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Controlled Coalitional Games for Cooperative Mobile Social Networks

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***Abstract*—Mobile social networks have been introduced as a new efficient (i.e., minimizing bandwidth usage) and effective (i.e., minimizing the delay or maximizing the number of target recipients) way of disseminating content and information to a particular group of mobile users who share similar interests. In this paper, we investigate how the content providers and the network operator can interact to distribute content in a mobile social network. The objective of each content provider is to minimize the cost that pertains to the time used to distribute the content to the subscribed mobile users and the cost due to the price paid to the network operator for transferring the content over a wireless connection through a base station. Although the content providers can cooperate by forming coalitions for sharing a wireless connection, the network operator can control the amount of bandwidth provided over the wireless connection. We introduce a novel coalitional game model, which is referred to as the controlled coalitional game, to investigate the decision-making process of the content providers and the network operator. Numerical studies show that, given the allocated bandwidth from the network operator, the content providers can self organize into coalitions while minimizing their individual cost. In addition, the results demonstrate that the revenue of the network operator can be maximized when the bandwidth allocation is performed while considering the coalitional structure of the content providers.**

***Index Terms*—Coalitional game, content provider, game theory, mobile social network.**

I. Introduction

THE CONCEPT of social networks has been introduced to enable people to keep in touch with friends, build social ties with people having similar interests, and facilitate communications and information sharing. This concept was extended to mobile environments to constitute the basis of mobile social networks [1]. In a mobile social network, the content distribution relies not only on the broadband connection from the base stations but also on the local connection when mobile users move and meet with one another. Such a content distribution scheme can reduce the radio resource usage of the base station and, hence, lower the cost (e.g., due to radio resource usage) for content providers by exploring the social relations and physical mobility of the mobile users. Although the content delivery and data routing among users in mobile social networks have been widely studied (e.g., [2]–[4]), to the best of our knowledge, none of the existing works have jointly considered the rationality of the content providers for sharing the wireless connection and the selfishness of the wireless infrastructure owner (i.e., network operator) to optimally manage the radio resources (i.e., bandwidth).

In this paper, we consider a mobile social network in which multiple content providers seek to buy a wireless connection from a network operator to distribute the content to the subscribed mobile users. To efficiently share their wireless connection, the content providers can cooperate by forming coalitions. Although this sharing will lower the cost incurred by the price charged by the network operator, the performance of content distribution may be degraded (e.g., due to larger delay). In addition, content providers can cooperate to allow their mobile users to forward the content of each other. In this case, the delay will be smaller due to more users forwarding the content, but the overhead of content transfer (e.g., battery energy consumption) becomes larger. For the network operator, the amount of bandwidth allocated to a wireless connection used by content providers can be controlled so that the revenue is maximized. However, while allocating bandwidth, the network operator has to take into account the quality-of-service (QoS) requirements of the users.

For this scenario, we introduce the idea of a *controlled coalitional game*, which is a novel game-theoretical model developed to jointly address the cooperative content forwarding and bandwidth sharing of multiple content providers and the bandwidth allocation of a network operator. This model is composed of a coalition formation scheme between the content providers and an optimization formulation for the network operator. In this case, the network operator can optimally "control" the coalition formation by adjusting its action. Similar to the well-known Stackelberg framework [5] (i.e., the hierarchical optimization model), the proposed game model allows us to obtain a solution for scenarios where these two formulations are intertwined. The main contributions of this paper can be summarized as follows.

- A novel analytical model for cooperative content forwarding among heterogeneous groups of mobile users who are

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subscribed to different content providers, is introduced. Because the mobile users who are subscribed to different content providers may have a varied mobility behavior, a multidimension absorbing Markov chain [6] is used to obtain various performance measures.

- A general coalition formation scheme between content providers with a composite strategy of cooperative content forwarding and bandwidth sharing is introduced. Along with the composite strategy of coalition formation (e.g., coalitions of content forwarding and bandwidth sharing can jointly or independently be formed), a 2-D Markov chain [6] is used to analyze the dynamics of coalition formation and to obtain the stable coalitional state of the content providers.
- Given the dynamics of the coalition formation of the content providers, the optimization model used by the network operator to allocate bandwidth to the wireless connection is introduced. This optimization model is based on the constrained Markov decision process (CMDP) and is used to maximize the revenue of the network operator with a constraint on the QoS requirement of the network operator. Using this model, we can obtain the optimal policy, which maps the coalitional state to the amount of allocated bandwidth.

Using the proposed controlled coalitional game, the numerical results show that the network operator can optimize the allocated bandwidth, given that the content providers perform, accordingly, a coalition formation process for cooperative content forwarding and bandwidth sharing.

The rest of this paper is organized as follows. Existing literature is reviewed in Section II. Section III describes the system model of the considered mobile social network. In Section V, the cost function of the content providers is defined, whereas Section VI introduces the proposed controlled coalitional game model. Section VII presents the numerical results. Conclusions are given in Section VIII.

II. Related Work

A. Mobile Social Networks

Recently, there has been an increased interest in studying models suitable for mobile social networks. The main field of application for mobile social networks is within the context of content distribution [2], [7]; however, it can also be adopted in a variety of other applications, e.g., health care [8], [9]. By exploring the special requirements and characteristics of the applications and their users, mobile social networks can improve the effectiveness of data transfer. In [10], a general architecture of the mobile social network was introduced. In this architecture, the major components are the client devices, the wireless access network, the Internet, and a server. Based on this architecture, a system prototype was developed to provide location-based information sharing. Routing in publish–subscribe mobile social networks is studied in [11] using a scheme called SocialCast. SocialCast estimates the social interaction metrics based on the patterns of movement among communities of users.

The authors in [12] proposed a content-delivery scheme for mobile social networks that performs carrier selection by taking into account both the mobility pattern and the meeting time of the people. Using this scheme, content delivery can be optimized for time-critical applications by significantly reducing the end-to-end delay. In [13], an optimal bandwidth allocation scheme was developed to transmit content from a content provider to users. The objective is to maximize the utility of all users, where utility is defined as a decreasing function of the content age. To efficiently utilize the network's resources, a message duplication reduction scheme was proposed in [14]. This scheme is based on the idea that messages will only be forwarded to users with matched interests. The work in [15] evaluated, using simulations, the performance of a mobile social network while taking into account the dynamic movement of the mobile users. The mobility model proposed in [15] can capture the speed, pattern, and interaction among the mobile users. In [16], a traffic modeling scheme that is suitable for mobile social network was presented. The relationship between mobile messaging and friendship was analyzed based on the trace data. Different types of behaviors were identified based on the users who engage in and respond to the incoming messages.

Although the existing literature has studied several interesting aspects of mobile social networks, in all of the aforementioned and other related works, the rational cooperation among the content providers and the radio resource management of the network operator were ignored.

B. Coalitional Game Theory

Coalitional game theory is a branch of game theory that is focused on studying the behavior and strategies of a group of rational players who might be interested in *cooperating* to improve their position and maximize their payoff in a given game or scenario. In particular, one class of coalitional games, which is known as coalition formation games, is dedicated to modeling and analyzing the process of forming coalitions between groups of players. Although coalition formation games are rooted in economics, they have also been applied to study different aspects of wireless communications and networking [17]–[19]. In [21], coalitional games were used to study the radio resource sharing in vehicular networks. The coalitional game formulated in [21] exploited the tradeoff between reducing the costs incurred by sharing wireless connections (between vehicular users) and the performance degradation that results from the vehicular users' cooperative behavior. In [22], a coalitional game for spectrum sensing in a distributed cognitive radio network was presented to reduce the false-alarm probability of the users and increase their throughput. A dynamic coalition formation algorithm was proposed in [23] to allocate the sleep time in a wireless sensor network.

Despite the variety of applications in which coalitional games have been used, to the best of our knowledge, this paper presents the first contribution that applies coalitional game theory in the context of mobile social networks. Moreover, in this paper, we introduce a novel approach to coalitional game theory, the *controlled coalitional game*, which combines

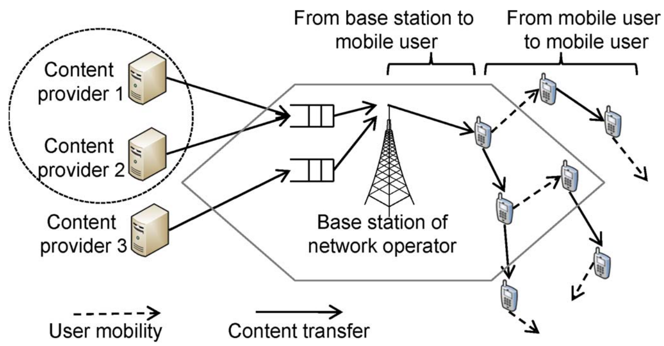

Fig. 1. Example of a mobile social network composed of multiple content providers and a network operator.

concepts from both hierarchical optimization techniques (e.g., Stackelberg games) and coalitional games. To the best of our knowledge, this novel class of coalitional games has never been considered in the literature and is being introduced in this paper.

III. System Model

In this section, we present the considered model for mobile social networks and provide one example scenario. Then, the hierarchical optimization model (i.e., controlled coalitional game) is introduced.

A. Mobile Social Network

Consider a mobile social network with the following three components (see Fig. 1).

- *Content providers*. We consider a mobile social network with a total of I content providers.[1] Let $\mathcal{I} = \{1, \ldots, I\}$ denote the set of all providers. These providers create a desired content for their subscribed mobile users (e.g., news, business data, and mobile applications). To transfer content, each content provider uses a wireless connection through a base station that belongs to a given network operator. The objective of the content providers is to minimize the cost of content distribution, which is a function of the content distribution delay, the bandwidth usage, and the content forwarding overhead.
- *Network operator*. A network operator provides a wireless data transfer service (i.e., a wireless connection) to the content providers in $\mathcal{I}$. The content received from the providers who use this service is buffered in a queue. Subsequently, the content at the head of the queue is transferred to the mobile users by the base station (e.g., using broadband wireless access) owned by the network operator. We consider that the network operator can control the amount of bandwidth b (i.e., the number of channels) allocated by the base station for transferring content to the mobile users. The price charged for each wireless connection is denoted by $b\theta$, where θ is a price constant with unit currency per bandwidth. Apart from mobile users subscribed to the content provider, the base station of the network operator serves "normal users", i.e., users who are not part of the mobile social network. Here, it is assumed that the objective of the network operator is to maximize the revenue from selling wireless connections to content providers while maintaining the QoS performance of the normal users at a given threshold.
- *Mobile users*. For any content provider i, there are N_i subscribed mobile users. However, only U_i subscribed mobile users will receive the new content through the base station (i.e., $U_i < N_i$). The rest of the mobile users can obtain the content through direct transfer. In particular, the content can directly be transferred between the subscribed mobile users when they move and meet each other.

We assume that the transmission rate of direct content transfer between mobile users is much larger than the transmission rate between the base station and any mobile user, because the transmission between mobile users is based on the local network, whereas the transmission between the base station and a mobile is based on the broadband wireless access network [24]. In this case, the local network (e.g., Wi-Fi with a speed of 54 Mb/s) has much faster speed than the broadband wireless access (e.g., a third-generation cellular network with speed of 2 Mb/s). In addition, the connection between mobile users is dedicated, and hence, the content transfer can be performed at the maximum speed of the local network. In contrast, the connection between the base station and a mobile user has to share the radio resource with other mobiles. As a result, the content transfer will receive the transmission rate lower than the maximum speed.

B. Example Scenario

One example scenario of a mobile social network with three content providers and a single network operator is shown in Fig. 1. In this scenario, content providers 1 and 2 form coalition $\mathcal{B} = \{1, 2\}$ to share a wireless connection from the network operator (i.e., bandwidth sharing). In this case, the network operator treats the content from the two providers equally and charges providers 1 and 2 for only one connection. The allocated bandwidth from the network operator is divided and used by providers 1 and 2 to transfer the content to their mobile users. In addition, the content providers can form another coalition $\mathcal{F}$ so that their subscribed mobile users can forward the content for each other (i.e., cooperative content forwarding). For example, for $\mathcal{F} = \{1, 2\}$, the mobile users of provider 1 can receive and forward the content from provider 2, and *vice versa*.

Within the aforementioned mobile social network, the content providers and the network operator must deal with a variety of tradeoffs when performing cooperation. First, by cooperating and forming coalitions for bandwidth sharing, the content providers can reduce the cost due to the price paid to the network operator. However, this cost reduction comes at the expense of an increased time for transferring the content (i.e., delay), because the shared bandwidth is limited. In addition, by forming coalitions for content forwarding, the delay experienced by the mobile users when receiving the

[1] In the rest of this paper, the terms *content provider* and *provider* are used interchangeably.

content will decrease, because there are more users helping in the content forwarding process. However, this cooperation for content forwarding increases the overhead, because more content has to be received, carried, and forwarded by the mobile users. We note that the coalition formation processes used for cooperative content forwarding and bandwidth sharing can jointly or independently be performed.

Furthermore, the formation of coalitions among content providers will depend on the amount of bandwidth allocated by the network operator. For example, if the amount of bandwidth per wireless connection is large, the content-transmission delay from the base station to the mobile users will be small, and thus, several content providers would be willing to cooperate and form a coalition. However, this case is undesirable for the network operator, because only one wireless connection will be sold. As a result, the network operator has an incentive to decrease the amount of allocated bandwidth to encourage the content providers to buy more bandwidth. Nonetheless, the network operator cannot indefinitely reduce its allocated bandwidth, because allocating a very small bandwidth will lead to a small revenue, because the network operator charges a price per unit of allocated bandwidth.

Consequently, we can clearly see that, in the studied model, there exists an inherent tradeoff that depends on the amount of bandwidth allocated by network operator. In essence, the amount of allocated bandwidth strongly impacts the cooperation strategies of the content providers, whereas this cooperative behavior of the content providers also impacts how the network operator selects its bandwidth. Hence, there is a need to investigate the optimal decisions of the network operator (i.e., bandwidth allocation) and content providers (i.e., coalition formation). To tackle this problem, we will next introduce the proposed controlled coalitional game framework.

C. *Controlled Coalitional Game*

To adequately model the decision-making process between the providers, who aim to minimize their cost, and the network operator, who aims to maximize its revenue given the QoS constraints, we formulate a hierarchical optimization model, referred to as *the controlled coalitional game*. The controlled coalitional game is, in essence, similar to the well-studied Stackelberg game, in which a player known as the *leader*, i.e., the network operator, can choose its strategy before the other players, known as followers, i.e., the content providers, make their strategy choices (see Fig. 2). As the leader, the network operator can optimize its reward (i.e., revenue) by controlling its action (i.e., amount of allocated bandwidth), given the state of the followers. The followers can observe the action of the leader and adopt their strategies (i.e., coalition formation) to minimize the cost. The coalition formation of followers is divided into the following two parts: 1) cooperative content forwarding and 2) bandwidth sharing.

To obtain the optimal action and strategies of leaders and followers, the controlled coalitional game is decomposed into the following two interrelated problems: 1) an optimization formulation based on a CMDP [25] for the network operator and 2) a coalitional game formulation for the content providers

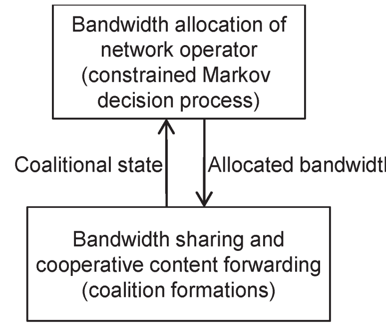

Fig. 2. Hierarchical optimization model (i.e., controlled coalitional game) for bandwidth allocation of the network operator and for cooperative content forwarding and bandwidth sharing of the content providers.

(see Fig. 2). In particular, the optimal action of network operator is obtained, given the coalitional structure of the content providers. In addition, the coalitional state transition of content providers is controlled by the action of the network operator. The details of this solution for the controlled coalitional game will be presented in Section VI.

IV. Markov Chain Model of Content Forwarding Among Mobile Users

In this section, we present an absorbing continuous-time Markov chain model for cooperative content forwarding among the mobile users. First, the state space and the corresponding transition matrix are defined. Then, various performance measures that will constitute the cost of content provider are obtained.

A. *State Space*

Without loss of generality, we consider the content forwarding of the mobile users subscribed to content provider i, who is a member of coalition $\mathcal{F} \subseteq \mathcal{I}$ (i.e., $i \in \mathcal{F}$) of size $|\mathcal{F}|$, where $|\cdot|$ denotes the cardinality of a set (i.e., coalition). In this case, $\mathcal{F}$ is a set of content providers who agree to allow their subscribed mobile users to forward the content of each other. An absorbing continuous-time Markov chain is used to model the content forwarding from the time the base station finishes transferring its content to the mobile users to the time when all mobile users of provider i receive the content (or when the deadline of content transfer is reached). The state of the content forwarding is the number of mobile users who received the content from provider i. The states can further be divided into *transient* and *absorbing states*. The transient state is the state at which not all mobile users of provider i received the content, and the absorbing state is the state at which all mobile users of provider i received the content.

The state space of the transient state can be defined as follows:

$$\Delta_{i,\mathcal{F}} = \mathbb{M}_i \times \prod_{\substack{j \neq i \\ j \in \mathcal{F}}} \mathbb{N}_j \tag{1}$$

where both $\times$ and $\prod$ are the Cartesian products. Set $\mathbb{M}_i$ is defined as $\mathbb{M}_i = \{\mathcal{N}_i | \mathcal{N}_i \in \{1, \ldots, N_i - 1\}\}$. Set $\mathbb{N}_j$ is defined as $\mathbb{N}_j = \{\mathcal{N}_j | \mathcal{N}_j \in \{0, \ldots, N_j\}\}$. $\mathcal{N}_i$ is the number of mobile users of provider i who received the content from provider i. $\mathcal{N}_j$ is the number of mobile users of provider $j \in \mathcal{F}$, $j \neq i$, and received the content from provider i.

The absorbing state can be defined as follows: $\delta_{i,\mathcal{F}} = \{N_i\}$, where N_i is the total number of mobile users that subscribe to content provider i.

B. Transition Matrix

Mobile users who receive content from a base station can directly transfer/forward this content to other users as they move and meet one another. We assume that the inter-meeting time interval of the mobile users is exponentially distributed. The mean time interval for the mobile users of providers i and j is denoted by $1/\Lambda_{i,j}$ [3], and hence, $\Lambda_{i,j}$ is the mean meeting rate. We assume $\Lambda_{i,j} = \Lambda_{j,i}$ for i, $j \in \mathcal{F}$. Given the state spaces for the transient and absorbing states (i.e., $\Delta_{i,\mathcal{F}}$ and $\delta_{i,\mathcal{F}}$, respectively), the transition matrix for the content forwarding case can be defined as follows:

$$\mathbf{Q}_{i,\mathcal{F}} = \left[\begin{array}{c|c} \mathbf{S}_{i,\mathcal{F}} & \vec{\mathbf{s}}_0 \\ \hline \mathbf{0} & 0 \end{array}\right] \tag{2}$$

where $\mathbf{S}_{i,\mathcal{F}}$ represents the transition matrix of the transient states in $\Delta_{i,\mathcal{F}}$. $\mathbf{0}$ is a matrix of zeros. Both $\mathbf{0}$ and 0 at the bottom of matrix $\mathbf{Q}_{i,\mathcal{F}}$ correspond to the absorbing state $\delta_{i,\mathcal{F}}$. $\vec{\mathbf{s}}_0$ is the vector whose elements are the transition rates from the transient state to the absorbing state.

The matrix $\mathbf{S}_{i,\mathcal{F}}$ can be expressed as follows:

$$\mathbf{S}_{i,\mathcal{F}} = \begin{bmatrix} \mathbf{N}^{(j)}_{0,0} & \mathbf{N}^{(j)}_{0,1} & & & \\ & \mathbf{N}^{(j)}_{1,1} & \mathbf{N}^{(j)}_{1,2} & & \\ & & \ddots & \ddots & \\ & & & \mathbf{N}^{(j)}_{N_j-1,N_j-1} & \mathbf{N}^{(j)}_{N_j-1,N_j} \\ & & & & \mathbf{N}^{(j)}_{N_j,N_j} \end{bmatrix} \tag{3}$$

where each row of the matrix $\mathbf{S}_{i,\mathcal{F}}$ represents the number of mobile users of content provider j for $j \neq i$, $j \in \mathcal{F}$ who received the content from provider i. In particular, $\mathbf{N}^{(j)}_{n_j,n'_j}$ is the transition matrix for the number of mobile users changing from n_j to n'_j. Matrix $\mathbf{N}^{(j)}_{n_j,n_j+1}$ accounts for the transition from states n_j to $n_j + 1$ for mobile users of provider j. Matrix $\mathbf{N}^{(j)}_{n_j,n_j+1}$ is composed of diagonal element $\eta^{(j)}_{(\ldots,n_k,\ldots)}$ associated with the number of mobile users n_k of the other providers $k \in \mathcal{F}$ and $k \neq j$. The diagonal element $\eta^{(j)}_{(\ldots,n_k,\ldots)}$ can be obtained from

$$\eta^{(j)}_{(\ldots,n_k,\ldots)} = (N_j - n_j)\left(\sum_{k\in\mathcal{F}} n_k \Lambda_{j,k}\right). \tag{4}$$

Matrix $\mathbf{N}^{(j)}_{n_j,n_j}$ accounts for the change in the number of mobile users of provider $k \in \mathcal{F}$ for $k \neq j$ who that received the content directly from provider i. The structure of matrix $\mathbf{N}^{(j)}_{n_j,n_j}$ is similar to $\mathbf{S}_{i,\mathcal{F}}$ in (3) and can be expressed as follows:

$$\mathbf{N}^{(j)}_{n_j,n_j} = \begin{bmatrix} \mathbf{N}^{(k)}_{0,0} & \mathbf{N}^{(k)}_{0,1} & & & \\ & \mathbf{N}^{(k)}_{1,1} & \mathbf{N}^{(k)}_{1,2} & & \\ & & \ddots & \ddots & \\ & & & \mathbf{N}^{(k)}_{N_k-1,N_k-1} & \mathbf{N}^{(k)}_{N_k-1,N_k} \\ & & & & \mathbf{N}^{(k)}_{N_k,N_k} \end{bmatrix}. \tag{5}$$

Again, matrix $\mathbf{N}^{(k)}_{n_k,n_k+1}$ accounts for the transition from states n_k to $n_k + 1$ for the mobile users of provider k. The diagonal element $\eta^{(k)}_{(\ldots,n_l,\ldots)}$ corresponds to the number of mobile users n_l of providers $l \in \mathcal{F}$ and $l \neq k$ who received the content from provider i. The diagonal element $\eta^{(k)}_{(\ldots,n_l,\ldots)}$ can be obtained similarly to the element in (4). The element $\mathbf{N}^{(k)}_{n_k,n_k}$ in $\mathbf{N}^{(j)}_{n_j,n_j}$ can be obtained similarly to the element in (5). The same steps are repeated for the rest of the providers in $\mathcal{F}$ until reaching the most inner matrix $\mathbf{N}^{(i)}_{n_i,n_i}$. The matrix $\mathbf{N}^{(i)}_{n_i,n_i}$ accounts for the change in the number of mobile users of provider i with the content.

The diagonal element of matrix $\mathbf{S}_{i,\mathcal{F}}$ corresponds to the number of mobile users of all providers $m \in \mathcal{F}$. It can be obtained from

$$\eta_{(\ldots,n_m,\ldots)} = -\sum_{m\in\mathcal{F}} \left(\eta^{(m)}_{(\ldots,n_{m'},\ldots)} + \zeta_{(\ldots,n_{m'},\ldots)}\right) \tag{6}$$

for $m' \in \mathcal{F}$, where $\zeta_{(\ldots,n_{m'},\ldots)}$ is the element of vector $\vec{\mathbf{s}}_0$ defined as follows:

$$\zeta_{(\ldots,n_{m'},\ldots)} = \begin{cases} (N_i - 1)\sum_{m\in\mathcal{F}} n_m \Lambda_{i,m}, & \text{if } n_i = N_i - 1 \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

$\zeta_{(\ldots,n_{m'},\ldots)}$ is the rate that the last mobile users of provider i will receive the content from the mobile users of providers $m' \in \mathcal{F}$.

C. Performance Measures

Based on the absorbing continuous-time Markov chain with transition matrix defined in (2), various performance measures for the content forwarding can be obtained for any provider i who is a member of a coalition $\mathcal{F}$ (used for cooperative content forwarding). Let $\vec{\boldsymbol{\xi}}$ denote the initial probability vector of the content forwarding, with each element denoted by $\xi_{(\ldots,n_i,\ldots)}$. Because U_i mobile users of content provider i will receive the content directly from the network operator's base station, $\xi_{(\ldots,n_i,\ldots)}$ can be obtained from

$$\xi_{(\ldots,n_i,\ldots)} = \begin{cases} 1, & \text{if } n_i = U_i \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

1) Average Content-Forwarding Delay: The average content-forwarding delay experienced by all mobile users of provider i is the average time to reach the absorbing state [6] and can be obtained from

$$D^{\text{fd}}_i(\mathcal{F}) = -\vec{\boldsymbol{\xi}}^T \mathbf{S}^{-1}_{i,\mathcal{F}} \vec{\mathbf{1}} \tag{9}$$

where $\vec{\mathbf{1}}$ is a column vector of ones.

2) Probability of All Mobile Users to Receive the Content: Assume that, at time 0, the base station finishes transferring the content of provider i to U_i mobile users. If the content of provider i has a deadline denoted by $\Gamma > 0$, the probability that all mobile users of provider i will receive the content is the probability that the absorbing state will be reached at time Γ [6] and can be obtained from

$$P_i^{\text{all}}(\mathcal{F}, \Gamma) = 1 - \vec{\boldsymbol{\xi}}^T \exp(\Gamma \mathbf{S}_{i,\mathcal{F}}) \vec{\mathbf{1}}. \tag{10}$$

3) Average Number of Mobile Users Receiving the Content: Given the deadline Γ, the average number of mobile users who received the content of provider i can be obtained from the transient-state probability. The transient-state probability vector $\vec{\mathbf{q}}(\Gamma)$ is

$$\vec{\mathbf{q}}(\Gamma) = \vec{\boldsymbol{\xi}}^T \exp(\mathbf{Q}_{i,\mathcal{F}} \Gamma) \tag{11}$$

where the element $q_{(\ldots,n_j,\ldots)}$ of vector $\vec{\mathbf{q}}(\Gamma) = [\cdots \quad q_{(\ldots,n_j,\ldots)}(\Gamma) \quad \cdots]^T$ corresponds to the probability that n_j mobile users of provider $j \in \mathcal{F}$ receive the content of provider i. The average number of mobile users of provider i who received the content from provider i at time Γ is given by

$$\overline{n}_i(\Gamma) = \sum_{n_i=1}^{N_i} n_i \left(\sum_{\substack{j \neq i \\ j \in \mathcal{F}}} \sum_{n_j=1}^{N_j} q_{(\ldots,n_j,\ldots)}(\Gamma) \right). \tag{12}$$

Note that these different performance measures can be used by content provider i to optimize its coalition formation strategy (e.g., with and without deadline).

V. Cost of Content Provider

Any content provider must deliver its content, in a timely manner, to its serviced mobile users while minimizing the cost of bandwidth usage. This cost for bandwidth usage is due to the following two factors: 1) the price paid to the network operator to allow the provider to transmit content from the base station to the mobile users, and 2) the content-forwarding overhead (e.g., energy consumption) among the mobile users. In this section, we formally define the cost for the content providers, which will be used in the controlled coalitional game formulation in the next section.

The time taken for content distribution can be divided into the following two parts: 1) content-transmission delay and 2) content-forwarding delay. The content-transmission delay is the time used to transfer the content from the base station to the mobile users, whereas the content-forwarding delay is the time used to forward content among the mobile users. The coalition formed among the content providers to share the bandwidth of the network operator influences the content-transmission delay. In general, the coalition of bandwidth sharing, denoted by $\mathcal{B} \subseteq \mathcal{I}$, can be different from the coalition of content forwarding $\mathcal{F} \subseteq \mathcal{I}$. Given the coalition of bandwidth sharing $\mathcal{B}$, any content received from content provider $i \in \mathcal{B}$ is buffered in a queue at the base station. We assume that content generation follows a Poisson process, with an average rate of α_i. Using an M/D/1 queuing model,[2] the content-transmission delay from the base station to U_i mobile users is given by [20]

$$D_i^{\text{td}}(\mathcal{B}, b) = \frac{LU_i}{b\kappa/|\mathcal{B}|} \left(1 + \frac{\rho_{\mathcal{B}}}{2(1-\rho_{\mathcal{B}})} \right) \tag{13}$$

where L is the content size. b is the amount of bandwidth measured in terms of the number of channels allocated by network operator. κ is the data rate per channel. $\rho_{\mathcal{B}}$ is the traffic intensity defined as $\rho_{\mathcal{B}} = LU_i\alpha_i/(b\kappa/|\mathcal{B}|)$. The content-forwarding delay can be obtained using (9). The cost of bandwidth usage due to the price paid to the network operator for provider i is denoted by $C_i^{\text{bu}} = \theta b/|\mathcal{B}|$. The cost of the content-forwarding overhead is considered as a function of the amount of content from all providers who belong to the same coalition and the number of subscribed mobile users, i.e., $C_i^{\text{cf}} = N_i \sum_{m \in \mathcal{F}} \alpha_m$.

Without loss of generality, the cost of content provider i that is a member of coalition $\mathcal{F}$ for content forwarding and a member of coalition $\mathcal{B}$ for bandwidth sharing (i.e., $i \in \mathcal{F}$ and $i \in \mathcal{B}$) is defined as follows:

$$C_i(\mathcal{F}, \mathcal{B}, b) = \omega_{\text{td}} D_i^{\text{td}}(\mathcal{B}, b) + \omega_{\text{bu}} C_i^{\text{bu}} + \omega_{\text{fd}} D_i^{\text{fd}}(\mathcal{F}) + \omega_{\text{cf}} C_i^{\text{cf}} \tag{14}$$

where ω_{td}, ω_{bu}, ω_{fd}, and ω_{cf} are the cost weights of content-transmission delay, bandwidth usage, content-forwarding delay, and content-forwarding overhead, respectively. The objective of content provider i is to minimize this cost $C_i(\mathcal{F}, \mathcal{B}, b)$.

Based on (14), the content provider has to take the cost C_i^{cf} of content forwarding of mobile users into account, because it can affect the performance and, hence, the satisfaction of the mobile users. If the mobile users forward too many contents, the battery of mobile can quickly be depleted, or users cannot use local network for other applications. These are considered as the dissatisfaction of the users. Therefore, the content provider can provide an incentive and compensate for this dissatisfaction to the mobile users by giving a payment to the mobile users who participate in the cooperative content forwarding.

The cost of provider i, in (14), considers a content without deadline. For any content with a deadline Γ, a similar cost function can be defined while taking into account the probability that the content is received by all mobile users at time Γ [i.e., $P_i^{\text{all}}(\mathcal{F}, \Gamma)$ in (10)] or the average number of mobile users who received the content at time Γ [i.e., $\overline{n}_i(\Gamma)$ in (12)].

VI. Controlled Coalitional Game Formulation

In this section, we introduce the controlled coalitional game to jointly address the coalition formation between the content providers (i.e., cooperative content forwarding and bandwidth sharing) and the bandwidth allocation problem of the network operator. First, the coalitional game formulation of content providers is presented. Then, the optimization problem of the network operator is introduced. Given the solution of the controlled coalitional game, the performance measures of both content providers and network operator will be derived.

[2]This model is selected for simplicity. Other models, e.g., M/G/1, can also be accommodated.

A. Coalitional Game Formulation for the Content Providers

Consider the content providers coalitional game as shown in Fig. 1. Given the amount of allocated bandwidth b by the network operator (i.e., the leader), a content providers' coalitional game is defined by the players (i.e., the content providers), who are the followers. Hence, the set of players in this coalitional game is $\mathcal{I}$. The strategy of any player is to form the coalitions $\mathcal{F}$ and $\mathcal{B}$ used, respectively, for cooperative content forwarding and bandwidth sharing. The negative payoff of any player $i \in \mathcal{I}$ is the cost $C_i(\mathcal{F}, \mathcal{B}, b)$, as defined in (14). We consider that the players are rational and aim at minimizing their individual costs, which is common in a coalitional game setting [17]. Furthermore, we note that the proposed coalitional game has a *nontransferable utility (NTU)*, because the value (i.e., cost) of any coalition of content providers is a function of delay components that cannot arbitrarily be transferred (divided) among the members of a given coalition.

1) Strategies for Cooperation: In the coalitional game, each content provider has the following two coalitions to form: 1) a coalition for cooperative content forwarding (i.e., $\mathcal{F}$) and 2) a coalition for bandwidth sharing (i.e., $\mathcal{B}$). As a result, the corresponding cooperative strategies of any content provider can be defined as follows.

Split from a cooperative-content-forwarding coalition: Consider a coalition $\mathcal{F}$ formed between content providers for cooperative content forwarding. The content providers in this coalition $\mathcal{F}$ can decide to split into multiple new coalitions $\mathcal{F}^\dagger$ if the following conditions are satisfied:

$$C_i(\mathcal{F}^\dagger, \mathcal{B}, b) \leq C_i(\mathcal{F}, \mathcal{B}, b) \quad \forall i \in \mathcal{F} \tag{15}$$

where $\mathcal{F} = \bigcup \mathcal{F}^\dagger$. In particular, the content providers agree to split into multiple coalitions $\mathcal{F}^\dagger$ for cooperative content forwarding if the costs of all content providers $i \in \mathcal{F}$ are lower than or equal to the costs in the original coalition $\mathcal{F}$.

Split from a bandwidth-sharing coalition: Consider a coalition $\mathcal{B}$ formed between a group of content providers and used for bandwidth sharing. The content providers in this coalition $\mathcal{B}$ can collectively decide to break this coalition into multiple new coalitions $\mathcal{B}^\dagger$ if the following conditions are satisfied:

$$C_i(\mathcal{F}, \mathcal{B}^\dagger, b) \leq C_i(\mathcal{F}, \mathcal{B}, b) \quad \forall i \in \mathcal{B} \tag{16}$$

where $\mathcal{B} = \bigcup \mathcal{B}^\dagger$. Hence, similar to the cooperative-content-forwarding case, the content providers can split a bandwidth sharing coalition into multiple new coalitions if, by doing so, the cost of the content providers is reduced (or remains equal).

Merge into a cooperative-content-forwarding coalition: The content providers who are grouped into multiple coalitions $\mathcal{F}$ can decide to collectively merge into a single new coalition $\mathcal{F}^\ddagger$ if the following conditions are satisfied:

$$C_i(\mathcal{F}^\ddagger, \mathcal{B}, b) \leq C_i(\mathcal{F}, \mathcal{B}, b) \quad \forall i \in \mathcal{F}^\ddagger \tag{17}$$

where $\mathcal{F}^\ddagger = \bigcup \mathcal{F}$. In particular, the content provider coalitions will merge and act as a single coalition if all content providers (in all coalitions) achieve a lower or equal cost following this merge strategy.

Merge into a bandwidth-sharing coalition: The content providers who are grouped into multiple coalitions $\mathcal{B}$ can collectively agree to form (i.e., merge into) a single new coalition $\mathcal{B}^\ddagger$ if the following conditions are satisfied:

$$C_i(\mathcal{F}, \mathcal{B}^\ddagger, b) \leq C_i(\mathcal{F}, \mathcal{B}, b) \quad \forall i \in \mathcal{B}^\ddagger \tag{18}$$

where $\mathcal{B}^\ddagger = \bigcup \mathcal{B}$. Similar to the content-forwarding case, multiple coalitions of content providers can merge and act as a single coalition if all content providers in all candidate coalitions achieve a lower or equal cost following this merge.

2) Stable Coalitional State: The set of coalitions of all content providers in the bandwidth-sharing case is defined as a coalitional structure $S = \{\mathcal{B}_1, \ldots, \mathcal{B}_x, \ldots, \mathcal{B}_X\}$, where $\mathcal{B}_x \cap \mathcal{B}_{x'} = \emptyset$, for $x \neq x'$, and $\bigcup_{x=1}^{X} \mathcal{B}_x = \mathcal{I}$, and X is the total number of coalitions in the structure S, i.e., $X = |S|$. Similarly, the set of coalitions of all content providers in the cooperative content forwarding case is defined as a coalitional structure $R = \{\mathcal{F}_1, \ldots, \mathcal{F}_y, \ldots, \mathcal{F}_Y\}$ where $\mathcal{F}_y \cap \mathcal{F}_{y'} = \emptyset$, for $y \neq y'$, $\bigcup_{y=1}^{Y} \mathcal{F}_y = \mathcal{I}$, and Y is the total number of coalitions in structure R, i.e., $Y = |R|$.

The state space of the coalition formation game is composed of coalitional structures used for bandwidth sharing and cooperative content forwarding, and it is defined as follows:

$$\Omega = \{(S_k, R_l) | k, l = \{1, \ldots, B_I\}\} \tag{19}$$

where B_I is the Bell number, given the total of I content providers. A change in the coalitional state is, in general, due to the strategies of the content providers who can decide to split or merge, depending on their payoffs. Given the allocated bandwidth b by the network operator, the transition probability matrix of a coalitional state is denoted by $\mathbf{P}(b)$ and can be expressed as follows:

$$\mathbf{P}(b) = \begin{bmatrix} \hat{\mathbf{P}}_{1,1}(b) & \cdots & \hat{\mathbf{P}}_{1,k'}(b) & \cdots & \hat{\mathbf{P}}_{1,B_I}(b) \\ \vdots & & \vdots & & \vdots \\ \hat{\mathbf{P}}_{k,1}(b) & \cdots & \hat{\mathbf{P}}_{k,k'}(b) & \cdots & \hat{\mathbf{P}}_{k,B_I}(b) \\ \vdots & & \vdots & & \vdots \\ \hat{\mathbf{P}}_{B_I,1}(b) & \cdots & \hat{\mathbf{P}}_{B_I,k'}(b) & \cdots & \hat{\mathbf{P}}_{B_I,B_I}(b) \end{bmatrix} \tag{20}$$

where element $\hat{\mathbf{P}}_{k,k'}$ is the transition probability matrix of the content providers who want to change their bandwidth-sharing coalition structure from S_k to $S_{k'}$. The block element $\hat{\mathbf{P}}_{k,k'}(b)$ can be defined as follows:

$$\hat{\mathbf{P}}_{k,k'}(b) = \begin{bmatrix} P_{1,1}^{k,k'}(b) & \cdots & P_{1,l'}^{k,k'}(b) & \cdots & P_{1,B_I}^{k,k'}(b) \\ \vdots & & \vdots & & \vdots \\ P_{l,1}^{k,k'}(b) & \cdots & P_{l,l'}^{k,k'}(b) & \cdots & P_{l,B_I}^{k,k'}(b) \\ \vdots & & \vdots & & \vdots \\ P_{B_I,1}^{k,k'}(b) & \cdots & P_{B_I,l'}^{k,k'}(b) & \cdots & P_{B_I,B_I}^{k,k'}(b) \end{bmatrix} \tag{21}$$

where $P_{l,l'}^{k,k'}(b)$ is the probability that the coalitional state changes from (S_k, R_l) to $(S_{k'}, R_{l'})$. $P_{l,l'}^{k,k'}(b)$ is at row $(k-1)B_I + l$ and column $(k'-1)B_I + l'$ of matrix $\mathbf{P}(b)$. Let $\mathbb{C}_{k,k'} \subseteq \mathcal{I}$ denote the set of content providers who are candidates for performing split and merge strategies, which result in a change in the *bandwidth-sharing* coalition from S_k to $S_{k'}$.

Let $\mathbb{D}_{l,l'} \subseteq \mathcal{I}$ denote the set of candidate content providers, which results in a change in the *cooperative content forwarding* coalition from R_l to $R_{l'}$. Let $F((S_{k'}, R_{l'})|(S_k, R_l))$ be a feasibility condition. In particular, if the coalitional state $(S_{k'}, R_{l'})$ is reachable from (S_k, R_l), given the strategies of all content providers in $\mathbb{C}_{k,k'}$ and $\mathbb{D}_{l,l'}$, then the condition $F((S_{k'}, R_{l'})|(S_k, R_l))$ is true; otherwise, it is false. The transition probability $P_{l,l'}^{k,k'}(b)$ can be obtained from

$$P_{l,l'}^{k,k'}(b) = \prod_{\substack{i \in \mathbb{D}_{l,l'} \\ i \in \mathbb{C}_{k,k'}}} \gamma \tau_i \left((S_{k'}, R_{l'})|(S_k, R_l)\right) \qquad (22)$$

if $F((S_{k'}, R_{l'})|(S_k, R_l))$ is true; otherwise, it is 0. γ is the probability that the content providers perform a merge or split strategy. $\tau_i((S_{k'}, R_{l'})|(S_k, R_l))$ is the best reply rule. That is, $\tau_i((S_{k'}, R_{l'})|(S_k, R_l))$ is the probability that the strategy of content provider i changes and the coalitional state changes from (S_k, R_l) to $(S_{k'}, R_{l'})$. This best reply rule can formally be defined as follows:

$$\tau_i((S_{k'}, R_{l'})|(S_k, R_l)) = \begin{cases} \hat{\tau}, & \text{if } C_i(\mathcal{B} \in S_{k'}, \mathcal{F} \in R_{l'}, b) \\ & \quad \leq C_i(\mathcal{B} \in S_k, \mathcal{F} \in R_l, b) \\ \epsilon, & \text{otherwise} \end{cases} \qquad (23)$$

for $i \in \mathcal{B} \in S_{k'}$, $i \in \mathcal{B} \in S_k$, $i \in \mathcal{F} \in R_{l'}$, and $i \in \mathcal{F} \in R_l$, where $0 < \hat{\tau} \leq 1$ is a constant, and ϵ is a small probability (e.g., $\epsilon = 10^{-2}$) that a content provider makes an irrational decision, which yields a higher cost.

Given the fixed bandwidth b allocated by the network operator, we can derive the stationary probability of the Markov chain defined by the state space in (19) and the transition probability in (22). The vector of the stationary probabilities is denoted by $\vec{\mathbf{p}}_b = [p_b(S_1, R_1), \ldots, p_b(S_k, R_l), \ldots, p_b(S_{B_I}, R_{B_I})]^T$. This vector can be obtained by solving the following set of equations: $\vec{\mathbf{p}}_b^T \mathbf{P}(b) = \vec{\mathbf{p}}_b^T$ and $\vec{\mathbf{p}}_b^T \vec{\mathbf{1}} = 1$. If the probability of irrational decision approaches zero (i.e., $\epsilon \to 0^+$), there could be an ergodic set $\mathbb{E}_b \subseteq \Omega$ of states (S_k, R_l). This ergodic set $\mathbb{E}_b$ exists if $P_{l,l'}^{k,k'}(b) = 0$, for $(S_k, R_l) \in \mathbb{E}_b$ and $(S_{k'}, R_{l'}) \notin \mathbb{E}_b$, and no nonempty proper subset of $\mathbb{E}_b$ has this property. In this regard, the singleton ergodic set is the set of absorbing states.

Once all the players have reached the coalitional state in an ergodic set $\mathbb{E}_b$, they will remain in this ergodic set forever. Therefore, the absorbing state is called the *stable coalitional state*. Within this stable coalitional state, no player has an incentive to change its decision, given the prevailing coalitional state.

B. Optimization Formulation for the Network Operator

For any given coalitional structure, the network operator must decide on its optimal allocation of bandwidth for the content providers. Hence, given the underlying coalitional game between the content providers, the optimization formulation for the network operator, in the controlled coalitional game, is a 4-tuple $(\Omega, \Xi, P_{l,l'}^{k,k'}(b), V(S_k, R_l, b))$, where Ω is a finite set of coalitional states as defined in (19), Ξ is a finite set of actions b, $P_{l,l'}^{k,k'}(b)$ is the transition probability defined in (22), and $V(S_k, R_l, b)$ is the immediate reward (i.e., revenue) received at coalitional structures S_k and R_l with action b.

Any action b for the network operator represents the amount of bandwidth (i.e., the number of channels) that this operator must allocate to each wireless connection to be used by the content providers. The action space is denoted by $\Xi = \{1, 2, \ldots, b_{\max}\}$. The action takes value from a discrete finite set (i.e., $b \in \Xi$), which is the number of channels, e.g., a subcarrier or time slot in an orthogonal frequency-division multiplexing (OFDM) or time-division multiple access (TDMA) system, respectively.

The immediate reward or revenue of the network operator is defined as follows:

$$V(S_k, R_l, b) = b\theta|S_k| \qquad (24)$$

where $|S_k|$ is the number of coalitions for the bandwidth sharing of content providers, in which each coalition is allocated a bandwidth b, and θ is a price constant charged for each connection.

Hence, in the controlled coalitional game, the network operator aims at optimizing its bandwidth allocation policy. This policy is a mapping from a coalitional state $(S_k, R_l) \in \Omega$ to the action $b \in \Xi$ that maximizes the long-term revenue. However, because the available bandwidth of the base station is used not only by the mobile users subscribed to the content providers but also by normal users of the network operator, the performance of the normal users has to be taken into account. In this case, if all the bandwidth (i.e., all channels) of the base station denoted by $B_{\max}$ is reserved for the mobile users of the content providers and occupied by the normal ongoing users, any new normal users cannot connect to the base station and will be blocked. In this regard, the network operator must ensure that the connection blocking probability of the new normal users is maintained at a certain threshold P_{bl}. Therefore, the optimization problem of the network operator can be formulated as $\max_\pi \mathcal{J}_{V,\pi}$ subject to $\mathcal{J}_{K,\pi} \leq P_{\text{bl}}$, where

$$\mathcal{J}_{V,\pi} = \lim_{T \to \infty} \inf \frac{1}{T} \sum_{t=1}^{T} \mathcal{E}_\pi \left(V\left(S_k(t), R_l(t), b(t)\right)\right) \qquad (25)$$

$$\mathcal{J}_{K,\pi} = \lim_{T \to \infty} \sup \frac{1}{T} \sum_{t=1}^{T} \mathcal{E}_\pi \left(K\left(S_k(t), R_l(t), b(t)\right)\right) \qquad (26)$$

where $\mathcal{J}_{V,\pi}$ and $\mathcal{J}_{K,\pi}$ are, respectively, the long-term average revenue and connection-blocking probability of the network operator. $S_k(t)$ and $R_l(t)$ are the coalitions used for bandwidth sharing and cooperative content forwarding at time t, respectively, and $b(t)$ is the allocated bandwidth. $\mathcal{E}_\pi(\cdot)$ denotes the expectation over policy π. Policy π is defined as $\pi = \{\psi(S_k, R_l, b)|k, l = \{1, \ldots, B_I\}, \forall b \in \Xi\}$, where $\psi(S_k, R_l, b)$ is the probability of taking action b at coalitional state (S_k, R_l). $K(S_k, R_l, b)$ is the immediate connection-blocking probability (i.e., Erlang-B), which can be obtained from [20]

$$K(S_k, R_l, b) = \frac{(\lambda\mu)^{B_{\max} - b|S_k|} / (B_{\max} - b|S_k|)!}{\sum_{x=0}^{B_{\max} - b|S_k|} \frac{(\lambda\mu)^x}{x!}} \qquad (27)$$

where $B_{\max} - b|S_k|$ is the number of channels available for normal users, λ is the new normal user's arrival rate, and μ is the connection holding time of normal users.

To obtain the optimal policy of CMDP as defined in (25) and (26), an equivalent linear programming (LP) model can be formulated. This equivalent model can be used to find the stationary probability of the coalitional state and action denoted by $\phi(S_k, R_l, b)$. The LP model with decision variable $\phi(S_k, R_l, b)$ for $(S_k, R_l) \in \Omega$ and $b \in \Xi$ is defined as follows:

$$\max_{\phi(S_k,R_l,b)} \quad \sum_{(S_k,R_l)\in\Omega} \left(\sum_{b\in\Xi} \phi(S_k, R_l, b) V(S_k, R_l, b) \right) \tag{28}$$

$$\text{subject to} \quad \sum_{(S_k,R_l)\in\Omega} \left(\sum_{b\in\Xi} \phi(S_k, R_l, b) K(S_k, R_l, b) \right) \le P_{\mathrm{bl}} \tag{29}$$

$$\sum_{b\in\Xi} \phi(S_{k'}, R_{l'}, b) = \sum_{(S_k,R_l)\in\Omega} \left(\sum_{b\in\Xi} P_{l,l'}^{k,k'}(b) \phi(S_k, R_l, b) \right) \tag{30}$$

$$\sum_{(S_k,R_l)\in\Omega} \left(\sum_{b\in\Xi} \phi(S_k, R_l, b) \right) = 1$$

$$\phi(S_k, R_l, b) \ge 0 \tag{31}$$

for $(S_{k'}, R_{l'}) \in \Omega$.

Given the optimal solution $\phi^*(S_k, R_l, b)$ of the LP model defined in (28)–(31), the optimal randomized policy of the network operator can be obtained as follows:

$$\psi^*(S_k, R_l, b) = \frac{\phi^*(S_k, R_l, b)}{\sum_{b'\in\Xi} \phi^*(S_k, R_l, b')} \tag{32}$$

for $\sum_{b'\in\Xi} \phi^*(S_k, R_l, b') > 0$, where $\psi^*(S_k, R_l, b)$ is the probability that the network operator allocates bandwidth b when the coalitional state of content providers is (S_k, R_l). The optimal policy is then defined as $\pi^* = \{\psi^*(S_k, R_l, b) | k, l = \{1, \ldots, B_I\} \forall b \in \Xi\}$.

C. Performance Measures

Depending on the optimal policy of the network operator, the stationary probability of the coalitional state that describes the content providers' coalitions can be found. For instance, given an optimal policy π^*, let the stationary probability of coalitional state (S_k, R_l) be denoted by $p_{\pi^*}(S_k, R_l)$. The vector of the stationary probabilities is denoted by $\vec{\mathbf{p}}_{\pi^*} = [p_{\pi^*}(S_1, R_1), \ldots, p_{\pi^*}(S_k, R_l), \ldots, p_{\pi^*}(S_{B_I}, R_{B_I})]^T$ and can be computed by solving the following set of equations: $\vec{\mathbf{p}}_{\pi^*}^T \mathbf{P}_{\pi^*} = \vec{\mathbf{p}}_{\pi^*}^T$ and $\vec{\mathbf{p}}_{\pi^*}^T \vec{\mathbf{1}} = 1$. $\mathbf{P}_{\pi^*}$ is the transition probability matrix when the optimal policy π^* is used by the network operator.

The average revenue of the network operator is

$$\overline{V} = \sum_{(S_k,R_l)\in\Omega} p_{\pi^*}(S_k, R_l) \left(\sum_{b\in\Xi} \psi^*(S_k, R_l, b) b\theta |S_k| \right). \tag{33}$$

The average cost of content provider $i \in \mathcal{I}$ is obtained from

$$\overline{C}_i = \sum_{(S_k,R_l)\in\Omega} p_{\pi^*}(S_k, R_l) \left(\sum_{b\in\Xi} \psi^*(S_k, R_l, b) C_i(\mathcal{F}, \mathcal{B}, b) \right) \tag{34}$$

where $C_i(\mathcal{F}, \mathcal{B}, b)$ is the cost of content provider i defined in (14).

Again, if the probability of irrational decision approaches zero (i.e., $\epsilon \to 0^+$), there could be an ergodic set $\mathbb{E}_{\pi^*} \subseteq \Omega$ of absorbing states. Given the optimal policy π^*, once all players have reached the coalitional state in an ergodic set $\mathbb{E}_{\pi^*}$, they will remain in this ergodic set forever.

VII. Performance Evaluation

A. Parameter Setting

We consider a mobile social network with $I = 3$ content providers (see Fig. 1). Unless otherwise mentioned, the number of mobile users subscribed to provider i is $N_i = 7$. The mean inter-meeting time among mobile users subscribed to the same and to the different providers is $1/\Lambda_{i,j} = 1$ h. The average content size is $L = 12.5$ MB, and the average content generation rate is $\alpha_i = 1$ content/h. For the base station of the network operator, the transmission rate per channel is $\kappa = 28$ kb/s. The network operator can allocate the maximum $b_{\max} = 9$ channels per each wireless connection for the content provider. The average connection arrival rate of the normal users is $\lambda = 12$ connections/h, and the average connection holding time is $\mu = 20$ min. The threshold of the connection-blocking probability is $P_{\mathrm{bl}} = 0.05$.

Furthermore, we consider that the content is transferred from a base station to one mobile user (i.e., $U_i = 1$) and the price constant is $\theta = 0.3$. For a provider, the cost weights of content-transmission delay, bandwidth usage, content-forwarding delay, and content-forwarding overhead are $\omega_{\mathrm{td}} = 1$, $\omega_{\mathrm{bu}} = 1$, $\omega_{\mathrm{fd}} = 1$, and $\omega_{\mathrm{cf}} = 0.1$, respectively. The parameters of the controlled coalitional game are $\gamma = 0.5$, $\hat{\tau} = 0.99$, and $\epsilon = 0.01$. The coalitional structures (i.e., states) are denoted as follows: $S_1, R_1 = \{\{1\}, \{2\}, \{3\}\}$, $S_2, R_2 = \{\{1, 2\}, \{3\}\}$, $S_3, R_3 = \{\{1, 3\}, \{2\}\}$, $S_4, R_4 = \{\{1\}, \{2, 3\}\}$, and $S_5, R_5 = \{\{1, 2, 3\}\}$. We consider two coalition formation schemes. In scheme 1, the providers form the same coalition for sharing bandwidth and cooperatively performing content forwarding. The best reply rule is defined as a special case of the rule in (23) as follows:

$$\tau_i \left((S_{k'}, R_{l'}) | (S_k, R_l) \right) = \begin{cases} \hat{\tau}, & \text{if } (C_i(\mathcal{B} \in S_{k'}, \mathcal{F} \in R_{l'}, b) \le C_i(\mathcal{B} \in S_k, \mathcal{F} \in R_l, b)) \\ & \quad \text{and } (S_{k'} = R_{l'}) \\ \epsilon, & \text{if } (C_i(\mathcal{B} \in S_{k'}, \mathcal{F} \in R_{l'}, b) > C_i(\mathcal{B} \in S_k, \mathcal{F} \in R_l, b)) \\ & \quad \text{and } (S_{k'} = R_{l'}) \\ 0, & \text{otherwise.} \end{cases} \tag{35}$$

In scheme 2, the content providers can independently form different coalitions for bandwidth sharing and cooperative content forwarding. In this scheme, the corresponding best reply rule is given by (23).

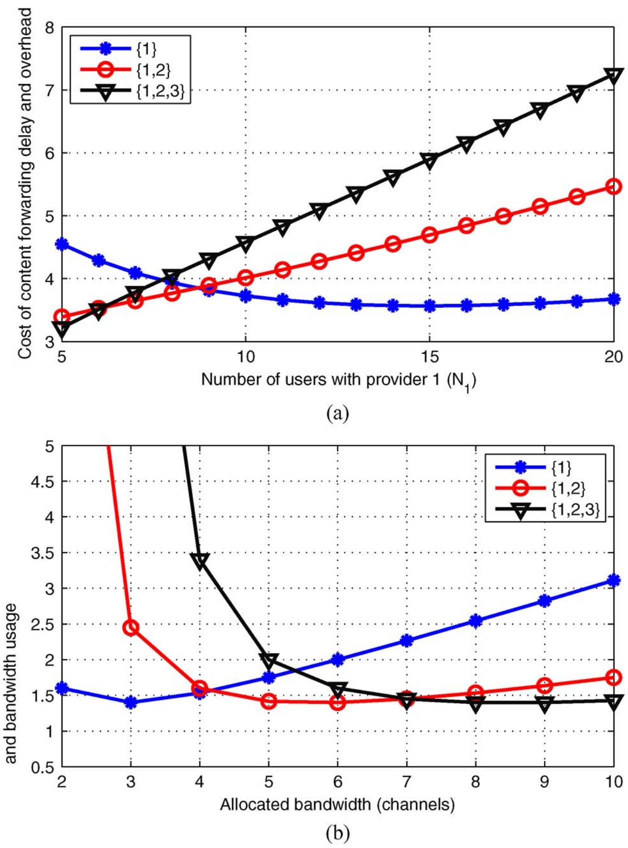

Fig. 3. (a) Cost of content provider 1 due to the content-forwarding delay and overhead. (b) Cost of content provider 1 due to the content-transmission delay and bandwidth usage under coalitions with providers 2 and 3.

B. Numerical Results

1) Impact of Coalition Formation on the Cost of Content Providers: We first consider the cooperative-content-forwarding coalition between the content providers and its impact on the cost. Given that the bandwidth allocation is fixed as $b = 3$ channels, Fig. 3(a) shows the cost of content provider 1 due to the content-forwarding delay and the mobile users' overhead under different numbers of subscribed users N_1, i.e., $\omega_{\rm fd} D_1^{\rm fd} + \omega_{\rm cf} C_1^{\rm cf}$. Noncooperatively, without forming any coalition with other providers (i.e., $\{1\}$), the cost first decreases as the number of mobile users increases. Because a larger number of mobile users can help each other forward the content, the content-forwarding delay decreases. However, at a certain number of users [i.e., 15 in Fig. 3(a)], the cost increases due to higher content-forwarding overhead, resulting from the increased number of mobile users. A similar effect is observed for different coalitions (i.e., as shown in Fig. 3(b) for coalitions $\{1, 2\}$ and $\{1, 2, 3\}$, when bandwidth is less than five channels, the cost first decreases and then increases). It is also observed that, at different network sizes, the lowest cost of the content-forwarding delay and overhead can be achieved under different coalitional structures. For example, when the number of users is small (i.e., $N_1 = 5$), provider 1 achieves the lowest cost by forming a coalition with providers 2 and 3 (i.e., $\{1,\ 2,\ 3\}$). When the number of users reaches $N_1 = 6$, the lowest cost is achieved when providers 1 and 2 merge into a single coalition (i.e., $\{1, 2\}$), whereas provider 3 noncooperatively acts. Then, if the number of users is large (i.e., $N_1 > 10$), provider 1 will not form a coalition. This case is because the cost increment due to the overhead incurred by carrying and forwarding the content of the other providers is higher than the cost decrement from the smaller delay.

Fig. 3(b) shows similar results with regard to the cost of provider 1 due to the content-transmission delay and the bandwidth usage (i.e., $\omega_{\rm td} D_1^{\rm td}(\mathcal{B}, b) + \omega_{\rm bu} C_1^{\rm bu}$). Under different coalitions of content providers, the lowest cost can be achieved. Note that, when the allocated bandwidth per connection increases, first, the cost decreases due to the smaller content-transmission delay. However, when the allocated bandwidth is large, the cost of bandwidth usage increases, and hence, the total cost increases.

Based on the results shown in Fig. 3(a) and (b), it is clear that content providers can cooperate and form coalitions to minimize their costs. Thus, it will be of interest to analyze the coalition formation process, give that the content providers act in a rational way to minimize their costs.

2) Stable Coalition Formation Between Content Providers: Next, we consider the coalition formation process between the content providers under a fixed bandwidth allocation by the network operator. To simplify the presentation of the results in this part, we assume that all content providers are homogeneous (e.g., they have the same content generation rate). Table I shows the stationary probability of the coalitional structure. Given that $\epsilon \rightarrow 0^+$, the stationary probability $p_b(S_k, R_l) > 0$ indicates that the coalitional structure is stable. As shown in Table I, when the bandwidth allocation is small (e.g., $b = 2, 3$), none of the providers forms a coalition for bandwidth sharing (i.e., in scheme 1 and bandwidth sharing in scheme 2). Because the bandwidth is small, sharing bandwidth will incur a high transmission delay. When the allocated bandwidth increases, it is beneficial for providers to form coalitions and share the bandwidth. In this case, coalition states S_2, S_3, and S_4 become stable for scheme 1 and bandwidth sharing in scheme 2. The grand coalition S_5 is stable only if a large bandwidth is allocated for each connection. In Table I, we observe that the coalition formation for cooperative content forwarding is not affected by the allocated bandwidth, and in this case, coalition states R_2, R_3, and R_4 are stable in scheme 2. Note that the cooperative content forwarding coalition formation is also affected by other parameters (e.g., the mean meeting rate and the number of subscribed users of each provider). We omit showing the intuitive results for brevity.

Furthermore, we consider the case with heterogeneous content providers with a fixed bandwidth allocation by the network operator. Fig. 4 shows those of the providers under different content generation rates for provider 1 (i.e., α_1), whereas those of providers 2 and 3 are fixed (i.e., $\alpha_2 = \alpha_3 = 1$). As expected, when the content generation rate of provider 1 increases, the corresponding cost increases. We observe that, when the content generation rate of provider 1 is less than the rates of providers 2 and 3, providers 2 and 3 will form coalition with provider 1. This case is because providers 2 and 3 will benefit from a lower content-forwarding overhead due to a smaller amount of content from provider 1. As a result, when the content generation rate increases for

TABLE I
STATIONARY PROBABILITIES OF COALITIONAL STRUCTURES

Bandwidth (channels)	Scheme 1			Scheme 2 (Bandwidth sharing)			Scheme 2 (Cooperative forwarding)		
	(S_1, R_1)	(S_2, R_2), (S_3, R_3), (S_4, R_4)	(S_5, R_5)	S_1	S_2,S_3,S_4	S_5	R_1	R_2,R_3,R_4	R_5
2	1	0	0	1	0	0	0	1/3	0
3	1	0	0	1	0	0	0	1/3	0
4	0	1/3	0	1	0	0	0	1/3	0
5	0	1/3	0	0	1/3	0	0	1/3	0
6	0	1/3	0	0	1/3	0	0	1/3	0
7	0	1/3	0	0	0	1	0	1/3	0
8	0	0	1	0	0	1	0	1/3	0
9	0	0	1	0	0	1	0	1/3	0

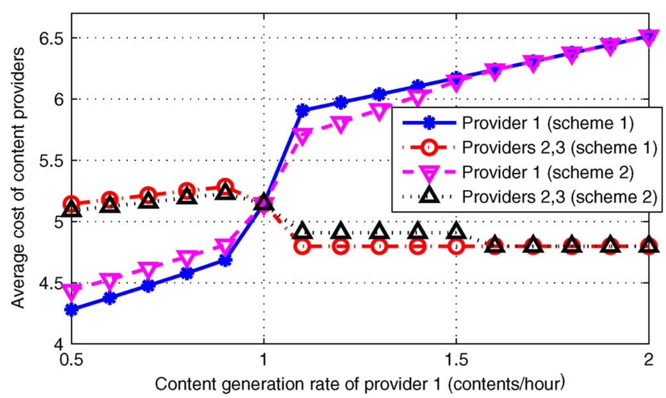

Fig. 4. Average cost of content providers under the content generation rate of provider 1.

$\alpha_1 < 1$, the costs of providers 2 and 3 increase. However, if the content generation rate of provider 1 is larger than the rates of providers 2 and 3, then it becomes unlikely that providers 2 and 3 will form a coalition with provider 1. As a result, the costs of providers 2 and 3 are not significantly affected for $\alpha_1 > 1$. In addition, Fig. 4 shows the difference between coalition formation schemes 1 and 2. Because with scheme 2, providers can independently form coalitions for bandwidth sharing and cooperative content forwarding, the associated costs of schemes 1 and 2 are different.

3) Bandwidth Allocation of the Network Operator: Fig. 5(a) shows the average cost of the content providers, given the optimal bandwidth allocation policy. As expected, the average cost increases as the connection-blocking probability threshold increases. As the bandwidth allocated by the network operator becomes larger, the providers must pay additional connection costs. In Fig. 5(a), we observe that, with coalition formation scheme 2, the average cost of providers is slightly lower than that in scheme 1. The lower cost is because scheme 2 offers a higher flexibility in the coalition formation as the providers can select different cooperative strategies for cooperative content forwarding and bandwidth sharing.

Fig. 5(b) shows the average revenue of the network operator. We observe that, for both coalition formation schemes, the difference in the average revenues is insignificant. In Fig. 5(b), the average revenue for static bandwidth allocation is also shown for comparison. In the static allocation, the fixed bandwidth is allocated to maximize the revenue, given that the connection-blocking probability requirement is not violated. The optimization problem of the static bandwidth allocation can be expressed as follows:

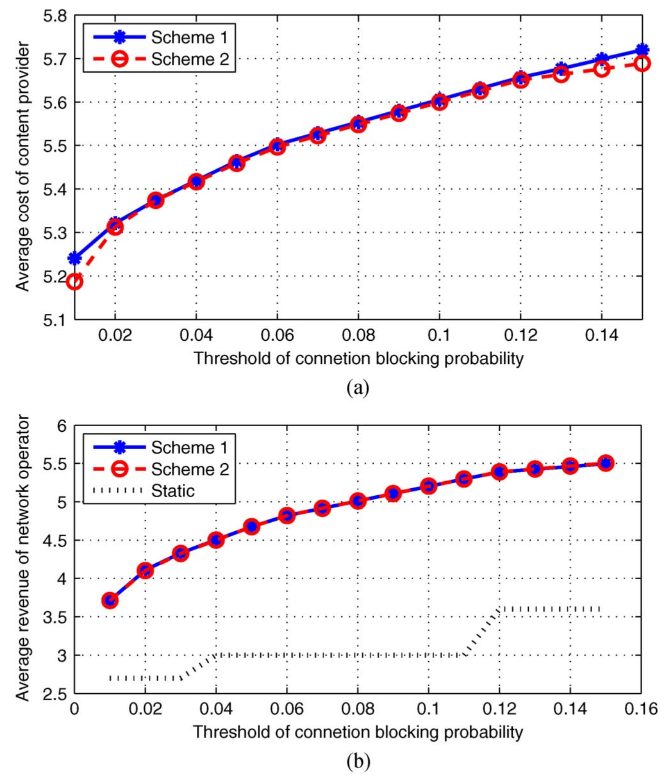

Fig. 5. (a) Average cost of content providers and (b) average revenue of network operator under different thresholds of the connection-blocking probability.

$$\max_{b \in \hat{\Xi}} \sum_{(S_k, R_l) \in \Omega} p_b(S_k, R_l) V(S_k, R_l, b)$$
$$\text{subject to} \quad \hat{\Xi} = \{b | K(S_k, R_l, b) \leq P_{\text{bl}}, (S_k, R_l) \in \Omega\} \tag{36}$$

where $V(S_k, R_l, b)$ and $K(S_k, R_l, b)$ are the immediate revenue and connection-blocking probability of new users obtained from (24) and (27), respectively. $p_b(S_k, R_l)$ is the stationary probability of state (S_k, R_l). $\hat{\Xi}$ is the feasible set of actions such that the immediate connection-blocking probability is maintained below or at the threshold. In Fig. 5(b), clearly, the average revenue from the optimal bandwidth

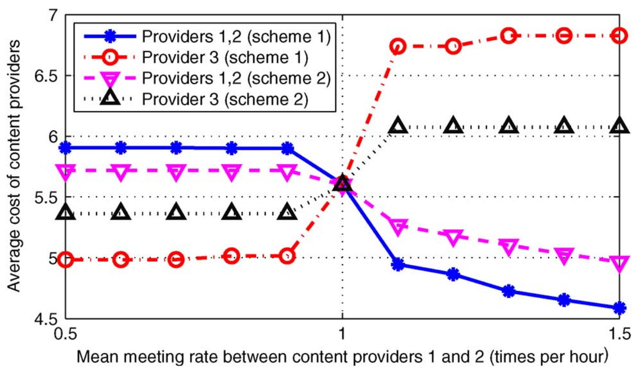

Fig. 6. Average cost of content providers under the mean meeting rate between content providers 1 and 2.

allocation policy is much larger than that in the static allocation. This case is because the network operator can achieve higher revenue when the bandwidth is adapted according to the coalitional state of providers.

Fig. 6 shows the average cost for the content providers, given the optimal bandwidth allocation policy of the network operator. When the mean meeting rate $\Lambda_{1,2}$ between providers 1 and 2 is varied, both providers 1 and 2 have the same average costs. When the rate is less than the rate of provider 3 (i.e., $\Lambda_{1,2} < \Lambda_{i,3}$ for $i \in \mathcal{I}$), providers 1 and 2 have higher average costs, because providers 1 and 2 have no benefit in forming a coalition. In contrast, when the rate is higher than the rate of provider 3 (i.e., $\Lambda_{1,2} > \Lambda_{i,3}$ for $i \in \mathcal{I}$), then providers 1 and 2 achieve a lower average cost when they cooperate and form a coalition due to the smaller content forwarding delay. In addition, coalition formation schemes 1 and 2 yield the different average costs for providers.

VIII. Conclusion

In mobile social networks, content providers create content and utilize the radio access network (e.g., a base station) of a network operator to distribute the content to subscribed mobile users. The content can directly be transferred among the subscribed mobile users when they move and meet each other. In this paper, we have introduced the framework of a *controlled coalitional game* that is suitable to analyze the decision-making processes of both the content providers and the network operator in a mobile social network. The proposed controlled coalitional game model is based on the following two components: 1) a coalitional game formulation between the content providers for bandwidth sharing and cooperative content forwarding, which enables the providers to minimize the individual costs, and 2) an optimization formulation, which enables the network operator to decide on its bandwidth allocation in such a way that maximizes the revenue while maintaining a certain QoS requirement. The solutions of the controlled coalitional game are the stable coalitional structure for the content providers and the optimal policy of bandwidth allocation for the network operator. We have performed a thorough performance evaluation, which clearly showed that, if the content providers and the network operator are rational, they can dynamically adapt their decisions to achieve the best benefit and optimize their performance.

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