2486, Jun. 2014.

[23] W. Ji, B.-W. Chen, Y. Chen, and S.-Y. Kung, "Profit improvement in wireless video broadcasting system: A marginal principle approach," *IEEE Trans. Mobile Comput.*, vol. 14, no. 8, pp. 1659–1671, Aug. 2015.

[24] S. Li, J. Huang, and S.-Y. R. Li, "Profit maximization of cognitive virtual network operator in a dynamic wireless network," in *Proc. ICC*, Jun. 2012, pp. 1–6.

[25] T. Schierl, T. Stockhammer, and T. Wiegand, "Mobile video transmission using scalable video coding," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 17, no. 9, pp. 1204–1217, Sep. 2007.

[26] M. S. Talebi, A. Khonsari, M. Hajiesmaili, and S. Jafarpour, "Quasi-optimal network utility maximization for scalable video streaming," *CoRR*, 2011 [Online]. Available: http://arxiv.org/abs/1102.2604

[27] J.-W. Lee, R. R. Mazumdar, and N. B. Shroff, "Non-convex optimization and rate control for multi-class services in the Internet," *IEEE/ACM Trans. Netw.*, vol. 13, no. 4, pp. 827–840, Aug. 2005.

[28] A. Shokrollahi, "Raptor codes," *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2551–2567, Jun. 2006.

[29] W. Ji, Z. Li, and Y. Chen, "Joint source-channel coding and optimization for layered video broadcasting to heterogeneous devices," *IEEE Trans. Multimedia*, vol. 14, no. 2, pp. 443–455, Apr. 2012.
[30] M. Maddah-Ali, A. Mobasher, and A. Khandani, "Fairness in multiuser systems with polymatroid capacity region," *IEEE Trans. Inf. Theory*, vol. 55, no. 5, pp. 2128–2138, May 2009.
[31] G. Nemhauser, L. Wolsey, and M. Fisher, "An analysis of approximations for maximizing submodular set functions—I," *Math. Programming*, vol. 14, no. 1, pp. 265–294, Dec. 1978.
[32] A. Krause, H. McMahan, C. Guestrin, and A. Gupta, "Robust submodular observation selection," *J. Mach. Learn. Res.*, vol. 9, pp. 2761–2801, Dec. 2008.
[33] J. Edmonds, "Submodular functions, matroids and certain polyhedra," in *Proc. Combinatorial Structures Their Appl.*, Jun. 1969, pp. 69–87.
[34] D. Tse and S. Hanly, "Multiaccess fading channels—Part I: Polymatroid structure, optimal resource allocation and throughput capacities," *IEEE Trans. Inf. Theory*, vol. 44, no. 7, pp. 2796–2815, Nov. 1998.
[35] S. Li and J. Huang, "Price differentiation for communication networks," *IEEE/ACM Trans. Netw.*, vol. 22, no. 3, pp. 703–716, Jun. 2014.

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