A Signaling-based Incentive Mechanism for Device-to-Device Content Sharing in Cellular Networks

Tao Zhang, Haibo Wang, Xiaoli Chu, and Jianzhang He

***Abstract*—In this letter, we model the Device-to-device (D2D) content sharing problem as a labor market where the base station (BS) acts as the principal and content providers serve as agents. A signaling-based content-sharing incentive (*SCSI*) mechanism is designed to encourage candidate content providers to participate in content sharing, and the optimal strategy for each content provider is derived to maximize their utility (monetary profit) while guaranteeing a non-negative utility for the BS. Simulation results show that the proposed *SCSI* mechanism can increase the content provider's utility and participating enthusiasm in D2D content sharing.**

***Index Terms*—content sharing, device-to-device communications, signaling, incentive mechanism.**

I. Introduction

THE global mobile data traffic has been predicted to increase nearly eightfold between 2015 and 2020 [1]. The proliferation of intelligent mobile devices running multimedia applications such as content sharing, social networking and online gaming brings a huge challenge to future wireless networks. Evolving from end-to-end communications to content-centric wireless networking has become an inevitable trend. Traditional cellular communications urgently need new technologies and methods to tackle the challenge [2]–[3].

Device-to-device (D2D) communications have been considered as a promising approach to improve spectrum and power efficiency [4]-[5] and offload traffic from cellular networks. For example, some UEs which have downloaded frequently requested content can store and share these content to other UEs via D2D links and avoid repeatedly downloading from the BS [6]. In this case, the BS's traffic load will be greatly reduced, and the cellular network capacity can be utilized more efficiently.

To promote D2D content sharing, the first problem is to motivate UEs to share with others using their own energy resource, e.g., the BS can offer a reward to compensate the content provider's cost to provide incentive [7]-[8]. Ideally the BS should select the UE with the best transmission capacity toward the content requester UE, and give reward according to its capacity. However, the content provider UEs may compete for the reward by claiming higher capacity than its true value, which is a type of *Information Asymmetry* [9]. It is our goal to design an effective incentive mechanism and solve the information asymmetry for D2D content sharing.

Contract theory is a powerful model to analyze incentive problem with information asymmetry from economics [10], and has been adopted in some contemporary research work [11]-[12]. In the contract-theoretical model, the BS play as the principal, who outsources the data transmission work to some content provider UEs near the content requester UE. The content provider UEs serve as the agent, who compete for the content sharing work and get corresponding reward from the principal. Nazari and Jamalipour adopted the contract and auction theory to design a forwarding incentive mechanism for multi–relay cooperative wireless networks [11]. Zhang *et al.* [12] proposed a contract-based incentive mechanism for content dissemination in D2D cooperative communications. The incentive mechanisms in [11]-[12] employs the screening mechanism from contract theory to solve the *Information Asymmetry* problem - the transmission ability of the agents toward the content requester are naturally known to themselves, but not known to the principal. In screening model, the principal (i.e., the BS) offers a menu of contracts to the agents to separate different types of agents, and the agents' choices reveals their types (transmission abilities). In this process, the agents are passive, and if the BS can not estimate the agents' capacity accurately, the contract will not be fair to all the agents and may reduce the participating enthusiasm of some agents. we formulate the D2D content sharing problem based on the Principal-Agent model and use the signaling method to solve the associated Information Asymmetry problem while the previous work [4] uses screening-based method to solve.

In this letter, we formulate the D2D content sharing incentive problem based on the *Principal-Agent* model, which is in the contract theory framework. The main contributions can be summarized as follows. First, we use the signaling method to solve the *Information Asymmetry* problem in the *Principal-Agent* model while the previous work is screening-based method [12]. Compared to the screening based method, higher accuracy of the agent types or capabilities will be known by the principal. Second, we tackle the deceit problem in contract signing by designing the signal sent from a candidate content provider to the BS as a guarantee, which includes the guaranteed compensation information if the D2D content sharing fails. We calculate the optimal guarantee and maximize the utility of the content provider while a non-negative utility

This research was supported partly through the National Natural Science Foundation of China [No.61471026], and in part through the Fundamental Research Funds for the Central Universities [No.2016JBZ003].

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is ensured for the BS. Performance of the proposed SCSI mechanism is compared with two existing agent selection and incentive schemes. Simulation results show that the proposed *SCSI* mechanism can much more effectively motivate the UE participation in D2D content sharing.

The rest of the letter is organized as follows. Section II presents the system model. In Section III, the *SCSI* mechanism is proposed. Simulation results are presented and analyzed in Section IV. Section V concludes this work.

II. System Model

We consider a single-cell cellular network where there are one BS in the center, a number of cellular UEs, one content requester (CR) UE far from the BS, and N potential content provider (CP) UEs (i.e., $CP_1, CP_2, \dots, CP_N$) randomly distributed around the CR within the maximum D2D communication range d_{max}, as shown in Fig. 1. Assume that all the D2D transmitters use the same transmission power P_D and the UE position is semi-static within the D2D session, since several mega-bytes can be transmitted within 1 second in LTE. The channel model consists of path-loss and Rayleigh

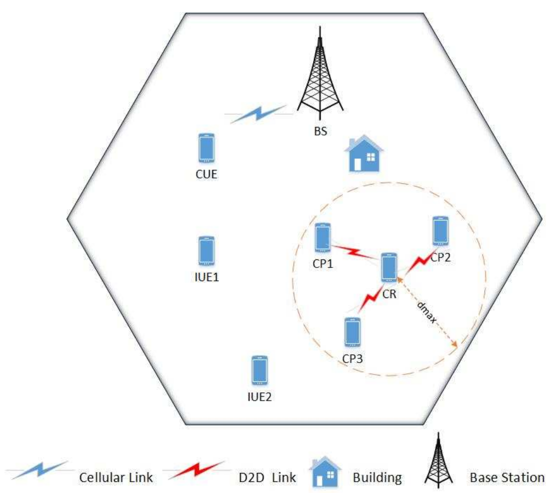

Fig. 1. The System Model

fading. The received power P_r at the CR from the CP_n can be expressed as $P_D {d_n}^{-\alpha} h_n$, where h_n stands for the Rayleigh fading power gain and follows a unit-mean exponential distribution, d_n is the distance between the CR and the CP_n, and α is the path loss exponent.

We consider the D2D overlay model, i.e., D2D communications are assigned with dedicated radio resources and there is no interference between D2D and conventional cellular links. Then the received signal-to-noise ratio (SNR) of CR from CP_n can be expressed as:

$$\gamma_n = \frac{P_D {d_n}^{-\alpha} h_n}{n_0 B}, \tag{1}$$

where n_0 is the power spectral density of the additive white Gaussian noise (AWGN), and B is the channel bandwidth, which is assumed to be the same for all D2D links. It is easy to show that γ_n follows an exponential distribution with $E[\gamma_n] = \frac{P_D {d_n}^{-\alpha}}{n_0 B}$. Given γ_{th} as the SNR threshold , the outage probability of the n^{th} D2D link (i.e., the link between the CR and the CP_n) can be calculated as:

$$\begin{aligned} P_{out_n} = & \int_0^{\gamma_{th}} \frac{n_0 B}{P_D {d_n}^{-\alpha}} \exp(-\frac{\sigma^2 n_0 B}{P_D {d_n}^{-\alpha}} x) dx \\ = & 1 - \exp(\frac{\gamma_{th} n_0 B}{P_D {d_n}^{-\alpha}}). \end{aligned} \tag{2}$$

The data rate of the n^{th} D2D link is given as:

$$\begin{aligned} R_n = & B \log_2(1 + \gamma_n) \\ = & B \log_2(1 + \frac{P_D {d_n}^{-\alpha} h_n}{n_0 B}). \end{aligned} \tag{3}$$

When the CR UE requests contents (e.g., video clips, news or music) from the BS, the BS can either provide the requested content directly through the cellular downlink, or select a CP UE to deliver the content via a D2D link. Since the candidate CP UEs have no obligation to help the CR UE, the BS should provide the selected CP UE with some reward, e.g., in money, once the D2D content sharing is successfully completed. In this case, the BS acts as a principle and the selected CP UE serves as an agent as in the contract theory [10]. Due to the space limit, we assume that there are two types of CP UE: high type (θ_H) and low type (θ_L) while the case more than two types will be considered in our future work.

Definition 1. *The type θ_n of CP_n is proportional to the channel gain g_n between CP_n and the CR UE, i.e.,*

$$\theta_n \propto g_n = {d_n}^{-\alpha} h_n. \tag{4}$$

A threshold g_0, which is designed by the BS, is used to decide a CP's type (CP's type is known among the CPs), i.e., $\theta_n = \theta_H$ if $g_n \leq g_0$, otherwise $\theta_n = \theta_L$. A θ_H-type CP UE is likely to offer a higher data rate on the D2D link to the CR UE than a θ_L-type CP using the same transmit power. Similar to the *Information Asymmetry* problem in microeconomics [9], the BS may not know the exact type of each CP. We assume that the BS knows that the portions of high-type CP UEs and low-type CP UEs are ρ and $1-\rho$ ($0 \leq \rho \leq 1$), respectively. Assuming that the CP_n is selected, we define the utility function of the BS as follows:

$$U_{BS} = \mu_B R_n - W_n, \tag{5}$$

where R_n is the data rate of the D2D content sharing link as given in (3), and W_n is the monetary reward given to the selected CP UE, $W_n = W_H$ if $\theta_n = \theta_H$, otherwise $W_n = W_L$, usually $W_H > W_L$, and μ_B is the per-packet gain of the BS measured in monetary units [10]. For simplicity, we assume $\mu_B = 1$ and the reservation utility level is no less than zero [10].

The utility of the CP_n is defined as:

$$U_{CP_n} = W_n - \frac{1}{2} c P_D^2, \tag{6}$$

where c is the monetary cost for the CP UE to transmit a packet to the CR UE with transmit power P_D.

III. Signaling-based Content-sharing Incentive Mechanism for D2D Content Sharing

A. Signaling

The signaling, also called signaling game, was first proposed to analyze the job market [13], in which the education level is considered as a trustworthy signal sent by the potential employee since it takes intelligence and years of efforts to acquire. In microeconomics [9], signaling is used to solve the problem of *Asymmetric Information*, where the principal cannot directly observe the abilities of the agents, and the agents send signals to the principal to expose their abilities. The principal will offer a higher reward to a high-type agent than to a low-type agent, and offer a higher reward to an agent who sends a signal than to one who does not. Sending a signal should be costly to an agent, otherwise low-type agents may send signals to pretend to be high-type agents in order to obtain a higher reward than they actually deserve. The risk of hiring a low-type agent can thus be reduced.

A successful signaling game will lead to a perfect Bayesian equilibrium [10], which includes the Separating and Pooling Equilibria. In the former, different types of agents send different signals. In the latter, the same signal is sent by all agents.

In our proposed *SCSI* mechanism, if no signal is received from CP UEs, i.e., in the pooling status, the BS would pay the expected reward, $\rho W_H + (1-\rho)W_L$, to the selected CP [9]. Since the expected reward is lower than W_H and higher than W_L, a high–type CP UE would like to reveal its type to the BS more than a low-type one given the cost of sending a signal.

B. Signal Design

We design the signal sent by a CP UE to the BS as a guarantee, which promises a certain amount of monetary compensation for the BS if the D2D content sharing fails. Let $\bar{O}_H$ and $\bar{O}_L$ denote the average communication failure probability of θ_H-type CP and θ_L-type CP UE, respectively, which can be calculated by (2); x and y denote the guarantee (i.e., the amount of money) promised by θ_H-type and θ_L-type CP UE in the guarantee signal, respectively. Since sending the signal (guarantee) requires additional cost, the utility function of the CP_n is modified to:

$$U_{CP_n} = W_n - \frac{1}{2}cP_D^2 - V_n. \tag{7}$$

where $V_n = \bar{O}_H x$ ($\bar{O}_L y$) is the guaranteed amount of compensation if CP_n is a high-type (low-type) CP UE.

In order to form the Separating Equilibrium, according to [10] and [9], two constraints must be satisfied: Incentive Compatible(IC) and Individual Rationality(IR).

Definition 2. *IC: CPs must prefer the guarantee designed specifically for their own types and , i.e.,*

$$W_L - \frac{1}{2}cP_D^2 - \bar{O}_L y \geq W_H - \frac{1}{2}cP_D^2 - \bar{O}_L x, \tag{8}$$

$$W_H - \frac{1}{2}cP_D^2 - \bar{O}_H x \geq W_L - \frac{1}{2}cP_D^2 - \bar{O}_H y, \tag{9}$$

where $\bar{O}_H y$ ($\bar{O}_L x$) is the guaranteed compensation of a high-type (low-type) CP UE if it pretends to be a low-type (high-type) CP.

Definition 3. *IR: The utility of a high-type CP UE after sending signal is no less than the former, i.e.,*

$$W_H - \frac{1}{2}cP_D^2 - \bar{O}_H x \geq (\rho W_H + (1-\rho)W_L) - \frac{1}{2}cP_D^2. \tag{10}$$

Note that low-type CP UEs will not send signals [9], and thus $y = 0$. Based on (8), (9) and (10), the value of x is bounded by:

$$\frac{(1-\rho)(W_H - W_L)}{\bar{O}_H} \geq x \geq \frac{W_H - W_L}{\bar{O}_L}. \tag{11}$$

C. Optimal Solution

We maximize the utility function of the selected high-type CP UE, and the optimization problem can be written as :

$$x^* = arg\max_x (W_H - \frac{1}{2}cP_D^2 - \bar{O}_H x), \tag{12}$$

$$s.t.\ \frac{(1-\rho)(W_H - W_L)}{\bar{O}_H} \geq x \geq \frac{W_H - W_L}{\bar{O}_L}.$$

This is a linear problem. The optimal x^* is found as:

$$x^* = \frac{W_H - W_L}{\bar{O}_L}. \tag{13}$$

Thus, the maximum utility of the high-type CP is:

$$\hat{U}_{CP} = W_H - \frac{1}{2}cP_D^2 - \bar{O}_H \frac{W_H - W_L}{\bar{O}_L}. \tag{14}$$

In practice, x might be higher than x^* and the selected CP's utility may be lower than $\hat{U}_{CP}$, since the CP UEs may increase the guarantee to win the competition. For example, among the high-type CP UEs, the ones with higher residual battery levels may send stronger signals than those with lower residual battery levels to increase the probability of being selected as the content provider. The detailed competition analysis is beyond the scope of this letter.

IV. Simulation Results

We evaluate the performance of the proposed *SCSI* mechanism in comparison with two existing agent selection approaches. The first one is *Random Selection (RS)*, in which the BS randomly selects a CP from the responding CP UEs. The second one is *No Information Asymmetry (NIA)* [10], in which the BS knows the exact type information of all the CP UEs without any *Information Asymmetry*. In the simulations, the high reward W_H is set as 0.4 while the low reward W_L has two different values: $W_{L1} = 0.1$ and $W_{L2} = 0.2$.

A. Utility of CP UE

The utility of CP UE versus ρ is shown in Fig. 2. In *NIA*, the CP utility is always zero since the CP's type is known by the BS and there is no need of a signaling game. No matter W_L is W_{L1} or W_{L2}, the CP utilities of both *SCSI* and *RS* increase with ρ (the percentage of θ_H-type CP UEs), but the utility of the former is larger than the latter. The two utilities become the same when ρ approaches 0 or 1. In *RS*, the BS does not know the types of CP UEs, and thus only wants to

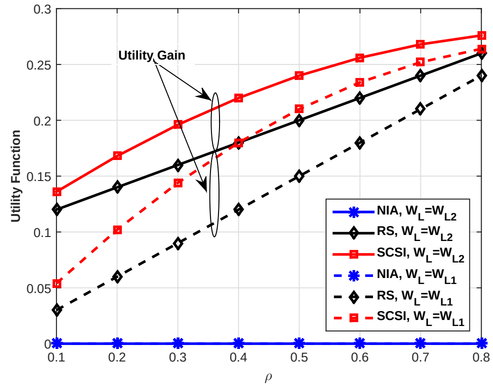

Fig. 2. Utility of CP vs. ρ

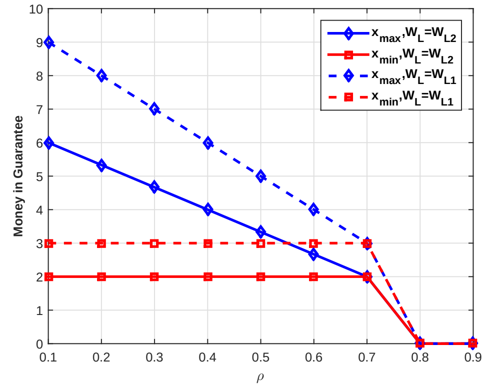

Fig. 3. Guarantee vs. ρ

pay the expected reward to the selected CP UE if the D2D content sharing succeeds. We can see that W_{L1} leads to a lower CP utility than W_{L2} because it offers a lower expected reward. When ρ is zero, there is no high type CP, both the expected reward in *RS* and the reward in *SCSI* are W_L, so the two utilities will be the same. In *SCSI*, when ρ approaches 1, there are more high-type CP UEs and the expected reward becomes very close to W_H . This leads to a reduced a desire of high-type CP UE to compete the high reward through sending signal. Therefore, when ρ approaches 1, signaling stops and the CP utilities of *SCSI* and *RS* will become the same again. Although the CP utility of *SCSI* is lower for W_{L1} than for W_{L2} , the utility gain of *SCSI* over *RS* is higher for W_{L1} as compared with that for W_{L2}.

B. Guarantee

The upper and lower bounds of x calculated in (11) are plotted versus ρ in Fig. 3. We can see that W_{L1} results in larger values of upper and lower bounds of x as compared with W_{L2}. Since the lower W_L causes a lower expected reward in the pooling status, and θ_H-type CP UEs are more eager to be selected by increasing the guarantee value. The minimum value of x (x_{min}) maintains constant while the maximum value (x_{max}) decreases with ρ for both W_{L1} and W_{L2}. This is because x_{min} is the lowest cost for a high-type CP UE to distinguish itself from the low-type CP UEs and could not be reduced any further. When ρ increases, there are more high-type CP UEs, the expected reward increases, and the desire of individual θ_H-type CP UEs to be distinguished from θ_H-type ones reduces, so x_{max} decreases. When x_{max} is equal to x_{min}, the θ_H-type CP UEs will stop sending signals and the guarantee goes down to 0.

V. Conclusion

In this letter, we adopt the signaling from microeconomics to design an incentive mechanism for D2D content-sharing in cellular networks. We propose a *SCSI* mechanism to motivate UEs to participate in D2D content sharing, and calculate the optimal signal (guarantee) for each CP UE to achieve Separating Equilibrium. Simulation results show that the *SCSI* mechanism can increase the the CP UE's utility and that the guarantee shall be adjusted according to the percentage of high type content providers and BS offered reward values. The signaling overhead and time delay of the *SCSI* will be studied in our future work.

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