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Incentive Mechanism and Content Provider Selection for Device-to-Device-based Content Sharing

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***Abstract*—Content sharing based on device-to-device (D2D) communications has been regarded as a promising technology to offload traffic from the overburdened cellular networks. Effective and efficient D2D content sharing requires an incentive mechanism to encourage mobile devices to participate and an optimized content-provider selection if multiple candidate providers exist. In this paper, we propose a comprehensive scoring mechanism (CSM), which calculates a score for each candidate content provider based on their historical content supply record, current transmission rate and expected reward. The CSM establishes the relationship between the historical content supply record and the expected reward, and makes it possible to select the content provider with an achievable transmission rate appropriate for the requested content. Based on the CSM and the Hungarian algorithm, we propose a content-sharing incentive and provider selection (CIPS) algorithm to optimize the selection of content providers for multiple concurrent content requesters. Through extensive simulations, we show that the proposed CIPS algorithm can effectively motivate mobile devices to participate in content sharing and can select the most appropriate content provider(s) from multiple candidates.**

***Index Terms*—device-to-device communications, content-sharing, Hungarian algorithm, incentive, provider selection.**

I. Introduction

With the increasing demand for various mobile services and applications, cellular networks are expected to face a capacity crunch in the near future. In order to offload traffic from the cellular eNodeBs (eNBs), device-to-device (D2D) communications [1] underlaying cellular systems have been widely considered in the design of the fifth-generation (5G) mobile systems. [2] proposed a D2D communication assisted mobile traffic offloading (DATO) scheme, with focus on massive connections for machine type communications . In [3], the authors used unmanned Aerial Vehicles to be a good candidate to promptly construct the D2D-enabled wireless network in remote, rural and disaster affected areas. Furthermore, [4] studied the problem of delay-constrained data transmission in mobile opportunistic D2D networks and authors investigated the joint resource block assignment and transmit power allocation problem to optimize the network performance in [5].

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Actually, there are a large number of scenes to use D2D networks. For example, if the content that user equipment (UE) wants to download from the Internet is available on some nearby UEs, then one of them can be selected to provide the requested content via D2D communications [6]. This is called D2D based content sharing, or D2D offloading, which can significantly reduce the traffic load of the cellular networks and improve the network spectral efficiency. However, D2D based content sharing faces two major challenges: i) how to motivate UEs to actively participate in content sharing; ii) how to select proper content providers from candidates and ensure the quality of service (QoS) simultaneously.

Recently, various incentive mechanisms have been proposed to promote cooperation among UEs for content sharing. They generally can be classified into two categories: reputation-based and price-based. In a reputation-based incentive mechanism [7]-[12], a node's reputation is built based on a collection of feedbacks from other nodes. A pre-defined reputation threshold is used to classify nodes into reputed and selfish nodes. Only the reputed nodes can enjoy high QoS transmissions from BSs and other nodes. In this case, a clever node can manage to be considered as a reputed node by maintaining its reputation just above the threshold. This will discourage the nodes from actively participating in content sharing to increase their reputation further above the threshold.

Price-based incentive mechanisms [13]-[19] treat content-sharing services as transactions that can be priced. The authors of [13] adopted the contract theory in resource allocation. A contract-based relay selection scheme was proposed in [14]. In [15], a cheat-proof, credit based system for stimulating cooperation among selfish nodes in mobile ad hoc networks was developed. The authors of [16] proposed price competition incentive mechanisms for bandwidth trading and allocation. In [17] and [18], virtual currency and micro payment were used to reward upload and charge download, respectively. A linear pricing scheme that maximizes the revenue of the network manager was investigated in [19]. However, the aforementioned price-based incentive mechanisms consider only the current transaction, regardless of UE behavior in the long term.

In addition, incentive mechanisms [20]-[21] based on game theory have proposed incentive mechanisms designed by theory, methods and models in the game theoretic approach and Stackelberg game approach. In [20], authors investigated the profit maximization problem for wireless network carrier and payment minimization for end-users. A marketplace based on risk sharing concept is achieved where the tension between carrier and end-users and the competition between end-users themselves has been formulated as a Stackelberg game. In [21], authors proposed an incentive mechanism in which the base station rewards those users that share contents with others with D2D communications. They formulated the conflict among utility for each user and the tension between the BS and the users as a Stackelberg game.

In this paper, we first propose a comprehensive scoring mechanism (CSM) for D2D content sharing. In CSM, the comprehensive score of each candidate content provider is the summation of three scores: the score of historical content supply record (which is different from the reputation-based mechanisms [7]-[12] in that a continuous valued score is calculated to represent the historical content supply record instead of simply using a pre-defined reputation threshold to classify nodes into reputed and selfish ones), the score of current transmission rate (which makes it possible to select the content provider with a transmission rate right for the requested content), and the score of the expected reward (which takes into account both the current and long-term UE performance as indicated by the other two scores).

The proposed CSM can effectively motivate UEs' participation in D2D content sharing because: on the one hand, a candidate provider with a higher reputation will have a higher probability of being selected and receiving a higher reward, which can avoid the UE behavior of maintaining a reputation just above the threshold [12]; on the other hand, UEs will need to actively participate in D2D content sharing in the long term for achieving a high reputation so as to receive a high reward. In addition, we introduce the concept of QoS sensitivity threshold. If the disparity of transmission duration due to different data rates is less than the QoS sensitivity threshold, then the score of current transmission rate will be considered less important than the other two scores; otherwise, the score of current transmission rate will be put more emphasis on in order to ensure the QoS.

When multiple UEs request contents concurrently, it would be difficult (if not impossible) to select the best content provider for each content requester at the same time. In this paper, we model this problem as an optimization that maximizes the total score of the selected content providers for all the concurrent content requesters, and devise a content-sharing incentive and provider selection (CIPS) algorithm based on the CSM and the Hungarian algorithm [26] to solve the optimization problem. The CIPS algorithm includes two steps: 1) for each content requester, calculate the scores of all potential providers by using CSM; 2) arrange the scores of potential providers for all concurrent content requesters into a matrix and find the content providers whose total score is the largest for all the content requesters by using the Hungarian algorithm.

The novelty of the proposed CSM and CIPS can be summarized as follows:

- We establish the relationship between the historical content supply record and the expected reward of a candidate content provider. The expected reward is increased for a content provider every time it has successfully and safely shared content. As a result, UEs can be effectively motivated to actively participate in D2D content sharing in the long term.
- We introduce the QoS sensitivity threshold in order to ensure that the selected content provider has a transmission rate appropriate for the requested content size and the associated QoS requirement.
- We formulate the problem of jointly optimizing the selection of content providers for multiple concurrent content requesters and use the Hungarian algorithm to solve it. To the best of our knowledge, this problem has not been studied in the related literature.

The rest of the paper is organized as follows. In Section II, we describe the system model for content sharing based on D2D communications underlaying cellular networks. The proposed CSM is presented in Section III. In Section IV, the CIPS algorithm is proposed. In Section V, we present the simulation results. Section VI concludes this paper.

II. System Model

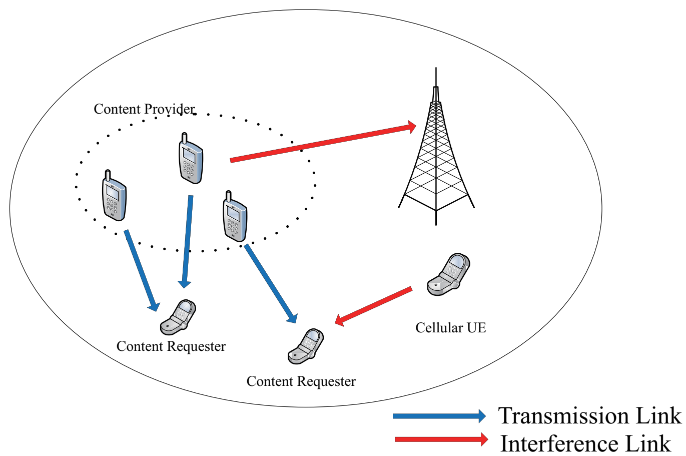


Fig. 1. System model of D2D communication underlaying cellular networks with uplink resource sharing.

A. Network Model

In this paper, we consider a single-cell Orthogonal Frequency Division Multiplexing (OFDM) cellular system where there are M potential content providers (i.e., $Q_1, Q_2, \ldots, Q_M$), N content requesters (i.e., $d_1, d_2, \ldots, d_N$), and Z cellular UEs (CUEs, i.e., $C_1, C_2, \ldots, C_Z$), whose uplink resources can be reused by content providers for D2D communications, i.e., the underlay mode is assumed for D2D communications. We assume that the content requested by any of the requesters has been cached by at least one of the content providers.

We assume that potential content providers, content requesters and cellular UEs are all mobile UEs with pedestrian speeds. If the requested file is very large, then it will be split into multiple small sub-files that can be transmitted within the channel coherence time, and the content provider selection process will be performed for each sub-file separately. The locations of the potential providers and the content requesters follow two independent homogeneous Poisson point processes

(PPPs) Φ_Q and Φ_D with density λ_Q and λ_D, respectively. The CUEs are distributed following another independent PPP with density of λ_I. For simplicity, it is assumed that all the content providers and all the CUEs transmit with the constant power μ_Q and μ_C ($\mu_Q \in (0, \mu_{max})$, $\mu_C \in (0, \mu_{max})$), respectively.

The D2D content-sharing process includes the following steps: 1) The content requester sends a content request to its serving eNB. The content requesting message sent from the requester to the eNB will be overhead by nearby content providers. These content providers will estimate the channel between them and the requester based on the overhead message, and obtain an estimate of the achievable data rate. 2) The eNB broadcasts the information of the requested content to the UEs within the D2D communication range to the requester. Only the UEs with the requested content will respond to the eNB and the others will keep silent. 3) If there is no response within a pre-defined period, which indicates that no potential provider is around the requester, then the eNB will send the content to the requester directly; otherwise, it will select the best potential provider to send the content via a D2D link to the requester. 4) The eNB will monitor the D2D transmission process until the content requester has successfully received the content. If the D2D content transmission process fails (e.g., a D2D link failure occurs or the D2D transmission rate falls below the content requester's minimum required data rate) at some point, then the eNB will ask the selected content provider to drop the D2D session and will complete the remaining content transmission, and the reward to the selected content provider will be decreased accordingly.

B. Channel Model

In the channel model, path loss is assumed to be inversely proportional to the distance with the distance exponent α, and all the links experience independent and identical frequency-flat Rayleigh fading, which results in a unit-mean exponential power distribution. Accordingly, the received power at the i^{th} content requester from the j^{th} transmitter can be expressed as $\mu_j h_{ij} L_{ij}^{-\alpha}$, where $\mu_j = \mu_Q$ and $\mu_j = \mu_C$ are the transmitter power of Q_j and C_j, respectivelyh_{ij} and L_{ij} are the Rayleigh fading power gain and the distance between the i^{th} content requester and the j^{th} transmitter, respectively.

C. Interference Analysis

In this work, D2D communications share uplink resources with CUEs. As shown in Fig.1, we consider that multiple content providers can share the uplink resources of a CUE, which means the content sharing process will be completed before the channel change significantly due to the low mobility. Since one uplink resource block is assigned to at most one CUE in a cell [11]-[13], the total interference to a content requester is from one CUE C_v (assuming all uplink resource blocks are in use) and all the other coexisting content-sharing D2D links that reuse the same uplink resource. The potential providers with requested contents for all content requesters in a cell form a set Φ_S. Assuming that $Q_k (k \in \{1, \dots, M\})$ is selected as the content provider for content requester $d_i (i \in \{1, \dots, N\})$, the signal-to-interference-plus-noise-ratio (SINR) of d_i can be expressed as:

$$\gamma_{k,i} = \frac{\mu_Q L_{ik}^{-\alpha} h_{ik}}{\mu_C h_{iv} L_{iv}^{-\alpha} + \sum\limits_{j \in \Phi_S \setminus Q_k} \mu_Q h_{ij} L_{ij}^{-\alpha} + \sigma^2} \tag{1}$$

where σ^2 is the power of the additive white Gaussian noise, L_{iv} and $L_{ij(k)}$ are the distances from interfering CUE C_v and from provider $Q_{j(k)}$ to content requester d_i, respectively, h_{iv} and $h_{ij(k)}$ are the Rayleigh fading power gains between C_v and d_i, and between $Q_{j(k)}$ and d_i, respectively.

Accordingly, the transmission rate (in bit/s/Hz) from content provider Q_k to content requester d_i is given by

$$R_{k,i} = \log_2(1 + \gamma_{k,i}) \tag{2}$$

III. Comprehensive Scoring Mechanism

In this section, we propose the CSM to calculate a comprehensive score of every potential content provider for each requester. The comprehensive score of a UE is the sum of the following three scores:

- The score of the historical content supply record, which shows how a UE has participated in content-sharing previously. (Note: the historical content supply record of each UE is stored in the network and can be accessed and modified by eNB s.)
- The score of the currently achievable transmission rate, which is estimated by each UE under the current channel condition. If the actual transmission rate is lower than the estimated achievable transmission rate, the actual reward paid by the eNB will be less than the expected reward.
- The score of the expected reward, which consists of the transmission cost and a profit.

Accordingly, the comprehensive score of content provider Q_j can be calculated as

$$S_j^T = aS_j^H + bS_j^R + cS_j^P, \tag{3}$$

in which S_j^H, S_j^R and S_j^P denote the score of historical content supply record, the score of current transmission rate, and the score of expected reward of content provider Q_j, respectively. $a \in 0, 1$, $b \in 0, 1$ and $c \in 0, 1$ are adjusted coefficient to determine which score is more important in different situations. If provider Q_j doesn't have the content requested by requester d_i, $S_j^T = 0$; otherwise, the values of S_j^H, S_j^R and S_j^P will be calculated as follows.

A. Score of Historical Content Supply Record

In market transactions, a seller's success depends not only on good service and products, but also on the reputation accumulated in many previous transactions. Similarly, a potential provider with a better record of previous content supply performance is more likely to provide a higher QoS and would be more willing to participate in the current content sharing. Moreover, in order to avoid unsafe, or even malicious behavior (e.g., sending false content or even virus in content sharing), the historical content-sharing safety record of potential providers should be taken into account in addition to the historical content-sharing participation record. if the eNB is reading the historical content supply record of one content provider, the new supply record will not be wrote in the database until this eNB finish the reading process. Based on this type of designed, in the initial stage of collection for the historical content supply record, there will be some impact for selecting providers based on their historical supply score. But, with the historical records accumulating, the impact will be smaller and smaller.

We define the score of historical content supply record of content provider Q_j as

$$S_j^H = \frac{1}{2}(W_j + G_j) \tag{4}$$

where W_j and G_j denote the score of historical content-sharing participation record and the score of historical content-sharing safety record of provider Q_j, respectively, where $W_j \in [0,1]$ and $G_j \in [0,1]$. When the current content sharing has been finished, the values of W_j and G_j will be updated (as detailed below).

The initial value of W_j is 0. Once content provider Q_j has successfully accomplished one content-sharing transmission, W_j grows by a positive constant value δ $(0 < \delta < 1)$. If Q_j has not participated in any content sharing during a certain time period τ (i.e., a time threshold), then W_j will be decreased by a value ν_j, which grows linearly with the accumulated idle time T_j of content provider Q_j when T_j becomes larger than τ, i.e.,

$$\nu_j = \begin{cases} 0 & T_j \le \tau \\ \frac{T_j}{\tau}\delta & T_j > \tau \end{cases} \tag{5}$$

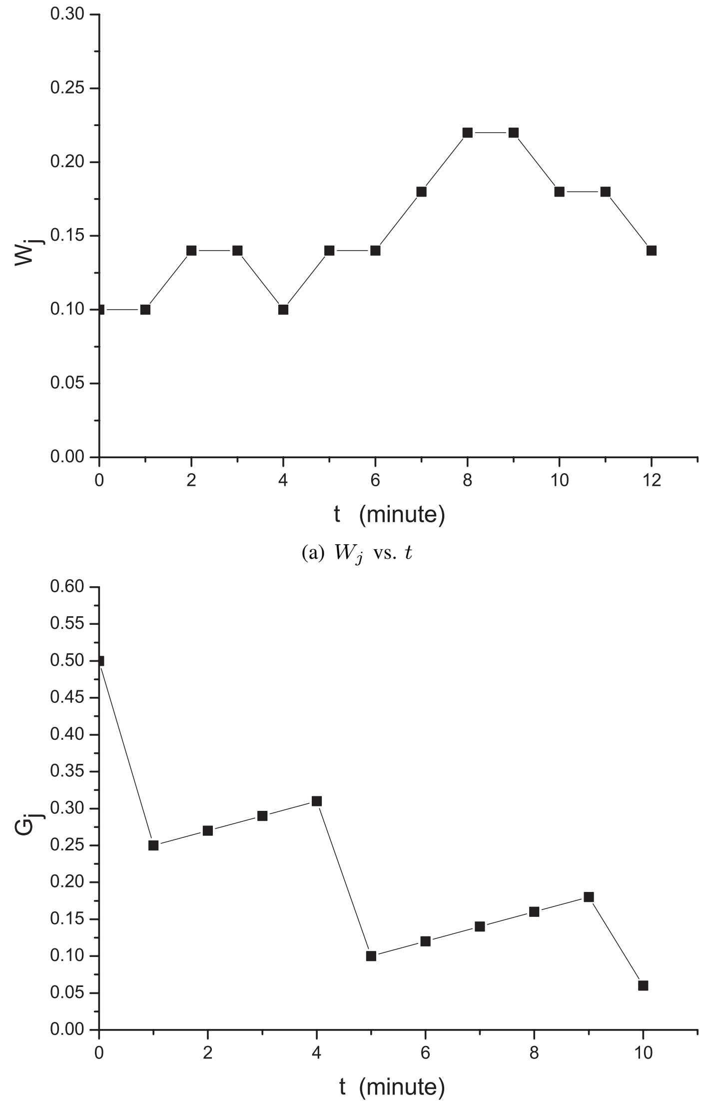
where T_j is timed from the completion of the last content-sharing participation to the start of the current content-sharing participation. In addition, T_j will be reset to 0 after each successful participation. From (5), we can see that if the idle time is less than the time threshold τ, W_j remains unchanged; otherwise, ν_j becomes larger than δ and W_j will be decreased at a rate increasing with the accumulated idle time.

Thus, the value of W_j is updated according to content provider Q_j's participation in D2D content sharing as follows,

$$W_j = \begin{cases} W_j + \delta & \text{successful participation} \\ W_j - \nu_j & \text{no participation during } T_j \end{cases} \tag{6}$$

Fig.2(a) shows the relationship between W_j and time t, where we assume that at the end of the last content-sharing participation $W_j = 0.1$, $\mu = 0.04$ and $\tau = 2$ (minute), and provider Q_j participates in content-sharing at $t = 2, 5, 7, 8$ (minute). Therefore, W_j increases by 0.04 at $t = 2, 5, 7, 8$ (minute). The idle time periods are 2 minutes (from $t = 2$ to $t = 4$) and 4 minutes (from $t = 8$ to $t = 12$). Therefore, W_j is decreased by 0.04 at $t = 4, 10$ and 12.

The initial value of G_j is ϑ, where $\vartheta > 0$. The value of G_j increases by a constant value ϕ $(0 < \phi < 1)$ every time provider Q_j participates a content-sharing transmission without any unsafe behavior. If provider Q_j is found to have had any malicious behavior in a content-sharing process, then the accumulated number (ι_j, which is initially 0) of malicious



(a) W_j vs. t

(b) G_j vs. t

Fig. 2. The relationship between the score of historical content supply record and the time period t of content provider Q_j.

content-sharing behaviors of Q_j is increased by 1 and G_j reduces to one ${\iota_j}^{th}$ of its previous value, i.e.,

$$G_j = \begin{cases} G_j + \phi & \text{without any malicious behavior} \\ \frac{1}{\iota_j} G_j & \text{malicious behavior} \end{cases} \tag{7}$$

Fig.2(b) shows the relationship between G_j and t, where we assume that the initial value of G_j is 0.5, $\phi = 0.02$, $\iota_j = 1$, provider Q_j completes a content-sharing transmission every minute, and provider Q_j has malicious behavior in content sharing at $t = 1, 5, 10$ (minute). The value of G_j is updated every 1 minute. We can see that G_j decreases by a factor of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$ at $t = 1, 5, 10$ (minute), respectively. In other periods, G_j increases by 0.02 every time it completes a content-sharing transmission safely.

For any potential content provider, Q_j $(j \in \{1, ..., M\})$, when it is considered for D2D content sharing for the first time, its score of historical participation record and score of historical safety record are initialized as $W_j = 0$ and $G_j = \vartheta$, respectively. The values of W_j and G_j will then be updated following (6) and (7), respectively, according to Q_j's behavior in subsequent content sharing processes.

B. Score of Current Transmission Rate

In the context of D2D content sharing, we define the score of current transmission rate in a way that links the estimated achievable transmission rate to the size of the requested content and the content requester's sensitivity to content transmission duration (i.e., the minimum difference in transmission durations that can be perceived by the content requester). For example, if the requested content has a size of X bits and it is available at two candidate providers with transmission rates of R and $R-m$, respectively, where m ($m>0$) is the difference between the two transmission rates, then the difference between the transmission durations of the two candidate providers is given by

$$\Omega_t = X(\frac{1}{R-m} - \frac{1}{R}). \tag{8}$$

Denoting ε as the content requester's sensitivity to transmission duration, which is defined as the QoS sensitivity threshold, in order to keep $\Omega_t \leq \epsilon$, we need to have

$$m \leq \frac{R^2\varepsilon}{X+R\varepsilon}. \tag{9}$$

When the transmission rate difference m satisfies (9), the content requester would not notice the difference between the content transmission durations of the two candidate providers. In that case, the two candidate providers could have the same score of current transmission rate.

We denote the estimated achievable transmission rate of potential provider Q_j as R_j $(j=1,...,M)$, and rank the M potential providers in the descending order of their rates, i.e., $Q_{a_1}, Q_{a_2}, ..., Q_{a_M}$, where $a_i \in \{1,...,M\}, i=1,2,\ldots,M$, and $R_{a_1} \geq R_{a_2} \geq \cdots \geq R_{a_M}$. Based on the above discussion and definitions, we define the relationship between the scores of current transmission rate for potential providers $Q_{a_{j+1}}$ and Q_{a_j} as follows,

$$S^R_{a_{j+1}} = S^R_{a_j} - b_j \tag{10}$$

where $S^R_{a_1}=1$, $b_j \geq 0, j=1,...,M-1$, and the value of b_j depends on the value of $m_j = R_{a_j} - R_{a_{j+1}}$. If $m_j \leq \frac{R^2_{a_j}\varepsilon}{X+R_{a_j}\varepsilon}$, then b_j is given by

$$b_j = \frac{S^R_{a_j}}{\zeta + \frac{R^2_{a_j}\varepsilon}{m_j(X+R_{a_j}\varepsilon)}}, \tag{11}$$

where $\zeta > 0$ is a parameter that can be used to adjust the difference between scores of two adjacent ranked potential providers, and the value of b_j increases with m_j. If $m_j > \frac{R^2_{a_j}\varepsilon}{X+R_{a_j}\varepsilon}$, then b_j is given by

$$b_j = (1 - \frac{1}{\chi + \frac{m_j(X+R_{a_j}\varepsilon)}{R^2_{a_j}\varepsilon}})S^R_{a_j} \tag{12}$$

where $\chi > 0$ is a parameter that can be used to adjust the value of b_j, and b_j increases with m_j. By using (10)-(12) and $S^R_{a_1}=1$, the scores of current transmission rate for all the potential providers can be calculated.

C. Score of Expected Reward

The score of expected reward for provider Q_j is given by

$$S^P_j = \frac{\min_{i=1}^M(P_i)}{P_j} \tag{13}$$

where $\min_{j=1}^M(P_j)$ is the minimum expected reward of all potential providers. Since a lower P_j leads to a higher S^P_j, the eNB tends to select the potential provider requiring less profit and less cost to share the content. Here, P_j is the expected reward of potential provider Q_j, which is defined as

$$P_j = A_j + B_j \tag{14}$$

where A_j denotes the cost of Q_j due to content-sharing participation, i.e., the cost of energy consumed by transmitting content from Q_j to the content requester via D2D communications, and A_j can be expressed as

$$A_j = \rho\mu_Q \frac{X}{R_j} \tag{15}$$

where ρ and μ_Q denote the cost per unit energy consumed and the D2D transmit power for content sharing, respectively, and X and R_j denote the size of the requested content and the achievable D2D transmission rate estimated by Q_j, $X \in (0, X_{max})$.

In (14), B_j is the profit of provider Q_j after having successfully completed a content-sharing transmission. Following the market pricing model in [22], we assume that the M potential providers are *M* competing suppliers in the market and define B_j as

$$B_j = \frac{\exp(S^H_j - \Upsilon)}{M} A_j \tag{16}$$

where $\Upsilon \in (0,1)$ are adjustable parameters, and S^H_j denotes the score of historical content supply record of provider Q_j. We can see that, profit B_j, which is calculated by the eNB , increases with S^H_j and decreases with M, which is send to each potential provider by the eNB . On the one hand, a higher score of historical content supply record is necessary for a potential provider to gain a higher reward, which encourages UEs to participate in content sharing actively and safely in the long term. On the other hand, more potential providers competing for supplying the same content will reduce the profit, which will encourage UEs to respond more to content requests with less potential providers available. Based on (15) and (16), (14) can be rewritten as

$$P_j = \rho\mu_Q \frac{X}{R_j}(1 + \frac{\exp(S^H_j - \Upsilon)}{M}). \tag{17}$$

in which $S^H_j \in (0,1)$, $\Upsilon \in (0,1)$, M is a limited value in [22], thus $\frac{exp(S^H_j - \Upsilon)}{M}$ and P_j are both bounded.

In the content-sharing process, the content requester will send status information about the current D2D transmission to the eNB . If the D2D transmission of content fails at some point, the eNB will transmit the remaining content to the requester directly and the reward paid to the content provider will be less than the expected reward accordingly. If the D2D transmission fails after a size X' of the requested content has been received by the requester, where $X' < X$, then the actual reward P'_j is a fraction of the D2D content-sharing cost, i.e.,

$$P'_j = \frac{X'}{X} A_j. \tag{18}$$

If the D2D content-sharing transmission is finished, but the actual transmission rate R'_j is less than the estimated achievable transmission rate R_j, then the actual reward P'_j is given by

$$P'_j = \frac{R'_j}{R_j} P_j. \tag{19}$$

IV. Content-Sharing Incentive and Provider Selection Algorithm

Based on the CSM proposed in Section III, the content provider with the highest score among all the potential providers can be selected for each content requester separately. However, when the N content requesters request contents concurrently, it would be difficult (if not impossible) to select the best content provider from the *M* potential providers for each content requester at the same time. In this section, we will formulate and solve the problem of optimally assigning content providers to multiple requesters.

A. Problem Formulation

Without loss of generality, we assume that the N content requesters share the same set of *M* potential providers, although different requesters may request different contents. Based on CSM, a score, $S_{i,j}$, is calculated of provider Q_j for content requester d_i $(i = 1, ..., N, j = 1, ..., M)$. Then, each of the originally calculated score is normalized as follows, $S_{i,j} = \frac{S_{i,j}}{\max_{j=1}^{M}(S_{i,j})}$, so that $S_{i,j} \in [0, 1]$. All the normalized scores are arranged into an M-by-N matrix $\boldsymbol{S}$, i.e.,

$$\boldsymbol{S} = \begin{bmatrix} S_{1,1} & S_{2,1} & \dots & S_{N,1} \\ S_{1,2} & S_{2,2} & \dots & S_{N,2} \\ \vdots & \vdots & & \vdots \\ S_{1,M} & S_{2,M} & \dots & S_{N,M} \end{bmatrix}$$

We define an M-by-N indicator matrix, $\mathbf{Y} = [y_{i,j}]$, where $y_{i,j} = 1$ indicates that provider Q_j is selected for requester d_i, otherwise $y_{i,j} = 0$. The problem of jointly optimizing the selection of content providers for multiple content requesters can be formulated into the following optimization problem, which maximizes the sum of scores of all the selected content providers, i.e.,

$$\mathbf{Y}^* = arg \max_{\mathbf{Y}} \sum_{i=1}^{N} \sum_{j=1}^{M} S_{i,j} y_{i,j} \tag{20}$$

$$s.t. \begin{cases} \sum_{i=1}^{N} y_{i,j} \le 1, \forall j \in \{1, 2, \dots, M\}, \\ \sum_{j=1}^{M} y_{i,j} \le 1, \forall i \in \{1, 2, \dots, N\}, \\ y_{i,j} \in \{0, 1\}, \forall i \in \{1, 2, \dots, N\}, \forall j \in \{1, 2, \dots, M\}. \end{cases}$$

If $M \ge N$, N different providers can be selected for the N content requesters. If $M < N$, M providers are selected for M content requesters and the eNB will send the contents to the other $N - M$ requesters. In the following, we present two lemmas to simplify the above optimization problem.

***Lemma** 1:* If $M = N$, matrix $\mathbf{S}$ remains unchanged. If $M < N$, we append $(N - M)$ rows of 0 's to matrix $\mathbf{S}$ to transform it into an $N \times N$ square matrix $\mathbf{S}'$:

$$\mathbf{S}' = \begin{bmatrix} S_{1,1} & S_{2,1} & \dots & S_{N,1} \\ S_{1,2} & S_{2,2} & \dots & S_{N,2} \\ \vdots & \vdots & & \vdots \\ S_{1,M} & S_{2,M} & \dots & S_{N,M} \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix}$$

If $M > N$, we append $(M - N)$ columns of 0 to matrix $\mathbf{S}$ to transform it into an $M \times M$ square matrix $\mathbf{S}''$:

$$\mathbf{S}'' = \begin{bmatrix} S_{1,1} & S_{2,1} & \dots & S_{N,1} & 0 & \dots & 0 \\ S_{1,2} & S_{2,2} & \dots & S_{N,2} & 0 & \dots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ S_{1,M} & S_{2,M} & \dots & S_{N,M} & 0 & \dots & 0 \end{bmatrix}$$

Then, replacing $\mathbf{S}$ with $\mathbf{S}'$ ($\mathbf{S}''$) and replacing M with N (N with M) and increasing the size of $\mathbf{Y} = [y_{i,j}]$ into N-by-N (M-by-M) in (20) if $M < N$ (if $M > N$), the solution to the optimization problem (20) will not be changed.

Proof: The objective function with $\mathbf{S}'$ can be expressed as

$$\sum_{i=1}^{N} \sum_{j=1}^{N} S'_{i,j} y_{i,j} = \sum_{i=1}^{N} \sum_{j=1}^{M} S_{i,j} y_{i,j} + \sum_{i=1}^{N} \sum_{j=M+1}^{N} S'_{i,j} y_{i,j} \tag{21}$$

Since $S'_{i,j} = 0$ for $j = M + 1, \dots, N$, we have

$$\sum_{i=1}^{N} \sum_{j=M+1}^{N} S'_{i,j} y_{i,j} = 0 \tag{22}$$

Thus, the objective function with $\mathbf{S}'$ is the same as the original objective function with $\mathbf{S}$, i.e.,

$$\sum_{i=1}^{N} \sum_{j=1}^{M} S_{i,j} y_{i,j} = \sum_{i=1}^{N} \sum_{j=1}^{N} S'_{i,j} y_{i,j}. \tag{23}$$

Similarly, it can be proven that the objective function with $\mathbf{S}''$ is the same as the original objective function with $\mathbf{S}$ as well.

***Lemma** 2:* Let

$$K = \max(S'_{i,j}), i = 1, \dots, N, j = 1, \dots, N \tag{24}$$

$$F_{i,j} = K - S'_{i,j} \tag{25}$$

We arrange $F_{i,j}(i = 1, 2, \ldots, N; j = 1, 2, \ldots, N)$ into the following $N \times N$ matrix

$$\boldsymbol{F} = \begin{bmatrix} F_{1,1} & F_{2,1} & \ldots & F_{N,1} \\ F_{1,2} & F_{2,2} & \ldots & F_{N,2} \\ \vdots & \vdots & & \vdots \\ F_{1,N} & F_{2,N} & \ldots & F_{N,N} \end{bmatrix}$$

The optimization problem in (20) can be converted to

$$\mathbf{Y}^* = arg \min_{\mathbf{Y}} \sum_{i=1}^{N} \sum_{j=1}^{N} F_{i,j} y_{i,j} \tag{26}$$

$$s.t. \quad \begin{cases} \sum\limits_{i=1}^{N} y_{i,j} \le 1, \forall j \in \{1, 2, \ldots, N\}, \\ \sum\limits_{j=1}^{N} y_{i,j} \le 1, \forall i \in \{1, 2, \ldots, N\}, \\ y_{i,j} \in \{0, 1\}, \forall i \in \{1, 2, \ldots, N\}, \forall j \in \{1, 2, \ldots, N\}. \end{cases}$$

The solution to the optimization problem in (26) is the solution to (20).

Proof:

$$\sum_{i=1}^{N} \sum_{j=1}^{N} (F_{i,j}) y_{i,j} = \sum_{i=1}^{N} \sum_{j=1}^{N} K y_{i,j} - \sum_{i=1}^{N} \sum_{j=1}^{N} S'_{i,j} y_{i,j} \tag{27}$$

Because $\sum_{i=1}^{N} \sum_{j=1}^{N} K y_{i,j} = NK$ or 0, minimizing the left-hand side is equivalent to maximizing the second term (without the minus sign) on the right-hand side, which is the same as the objective function in (20) according to Lemma 1.

B. Hungarian Algorithm

The optimization problem in (26) is an Assignment Problem [26], which can be solved using the Hungarian algorithm [23]-[25]. The time complexity of the Hungarian algorithm is $O(n^3)$ in the worst situation and the space complexity is $O(n^2)$ [19].

The Hungarian algorithm is based on the following two lemmas [25]:

***Lemma** 3:* Let $F'_{i,j} = F_{i,j} + a_j + b_i$, where a_j and b_i are constants, $j = 1, \ldots, N$, and $i = 1, \ldots, N$. Then, replacing $F_{i,j}$ with $F'_{i,j}$ in the objective function in (26) we have

$$\begin{aligned} \sum_{i=1}^{N} \sum_{j=1}^{N} F'_{i,j} y_{i,j} &= \sum_{i=1}^{N} \sum_{j=1}^{N} (F_{i,j} + a_j + b_i) y_{i,j} \\ &= \sum_{i=1}^{N} \sum_{j=1}^{N} F_{i,j} y_{i,j} + \sum_{i=1}^{N} \sum_{j=1}^{N} (a_j + b_i) y_{i,j} \end{aligned} \tag{28}$$

where $\sum_{i=1}^{N} \sum_{j=1}^{N} (a_j + b_i) y_{i,j} = \sum_{j=1}^{N} a_j + \sum_{i=1}^{N} b_i$ is a constant.

***Lemma** 4:* If some elements of a matrix are zeroes and the other elements are not zeroes, then the least number of rows and columns that contain all the zero elements is equal to the largest number of independent zeroes, which are the zero elements in different rows or in different columns. The multiple zero elements in the same row or column are regarded as one independent zero.

In the previous subsection, when $M < N$, we transform matrix $\mathbf{S}$ to matrix $\mathbf{S}'$, and transform matrix $\mathbf{S}'$ to matrix $\mathbf{F}$, which satisfies the initial condition in the Hungarian algorithm [19]. In the algorithm designed in this paper based on the Hungarian algorithm, we define the $\clubsuit$ as the zero element which has only one zero element in it and replace other zero elements with $\diamondsuit$ in the same column with $\clubsuit$. Based on ***Lemma*** 3 and 4, the Hungarian algorithm can be implemented as follows:

Step I: Simplify matrix $\boldsymbol{F}$.

(i) $F_{i,j} = F_{i,j} - \min_{i'=1}^{N}(F_{i',j}), \forall i, j \in \{1, ..., N\}$.

(ii) $F_{i,j} = F_{i,j} - \min_{j'=1}^{N}(F_{i,j'}), \forall i, j \in \{1, ..., N\}$.

Algorithm 1 Content-sharing incentive and provider selection (CIPS) algorithm

Input:

The set of N content requesters $D = \{d_1, d_2, \ldots, d_N\}$; the set of M potential providers $Q = \{Q_1, Q_2, \ldots, Q_M\}$; each potential provider Q_j has its historical content-sharing participation record W_j and historical content-sharing safety record $G_j(j = 1, 2, \ldots, M)$; the size of content requested by d_i is $X_i(i = 1, 2, \ldots, N)$.

Steps:

for content requester $d_i(i = 1, 2, \ldots, N)$ **do**

d_i asks the eNB for a content with size X_i.

The eNB broadcasts the content information, i.e., the location of d_i to estimate CSI and R_j, the X_i to estimate E_j, to the potential providers $Q = \{Q_1, Q_2, \ldots, Q_M\}$.

If Q_j has the requested content, Q_j will respond to the eNB with estimated transmission rate R_j and energy cost E_j for sending the content to d_i via D2D link; otherwise, it does not responds.

The eNB calculates the CSM score of potential provider Q_j.

(i) If Q_j has the requested content:
$S_j^H = \frac{1}{2}(W_j + G_j)$ according to (4)-(7); $S_j^R = S_{j-1}^R - b_j$ according to (8)-(12); $S_j^P = \frac{\min_{j=1}^{M}(P_j)}{P_j}$ according to (13)-(17);
then, $S_j^T = S_j^H + S_j^R + S_j^P$;
$S_j^T = \frac{S_j^T}{\max_{j=1}^{M} S_j^T}$;
$S_{i,j} = S_j^T$.

(ii) If Q_j dose not have the requested content: $S_{i,j} = 0$.

end for

$S_{i,j}(i = 1, 2, \ldots, N; j = 1, 2, \ldots, M)$ form the matrix $\boldsymbol{S}$, $\boldsymbol{S}$ is transformed to $\boldsymbol{F}$ as in (24)-(26), and the Hungarian algorithm is adopted as described in Section IV-B to optimally assign providers to the requesters. For the requesters without any selected provider, the eNB will send the content directly.

for each content requester d_i that has been assigned a provider Q_k **do**

If the D2D content-sharing process fails, d_i will inform the eNB of its received content size X_i, and the eNB will send the remaining content to d_i and pay the reward $P = \frac{X'_i}{X_i} A_{i,k}$ to provider Q_k (Eq.(14), (16)). If D2D content-sharing process completes, d_i will inform the eNB of the actual transmission rate R'_k, and the eNB will pay $P = \frac{R'_k}{R_k} P_{i,k}$ to provider Q_k. Historical supply record W_k and G_k will be updated according to (6) and (7), respectively, by the eNB .

end for

Step II: Find the independent zero elements

(i) Mark the zero element which is the only zero in a row with ♣, then replace the other zero elements in the same column of that ♣ with ♢.
(ii) Mark the zero element which is the only zero in a column with ♣ , then replace the other zero elements in the same row of that ♣ with ♢.
(iii) Repeat (i) and (ii) in Step II to mark and replace as many zero elements as possible.
(iv) If there are zero elements that have not been marked or replaced, then first select the row with the least zero elements, find the column with the least zero elements among the columns containing the zero elements of the selected row, mark the zero element belonging to both the selected row and column with ♣, and then replace the other zero elements in the selected row and column with ♢. Repeat this step until all the zero elements have been marked or replaced.
(v) Denote the number of ♣ elements in matrix **F** as K. If $K = N$, the optimal solution to the assignment problem in (26) is obtained and the algorithm terminates. If $K < N$, go to Step III.

Step III: Find the least number of rows and columns that can contain all the remaining zero elements in matrix **F**.

(i) Mark each row without any ♣ with $\surd$.
(ii) For each row labeled with $\surd$, mark all the columns that contain a ♢ or a ♣ belonging to that row with $\surd$.
(iii) Repeat (ii) of Step III, until there is no more row or column that can be marked with $\surd$.
(iv) Cross each row without $\surd$ with a horizontal line and cross each column without $\surd$ with a vertical line, then denote l as the total number of lines, which cross out all the rows and columns that contain all the remaining zero elements.

If $l \neq N$, then there must be a mistake in the previous process, and go back to (iv) of Step II. If $l = N$, go to Step IV.

Step IV: Introduce N independent zero elements in matrix **F**.

(i) Find the minimum element θ among the elements that are not crossed by any line.
(ii) Subtract θ from each element of all the rows labeled with $\surd$.
(iii) Add θ to each element of all the columns labeled with $\surd$ (to guarantee there is no negative element in $\boldsymbol{F}$);
(iv) Return to Step II.

When the above algorithm terminates, we obtain a matrix **F** which contains one and only one ♣ element in each row and in each column. For each content requester $d_i, i \in \{1, \ldots, N\}$, if $F_{k,i} = ♣, k \in \{1, \ldots, M\}$, then, provider Q_k is selected to transmit content to requester d_i via D2D.

C. Content-sharing Incentive and Provider Selection Algorithm

Based on the proposed CSM and the Hungarian algorithm, we devise the CIPS algorithm (Algorithm 1) to motivate the participation of candidate content providers and assign them optimally to the content requesters.

V. Simulation Results

In this section, we provide numerical results to illustrate the performance of the proposed CSM and CIPS algorithm. We consider a single-cell with 10 content requesters and various numbers of content providers and CUEs. The size of requested content is a logarithmic distributed between 0MBytes and 100MBytes[23]. The historical content supply record of each potential provider is a random value uniformly distributed in [0,1]. The probability for each requester to request one of the N available contents is $\frac{1}{N}$. Other key parameters are listed in Table I. Both pathloss and shadow fading are considered for each cellular or D2D link.

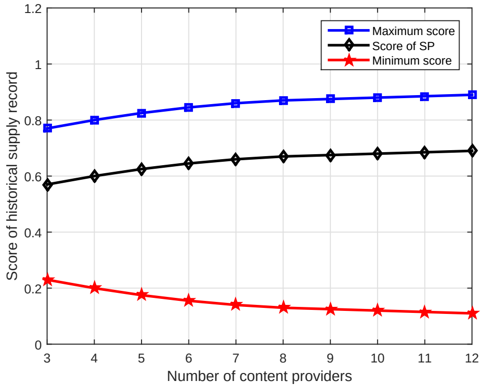
TABLE I
SIMULATION PARAMETERS

Parameter	**Value**
Cell radius	250m
D2D Bandwidth	10MHz
α	2
Noise spectral density	-174 dBm/Hz
μ_C	23dbm
μ_Q	20dbm
λ_D	$1/(\pi \cdot 250^2)$
SINR threshold of the D2D requester	0dB

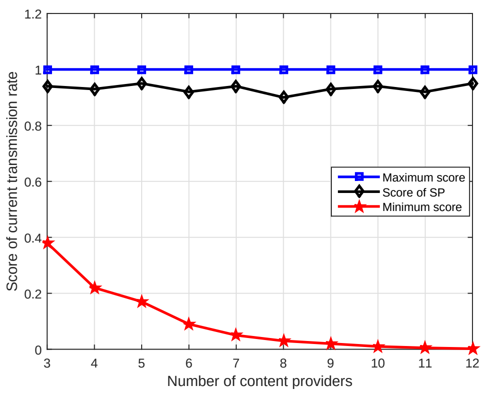
A. Performance of Comprehensive Scoring Mechanism

Fig.3 plots the maximum score, the minimum score and the score of selected provider (SP) among all providers versus the total number of providers calculated with CSM. In addition, the maximum score, the minimum score and the score of SP are the average values among 1000 simulations. Fig.3(a) shows the relationship between S^H and the number of providers. It can be observed that with the increasing number of providers, both the maximum score and the score of SP increase, while the minimum score decreases. Fig.3(b) illustrates the relationship between S^R and the number of providers. It shows that with the increasing of number of providers, the minimum score decreases, while both the maximum score and the score of SP almost remain unchanged. Fig.3(c) shows the relationship between S^P and the number of providers. We can see that with the increasing number of providers, the maximum score remains at one, the minimum score decreases, and the score of SP increases. Fig. 3 reveals that: i) the historical score and expected reward of the selected provider will increase as the candidate group becomes larger, as more potential providers participate the competition; ii) the S^R of the selected provider is always high (close to the highest S^R of all candidates) regardless of the increase of the group size, since the highest data rate is limited by the maximum transmission power and the minimum D2D distance; iii) the score of SP is not the highest in all three subplots, since S^T reflects the balance of S^H, S^R and S^P.

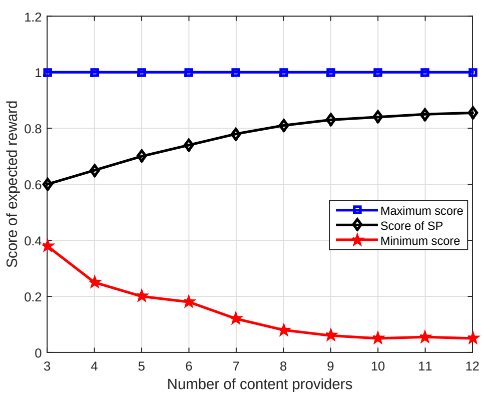
Fig.4 presents the probability of being selected versus S^H, S^R and S^P in the simulations. It reveals that with the increasing of S^H, the probability of being selected increases until the score goes beyond 0.9, then the probability starts to



(a) Score of historical content supply record



(b) Score of current transmission rate



(c) Score of expected reward

Fig. 3. The maximum score, the minimum score and the score of SP among all providers versus the total number of providers calculated by the CSM

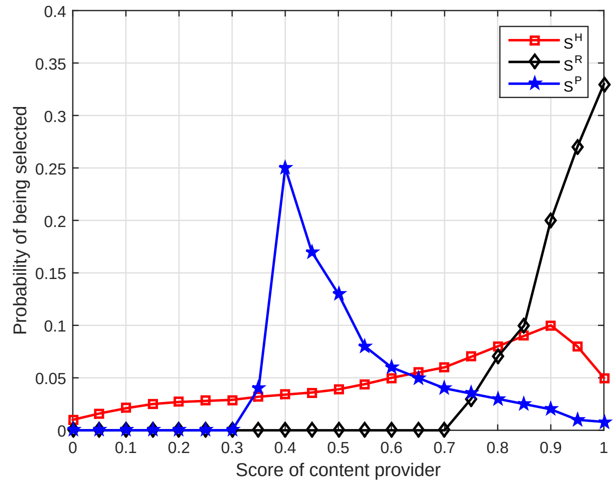


Fig. 4. Probability of being selected Versus the scores of content providers

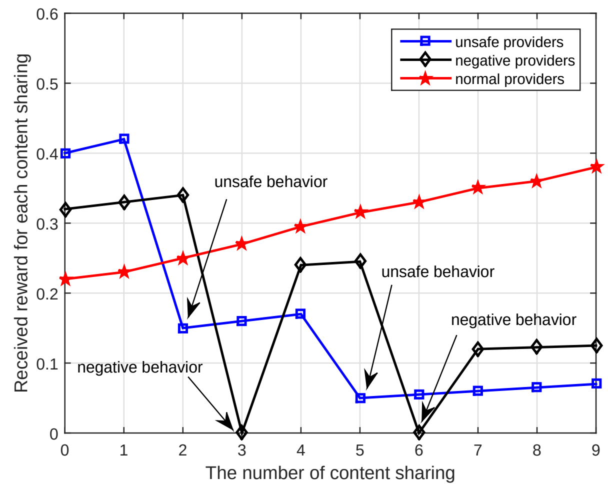


Fig. 5. Actual rewards of three types of providers versus the number of content sharing.

decrease, since a very a high S^H leads to a high reward, which can decrease S^P significantly. Interestingly, when $S^P < 0.35$, no provider is selected; the maximum probability of being selected is achieved at $S^P = 0.4$. It is because when S^P is of a higher value, S^H has a lower value, which decreases the probability of being selected. The inflection points in the curves of S^H and S^P reflect the relationship between them in the probability of being selected. It can also be observed that when $S^R < 0.75$, no provider is selected, then with the increase of S^R, the probability of being selected increases rapidly. It indicates that providers with higher transmission rates are more likely to be selected.

B. Incentive and Safety

We simulate the received rewards of three types of content providers (i.e., normal providers, negative providers and unsafe providers) in 10 content sharing events, so as to reveal the impact of CSM on the incentive and safety issues in D2D content sharing. A normal provider is always willing to share content with others and will never provide unsafe data files. A negative provider only wants to receive content from others but seldom provides content. An unsafe provider would like to share content but may provide files containing virus, worms, or trojan horses. Accordingly, a negative behavior refers to the act of a candidate provider refusing to share content, while an unsafe behavior refers to the act of a candidate provider sending false content or even virus to the content

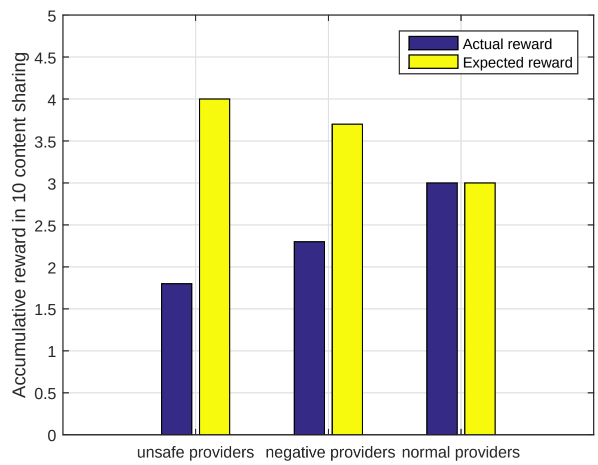


Fig. 6. Actual reward and expected reward of three types of providers.

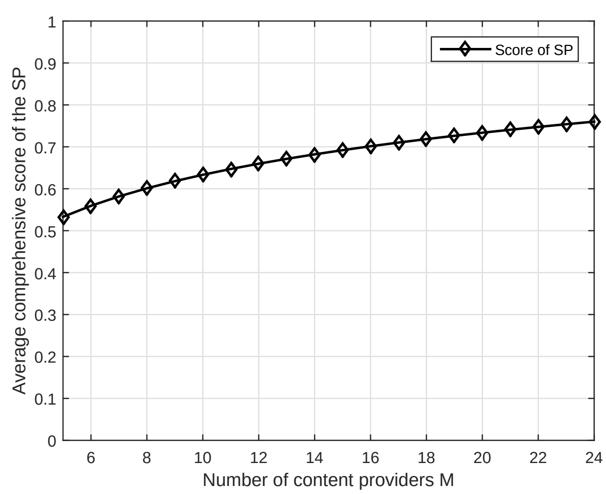


Fig. 7. The average comprehensive score of the SP versus the number of potential content providers.

requester. In Fig.5, we set the initial values of W_j and G_j as $W_j = G_j = 0.4$, 0.6 and 0.5 for normal providers, negative providers and unsafe providers, respectively. It can be observed that initially the unsafe providers receives the highest reward because of its highest initial S^H. However, its received reward suddenly drops at content sharing number 2 and 5 due to its unsafe behavior, and reduces to the lowest among the three providers after 10 content sharing processes. Similarly, the received reward of the negative provider is higher than the normal provider at the beginning , but suddenly decrease at content sharing number 3 and number 6 due to its negative behavior. But after some active participations, it finally increases to be the second highest. The received reward of the normal provider increases and becomes the highest at last. Fig.6 shows the total received reward and the total expected reward of all three types of providers at the end of the simulation, where the expected reward is the reward which could have been gained if without any negative and unsafe behavior. It is obvious that the actually received rewards of both the negative provider and unsafe provider are much lower than their expected rewards, while the normal provider receives a reward equals to the expected value. Fig.5 and Fig.6 indicate that the proposed CSM would be able to discourage the negative and unsafe behaviors of providers by adaptively controlling their received rewards.

C. Quality of Service

We evaluate the performance of the proposed CIPS algorithm for different numbers of providers. Fig.7 shows the average comprehensive score of the SP versus the number of potential content providers. As shown in Fig.7, the average maximum comprehensive score is 1, and the average comprehensive score of the selected providers for each requester is the average score of selected content providers for 10 content requesters by using CIPS. From Fig.7, we can see that the increasing number of potential providers, the average comprehensive score of SP increases. This is because assigning potential providers to different content requesters may appear repeat, which can reduce the average comprehensive score of the selected providers.

VI. Conclusion and Future Work

In this paper, we have investigated the content-sharing incentive and provider selection problem for D2D communications underlaying cellular network. We propose CSM, which calculates a score for each candidate content provider based on their historical content supply record, current transmission rate and expected reward. Based on the CSM and the Hungarian algorithm, we devise a content-sharing incentive and provider selection (CIPS) algorithm to optimize the selection of content providers for multiple concurrent content requesters. Numerical results have shown that the proposed CSM can promote UEs to participate in D2D content sharing as frequently as possible without any malicious behaviors by controlling the received reward of providers. The proposed CIPS can assign optimal content providers to each content requester and increase the average comprehensive score of selected providers with the increase number of content providers.

It should be noted that in realistic D2D content-sharing systems, the physical contact period within D2D communications distance may impose a limitation on D2D content sharing. In our future work, we will investigate the life time of D2D pairs and the probability of content-sharing completion using realistic human mobility models.

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