A Cooperative D2D Content Sharing Scheme Using NOMA Under Social Ties

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***Abstract*— With the merit of bypassing the base station (BS) to directly communicate between user equipment (UE), D2D content sharing between socially connected users has revealed promising potential in future networks. However, D2D receivers (DRs) in different D2D pairs (DPs) may also have demand for additional content sharing services from the D2D transmitters (DTs), who also have considerable social ties with them, in other surrounding DPs to enhance or supplement their received sharing services. In this letter, we propose a cooperative D2D content sharing scheme using NOMA technique under social ties, where the DRs in different DPs, who have social similarities in interested files, separately spare a portion of the transmit power of their corresponding DT to each other to improve the received sharing services in DRs. Based on this, the performance of the proposed scheme underlaying cellular network with partial channel state information (CSI) is analyzed, which is suitable for distributed deployment. Finally, the simulations validate the effectiveness of our proposed scheme.**

***Index Terms*— D2D communication, cooperative sharing, NOMA, social tie.**

I. Introduction

DEVICE-TO-DEVICE (D2D) communication endows user equipment (UE) with the ability to bypass the base station (BS) to directly communicate with each other, which reveals significant advantages in saving communication resources, enabling efficient content sharing, etc [1]. Particularly, the underlay D2D communication features in reusing cellular spectrum to improve the system spectral efficiency. With those inherent advantages in saving energy and scarce spectrum, D2D content sharing has revealed great potential in the multimedia era and thus attracted researchers to focus on the sharing schemes, resource allocation, etc [2], [3]. Consider that there exist two D2D pairs (DPs) in proximity, where each D2D transmitter (DT) is dedicated for providing content sharing service to its corresponding D2D receiver (DR), where the DT and DR are correspondingly called the provider and demander in the social domain. However, in the social domain, there also exist considerable social ties between the DTs and DRs who belong to different DPs [3], which means that they also have social similarities in interested files. In another word, apart from the existing sharing links in two DPs, the DRs may also want to receive content sharing services from the DTs in other DPs. However, most existing D2D sharing schemes generally ignore the potential need for diverse content sharing services from multiple DTs or simply assume that multiple DTs exclusively provide sharing service to a single DR [2]–[4], which are apparently not efficient for providing sharing services and saving communication resources. Therefore, for the purpose of developing a more suitable scheme to impel the cooperative sharing between DPs, who have crossed social ties with each other, to enhance the received sharing services in DRs, we propose to invoke NOMA technique into the D2D content sharing scheme to tackle this issue.

Except for the same merit of improving spectral efficiency as underlay D2D communication, NOMA can provide multiple access to users simultaneously on the same spectrum by employing successive interference cancellation (SIC) technology [5]. Therefore, some researchers attempt to invoke NOMA into D2D communication to provide multiple access as well as further improve the spectral efficiency, where a DT can transmit to multiple DRs within a NOMA-based D2D group [6]. In a NOMA-based D2D group, the DT transmits superimposed signals to multiple DRs using the same time-frequency resource, then the DRs can subtract the undesired signals from the received signals during successful SIC process. However, for the scattered DPs that have no direct connections to the BS, existing works only involved the NOMA-based D2D communication under full CSI [6], [7], which is costly in collecting CSI and not practical for realizing NOMA-based D2D communication in a distributed manner. For the scattered DPs that have no direct connections to the BS in the cellular area, it can be pretty costly to collect the CSI of each communication and interference link to realize the centralized management. Therefore, it is necessary to dig into the performance of this NOMA-based cooperative D2D content sharing scheme under the condition of partial CSI, where the DPs cooperate by letting their DRs reciprocally spare a portion of the transmit power of their corresponding DTs to enhance their received sharing services based on NOMA technology.

In this letter, we propose the NOMA-based cooperative D2D content sharing under social ties for the first time. Herein, we adopt the social tie model in [3] to incorporate the content dimension and physical links between DTs and DRs, where the social tie (standing for the social similarities between users in interested files) acts as a weight on the physical link rate. In particular, for the scattered DPs that have no direct communication links to the BS, we consider a more practical scenario, where only partial CSI is available (i.e., a DR knows the full CSI of its communication links but only statistical CSI of other links), for the implementation of the proposed scheme in a distributed way. To this point, we present elaborated mathematical analysis of the proposed scheme and finally

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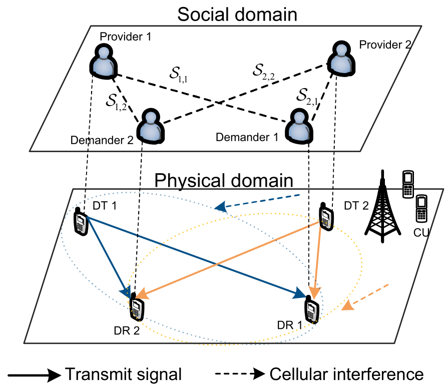


Fig. 1. System model of the cooperative D2D content sharing with NOMA under social ties underlaying cellular network.

derive practically computable analytical expressions of the expected communication rates. Then, analysis of the expected rate of the NOMA-based communication links between D2D transceivers is conducted, where the external interference from cellular users due to spectrum reusing and internal interference caused by NOMA are jointly considered. In addition, the conditions under which our proposed scheme can outperform the traditional scheme and OMA-based cooperative scheme are presented. Finally, numerical simulations validate the feasibility and effectiveness of the proposed scheme.

II. Network Model

We first consider a simplified D2D underlaid cellular network system in Fig. 1, where the NOMA-based cooperative D2D content sharing scheme is adopted.[1] Note that, as existing works [7], only 2-user NOMA is adopted here for practicability. As shown in Fig. 1, the social tie between DT $i \in \{1,2\}$ and DR $j \in \{1,2\}$, which reflects their social similarity in interested files in social domain, is denoted as $\mathcal{S}_{i,j} \in (0,1]$ [3]. With this content sharing model, while DT 1 is providing sharing service to DR 1, the social tie value $\mathcal{S}_{1,2}$ reveals that DR 2 could also have demand for the sharing service from DT 1 for their common interested files to enhance the received sharing service. Based on this, DR 1 and DR 2 can spare a portion of the transmit power of their corresponding DTs to each other to realize the cooperative content sharing between DPs. To quantify the content sharing service, the social-aware rate [3] is adopted here, which is a social tie value-weighted physical link rate. Apparently, the social similarity in interested files and physical link rate jointly determine the received content sharing service, for example, a close social tie does not promise good content sharing services when the physical link status is bad. Besides, each DT transmits by reusing the uplink spectrum of a cellular user (CU). In each DT, the signals to both DRs are superimposed on the same time and frequency resource, then the DRs can extract their desired signals after a successful SIC process. Note that, the successful SIC process is assumed to be perfect [6].

Unlike most existing works, we consider that the DRs can only obtain partial CSI, i.e., each DR can obtain full CSI of its corresponding communication links and only statistical CSI of the other communication and interference links. The Rayleigh fading channel model, which is commonly adopted in D2D communications [6], [8], is used here. Thus, the channel gain between DT i and DR j follows $g_{i,j} \sim exp(1/\lambda_{i,j})$, where the exponential distribution coefficient is generally related to the distance and path-loss exponent. Besides, the transmit power of DT i is denoted as p_i. Similarly, the received interference on the communication link between i and j is denoted by $p_i^c g_{i,j}^c$, where p_i^c is the transmit power of the cellular user whose uplink spectrum is reused by DT i, and $g_{i,j}^c \sim exp(1/\lambda_{i,j}^c)$.

[1]This simplified model, which can be generalized into the scenario where multiple DPs and CUs coexist, is adopted here to distinguish the proposed scheme.

III. Performance of the Proposed Scheme

A. Social-Aware Rate of D2D Links

Consider the cooperative content sharing model depicted in Fig. 1, the received content sharing services in DR $j \in \{1,2\}$ comes from two D2D links. The social tie values between D2D users can be easily obtained according to their social similarities in their interested files [3], thus our focus is deriving the physical link rates of D2D links in DRs with limited CSI. For each D2D link, the DR will first attempt to apply SIC to subtract the interference caused by NOMA, once the SIC process fails, the DR can only decode the desired signal under the interference caused by NOMA. Generally, for a D2D link between DT $i \in \{1,2\}$ and DR $j \in \{1,2\}$, the SIC process in DR j is successful when the received signal-to-interference-plus-noise ratio (SINR) of the signal for $j' = \{1,2\}\backslash j$ in DR j is not smaller than that in $j' = \{1,2\}\backslash j$, i.e.,

$$\frac{\alpha_{i,j'} p_i g_{i,j}}{p_i^c g_{i,j}^c + \alpha_{i,j} p_i g_{i,j} + n} \geq \frac{\alpha_{i,j'} p_i g_{i,j'}}{p_i^c g_{i,j'}^c + \alpha_{i,j} p_i g_{i,j'} + n}, \quad (1)$$

where $\alpha_{i,j'}$ is power allocation coefficient, n is the noise power. After simplifications, we have the condition of successful SIC on DT i's signals in DR j as

$$g_{i,j}(p_i^c g_{i,j'}^c + 1) \geq g_{i,j'}(p_i^c g_{i,j}^c + 1), \quad (2)$$

where the noise is normalized as 1.

Thus, for a D2D link between DT $i \in \{1,2\}$ and DR $j \in \{1,2\}$, its achievable rate can be separately expressed in two cases:

1) Case I: The DR can successfully subtract the interference caused by NOMA through SIC if (2) is satisfied, thus the amount of received content sharing service, i.e., the social-aware rate can be expressed as

$$r_{i,j}^s = \mathcal{S}_{i,j} \cdot \log(1 + \frac{\alpha_{i,j} p_i g_{i,j}}{1 + p_i^c g_{i,j}^c}), \quad (3)$$

where $\log(\cdot)$ represents the natural logarithm function.

2) Case II: The DR fails in subtracting the interference caused by NOMA during the SIC process, then we have

$$r_{i,j}^s = \mathcal{S}_{i,j} \log(1 + \frac{\alpha_{i,j} p_i g_{i,j}}{1 + \alpha_{i,j'} p_i g_{i,j} + p_i^c g_{i,j}^c}), \quad (j' = \{1,2\}\backslash j). \quad (4)$$

B. Expectation of Communication Rates

In the partial CSI scenario, a DR knows the full CSI of its communication link and only statistical CSI of other communication and interference links. Recall the expressions of the social-aware rates of D2D links in the above subsection, thus the expectation of the received social-aware rate in DR j can be expressed as

$$\bar{r}_j^s = E\{r_{i,j}^s + r_{i',j}^s | g_{i,j}, g_{i',j}\}, \quad (i' = \{1,2\} \setminus i), \quad (6)$$

which can be further expressed as $E\{r_j^s\} = E\{r_{i,j}^s | g_{i,j}\} + E\{r_{i',j}^s | g_{i',j}\}$.

Recall the SIC condition in the above subsection, $E\{r^s_{i,j}|g_{i,j}\}$ can be jointly expressed considering the successful and failed cases, i.e., (7), as shown at the bottom of the page.

In terms of the mathematical expectation expression $Q^1_{i,j}$, let us define random variables $X = g^c_{i,j}, Y = g^c_{i,j'}, Z = g_{i,j'}$, thus it can be calculated through the integral operation in (5), as shown at the bottom of the page, which is composed of $Q^{11}_{i,j}$ and $Q^{12}_{i,j}$.

As for $Q^{11}_{i,j}$, it can be evaluated as

$$\begin{aligned}Q^{11}_{i,j} &= \int_{x=0}^{\infty}\log\left(\frac{1+p^c_i x+\alpha_{ij}p_i g_{ij}}{1+p^c_i x}\right)\lambda^c_{ij}e^{-\lambda^c_{ij}x}dx\\ &= \log(1+\alpha_{i,j}p_i g_{i,j}) + e^{\frac{\lambda^c_{i,j}}{p^c_i}}\mathrm{Ei}\left(-\frac{\lambda^c_{i,j}}{p^c_i}\right)\\ &\quad -e^{\frac{\lambda^c_{i,j}}{p^c_i}(1+\alpha_{i,j}p_i g_{i,j})}\mathrm{Ei}\left(-\frac{\lambda^c_{i,j}}{p^c_i}(1+\alpha_{i,j}p_i g_{i,j})\right), \quad (8)\end{aligned}$$

where $\mathrm{Ei}(-x) = -\int_x^{\infty}(1/t)e^{-t}dt,\ x > 0$, is the exponential integral function [9], which can be calculated through Taylor series expansion as $\mathrm{Ei}(-x) = C + \ln x + \sum_{n=1}^{\infty}\frac{(-x)^n}{n\cdot n!}$, where C is Euler's constant.

By observing the expression of $Q^{11}_{i,j}$, it actually stands for the expectation of the physical communication rate between DT i and DR j under the condition that the SIC process is always successful (i.e., with probability 1).

Besides, let us concentrate on $Q^{12}_{i,j}$, for the double integral of the complicated function, which is hard to obtain the closed-form result, we first calculate the integral about variable y and transform it, thus we have

$$\begin{aligned}&Q^{12}_{ij}\\ &= \int_{x=0}^{\infty}\log(1+\frac{\alpha_{ij}p_i g_{i,j}}{1+p^c_i x})\left(\int_{y=0}^{\infty}e^{-\lambda_{ij'}g_{ij}\frac{p^c_i y+1}{p^c_i x+1}-\lambda^c_{ij'}y}\lambda^c_{i,j'}dy\right)\\ &\quad \cdot\lambda^c_{i,j}e^{-\lambda^c_{i,j}x}dx\\ &= -\int_0^{\infty}\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+p^c_i x})\frac{\lambda^c_{i,j'}e^{-\frac{\lambda_{i,j'}g_{i,j}}{p^c_i x+1}}}{\lambda^c_{i,j'}+\frac{\lambda_{i,j'}g_{i,j}p^c_i}{p^c_i x+1}}d(e^{-\lambda^c_{i,j}x})\\ &= \log(1+\alpha_{i,j}p_i g_{i,j})\frac{\lambda^c_{i,j'}e^{-\lambda_{i,j'}g_{i,j}}}{\lambda^c_{i,j'}+\lambda_{i,j'}g_{i,j}p^c_i}\\ &\quad \underbrace{+\int_0^{\infty}e^{-\lambda^c_{i,j}x}\left[\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+p^c_i x})\frac{\lambda^c_{i,j'}e^{-\frac{\lambda_{i,j'}g_{i,j}}{p^c_i x+1}}}{\lambda^c_{i,j'}+\frac{\lambda_{i,j'}g_{i,j}p^c_i}{p^c_i x+1}}\right]'dx,}_{Q^{121}_{i,j}}\end{aligned} \quad (9)$$

where the operation $'$ stands for taking derivation. For the above integral $Q^{121}_{i,j}$ on the open interval $[0,\infty)$, it is practically incalculable, thus, we propose to transform it into the integral on a closed interval, which can be practically computed and evaluated. We introduce the reciprocal of the normalized received interference and noise, i.e., $\hat{x} = 1/(p^c_i x + 1)$, which ranges during the interval $(0, 1]$. Thus, we have $Q^{121}_{i,j} \triangleq -\int_{\hat{x}\to 0}^{1} f^{121}_{i,j}(\hat{x})d\hat{x}$ according to (10), as shown at the bottom of the page.

For $f^{121}_{i,j}(\hat{x})$, it is obvious that $\lim_{\hat{x}\to 0} f^{121}_{i,j}(\hat{x}) = 0 < \infty$, thus we additionally define $f^{121}_{i,j}(0) \triangleq 0$. For the continuous function $f^{121}_{i,j}(\hat{x})$ on a nonempty closed interval $[0, 1]$, its integral can be approximated by composite Simpson rule [10] as

$$\int_{\hat{x}=0}^{1} f^{121}_{ij}(\hat{x})d\hat{x} \approx \sum_{k=1}^{m}\frac{h}{3}\left[f^{121}_{ij}(\hat{x}_{2k-2})+4f^{121}_{i,j}(\hat{x}_{2k-1})+f^{121}_{i,j}(\hat{x}_{2k})\right], \quad (11)$$

where $h = \frac{1}{2m}$ $(m \geq 2)$, $\hat{x}_i = ih$.

Therefore, the expectation of the physical link rate under the condition of successful SIC, i.e., $Q^1_{i,j}$, can be calculated

$$\begin{aligned}Q^1_{i,j} &= \int_{y=0}^{\infty}\int_{x=0}^{\infty}\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+p^c_i x})\int_{z=0}^{g_{i,j}\frac{p^c_i y+1}{p^c_i x+1}}\lambda_{i,j'}e^{-\lambda_{i,j'}z}dz\cdot\lambda^c_{i,j}e^{-\lambda^c_{i,j}x}dx\cdot\lambda^c_{i,j'}e^{-\lambda^c_{i,j'}y}dy\\ &= \underbrace{\int_{x=0}^{\infty}\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+p^c_i x})\cdot\lambda^c_{i,j}e^{-\lambda^c_{i,j}x}dx}_{Q^{11}_{i,j}} - \underbrace{\int_0^{\infty}\int_0^{\infty}\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+p^c_i x})e^{-\lambda_{i,j'}g_{i,j}\frac{p^c_i y+1}{p^c_i x+1}}\lambda^c_{i,j}e^{-\lambda^c_{i,j}x}dx\cdot\lambda^c_{i,j'}e^{-\lambda^c_{i,j'}y}dy}_{Q^{12}_{i,j}}\end{aligned} \quad (5)$$

$$\begin{aligned}E\{r^s_{i,j}|g_{i,j}\} &= \mathcal{S}_{i,j}\cdot\underbrace{E\{\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+p^c_i g^c_{i,j}})|g_{i,j'} \leq \frac{p^c_i g^c_{i,j'}+1}{p^c_i g^c_{i,j}+1}g_{i,j}, g_{i,j}\}}_{Q^1_{i,j}}\\ &\quad +\mathcal{S}_{i,j}\cdot\underbrace{E\{\log(1+\frac{\alpha_{i,j}p_i g_{i,j}}{1+\alpha_{i,j'}p_i g_{i,j}+p^c_i g^c_{i,j}})|g_{i,j'} > \frac{p^c_i g^c_{i,j'}+1}{p^c_i g^c_{i,j}+1}g_{i,j}, g_{i,j}\}}_{Q^2_{i,j}}.\end{aligned} \quad (7)$$

$$f^{121}_{i,j}(\hat{x}) = e^{-\frac{\frac{1}{\hat{x}}-1}{p^c_i}\lambda^c_{ij}}\left[\frac{\alpha_{ij}p_i g_{ij}\lambda^c_{ij'}e^{-\lambda_{ij'}g_{ij}\hat{x}}}{(1+\alpha_{ij}p_i g_{ij}\hat{x})(\lambda^c_{ij'}+\lambda_{ij'}g_{ij}p^c_i\hat{x})} - \log(1+\alpha_{ij}p_i g_{i,j}\hat{x})\frac{\lambda_{ij'}g_{i,j}\lambda^c_{i,j'}e^{-\lambda_{ij'}g_{i,j}\hat{x}}}{\lambda^c_{i,j'}+\lambda_{i,j'}g_{ij}p^c_i\hat{x}}\left(1+\frac{p^c_i}{\lambda^c_{ij'}+\lambda_{ij'}g_{ij}p^c_i\hat{x}}\right)\right] \quad (10)$$

$$\begin{aligned}f^2_{ij}(\hat{x}) &= e^{-\frac{\lambda^c_{ij}}{p^c_i}(\frac{1}{\hat{x}}-1)}\left[\frac{-\alpha_{i,j}p_i g_{i,j}\lambda^c_{i,j'}e^{-\lambda_{ij'}g_{i,j}\hat{x}}}{(\hat{x}+p_i g_{ij})(\hat{x}+\alpha_{ij'}p_i g_{ij})(\lambda^c_{ij'}+\lambda_{ij'}g_{ij}p^c_i\hat{x})} - \log(\frac{p_i g_{i,j}+1/\hat{x}}{\alpha_{i,j'}p_i g_{ij}+1/\hat{x}})\frac{\lambda_{i,j'}g_{i,j}\lambda^c_{i,j'}e^{-\lambda_{i,j'}g_{i,j}\hat{x}}}{\lambda^c_{ij'}+\lambda_{i,j'}g_{ij}p^c_i\hat{x}}\right.\\ &\quad \left.\times\left(1+\frac{p^c_i}{\lambda^c_{ij'}+\lambda_{ij'}g_{ij}p^c_i\hat{x}}\right)\right]\end{aligned} \quad (13)$$

Algorithm 1 Searching Algorithm for Determining the Power Coefficients of NOMA

Initialize: For DR j and j', initialize $\alpha_{i,j} = 1$ and $\alpha_{i',j'} = 1$, define searching step δ, difference threshold ϵ of performance gains;
do
  Let $\alpha_{i,j} = \alpha_{i,j} - \delta$ and $\alpha_{i',j'} = \alpha_{i',j'} - \delta$;
while *both* $\bar{r}^s_j - \bar{r}^{s\_nocoop}_j$ *and* $\bar{r}^s_{j'} - \bar{r}^{s\_nocoop}_{j'}$ *do not decrease*;
while $|(\bar{r}^s_j - \bar{r}^{s\_nocoop}_j) - (\bar{r}^s_{j'} - \bar{r}^{s\_nocoop}_{j'})| > \epsilon$ **do**
  if $\bar{r}^s_j - \bar{r}^{s\_nocoop}_j > \bar{r}^s_{j'} - \bar{r}^{s\_nocoop}_{j'}$ **then**
    Randomly let $\alpha_{i,j} = \alpha_{i,j} - \delta$ or $\alpha_{i',j'} = \alpha_{i',j'} + \delta$;
  else
    Randomly let $\alpha_{i',j'} = \alpha_{i',j'} - \delta$ or $\alpha_{i,j} = \alpha_{i,j} + \delta$;
  end
end
Return allocation results $\alpha^*_{i,j} = \alpha_{i,j}$, $\alpha^*_{i',j'} = \alpha_{i',j'}$.

according to (5), (8), (9), (11). Similarly, for $Q^2_{i,j}$, we have

$$Q^2_{i,j} = \log(\frac{1+p_i g_{i,j}}{1+\alpha_{ij'} p_i g_{ij}}) \frac{\lambda^c_{i,j'} e^{-\lambda_{i,j'} g_{i,j}}}{\lambda^c_{i,j'} + \lambda_{ij'} g_{ij} p^c_i} - \int_{\hat{x}=0}^{1} f^2_{ij}(\hat{x}) d\hat{x}, \tag{12}$$

where $f^2_{i,j}(\cdot)$ is expressed in (13), as shown at the bottom of the previous page, and $f^2_{i,j}(0)$ is defined with value 0. Thus, the expected social aware rate of DR j and j' are $\bar{r}^s_j = \mathcal{S}_{i,j}(Q^1_{i,j} + Q^2_{i,j}) + \mathcal{S}_{i',j}(Q^1_{i',j} + Q^2_{i',j})$, $\bar{r}^s_{j'} = \mathcal{S}_{ij'}(Q^1_{i,j'} + Q^2_{i,j'}) + \mathcal{S}_{i'j'}(Q^1_{i',j'} + Q^2_{i'j'})$, $(i' = \{1,2\} \setminus i)$.

By observing $\bar{r}^s_j$ and $\bar{r}^s_{j'}$, it is easy to have the following theorem on them. Compared with traditional sharing schemes, like using traditional OMA to provide simultaneous sharing service, the effectiveness of our proposed NOMA-based cooperative sharing scheme under social ties can be judged by the following.

Firstly, compared with traditional D2D content sharing, we have Theorem 1.

Theorem 1: The proposed scheme is only effective when $\bar{r}^s_j > \bar{r}^{s\_nocoop}_j \triangleq \mathcal{S}_{i,j} Q_{i,j}$, $(i = j)$ *and* $\bar{r}^s_{j'} > \bar{r}^{s\_nocoop}_{j'} \triangleq \mathcal{S}_{i'j'} Q_{i',j'}$, $(i' = j')$ *holds, where*

$$Q_{i,j} = \Bigg[\log(1+p_i g_{i,j}) + e^{\frac{\lambda^c_{i,j}}{p^c_i}} \mathrm{Ei}\left(-\frac{\lambda^c_{i,j}}{p^c_i}\right) - e^{\frac{\lambda^c_{i,j}}{p^c_i}(1+p_i g_{ij})} \mathrm{Ei}\left(-\frac{\lambda^c_{i,j}}{p^c_i}(1+p_i g_{i,j})\right)\Bigg]. \tag{14}$$

Besides, we also have a similar theorem for comparing with OMA-based schemes in the following.

Theorem 2: For both DRs, the proposed scheme is superior to the OMA scheme when $\bar{r}^s_j > \mathcal{S}_{i,j} Q^{OMA}_{i,j} + \mathcal{S}_{i',j} Q^{OMA}_{i',j}$ *and* $\bar{r}^s_{j'} > \mathcal{S}_{ij'} Q^{OMA}_{i,j'} + \mathcal{S}_{i'j'} Q^{OMA}_{i',j'}$ *hold, where* $Q^{OMA}_{i,j} = \frac{1}{2} Q_{i,j}$.

C. Application of the Proposed Scheme

Note that, the social-aware rate of DRs ($\bar{r}^s_j$ and $\bar{r}^s_{j'}$) have a conflict of interest with each other, but there exists a tradeoff area of the allocation of power coefficients in NOMA. Since the consideration of partial CSI and the derived practically computable results make our work suitable for implementing in a distributed way. Thus, for any given transmit power in DTs,[2] the DRs only require appropriate power coefficients (i.e., $\alpha_{i,j}$) to evaluate if the cooperative sharing scheme is effective compared with traditional sharing schemes. Therefore, a simple searching method can be applied in DRs to determine if the proposed cooperative sharing scheme is feasible. For simplicity, we recognize reaching identical maximal performance gain over not using the cooperative sharing scheme in both DRs as the optimal situation. It is easy to find that the social-aware rate of each D2D link is monotonically increasing with the corresponding power coefficient in NOMA. Therefore, for two DPs attempting to apply the NOMA-based content sharing scheme (denoted as DT i and DR j, DT i' and DR j'), we can easily derive a searching method as Algorithm 1. Then, each DP can obtain a list of the DPs that it can cooperate with.

Finally, for the DPs that can obtain performance gains by applying the proposed scheme, each DP can choose the optimal one (i.e., the one that brings the highest performance gain) from its candidate DPs for establishing cooperative content sharing until no new cooperation can be established.

TABLE I
SOCIAL TIE VALUE SETTINGS

Social ties \ i,j	$1,1$	$1,2$	$2,2$	$2,1$
$\mathcal{S}^1_{i,j}$	0.6	0.35	0.6	0.35
$\mathcal{S}^2_{i,j}$	0.5	0.45	0.5	0.45

IV. NUMERICAL RESULTS

In this section, we present numerical simulations to evaluate the proposed scheme. In the simulations, 50 CUs and $20 \sim 50$ DPs are randomly deployed in the cellular area with a radius of 300 meters, and the social tie values between D2D users are also randomly set. The maximum transmit power of UE is set as 23dBm, the D2D communication range is set as 50 meters, and the path-loss exponent is 3. To initialize the system, the spectrum reusing is determined based on interference channel gains [11], and the transmit power of DTs are allocated to maximize the achievable rate of DPs while ensuring the quality of service of CUs [12]. Moreover, we elaborately choose examples of social ties settings shown in Table I of two cooperative DPs to distinguish the performance features of the proposed scheme in the 2-dimensional space. Without loss of generality, the power coefficients of NOMA satisfy $\sum_{j \in \{1,2\}} \alpha_{i,j} = 1$ for any pair of cooperative DPs. For comparison, the traditional content sharing without cooperation between DPs and the OMA-based cooperation scheme are adopted, where the power consumptions are identical in these involved schemes. The simulations are repeated 100 times for averaging.

Firstly, to distinguish the superiority of the proposed scheme, we compare the proposed scheme with the OMA-based scheme in Fig. 2 under $\mathcal{S}^2_{i,j}$ by choosing a pair of

[2]Note that, using NOMA will neither change the transmit power nor cause more interference to CUs, since only the power coefficients are introduced to split the total power to NOMA users.

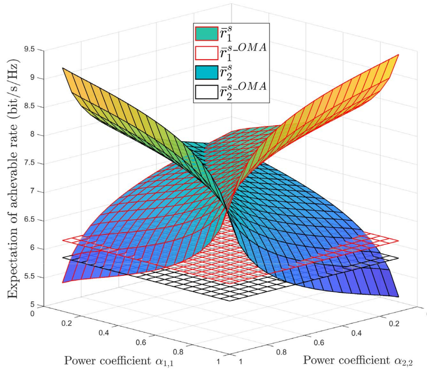
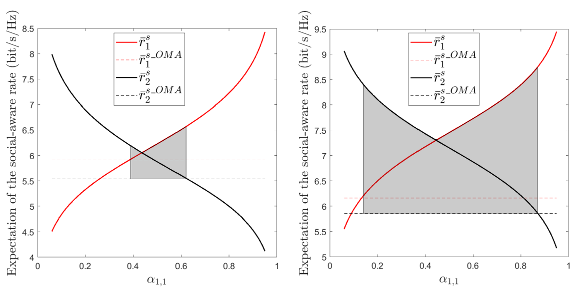


Fig. 2. Expectation of the achievable social-aware rate of DRs under $\mathcal{S}_{i,j}^2$.



(a) Under $\mathcal{S}_{i,j}^1$ (b) Under $\mathcal{S}_{i,j}^2$

Fig. 3. Expectation of the achievable social-aware rate under different social ties.

cooperative DPs as an example. It is easy to find that the DRs in both DPs actually compete for their own benefit while sparing the transmit power of their corresponding DTs to other DRs. However, there exists a tradeoff area within which both DRs can be better off compared with the OMA-based scheme.

In addition, we also choose a cross profile of Fig. 2 to make the comparison results more intuitive, where the power coefficients satisfy $\alpha_{1,1} + \alpha_{2,2} = 1$. Therein, the social tie values are set according to Table I. By observing the subgraphs of Fig. 3, only the intersection of two curves are above the two straight horizontal lines (i.e., OMA scheme), there exists a value range under which both DRs are satisfied and willing to accept the cooperative sharing scheme. Besides, with a larger social tie value gap between $\mathcal{S}_{i,j}$ $(i \neq j)$ and $\mathcal{S}_{i,j}$ $(i = j)$, the feasible area narrows down, and meanwhile, the performance superiority is decreasing. Thus, a larger social tie value gap between DT i to DR j $(i = j)$ and DT i to DR j $(i \neq j)$ is beneficial for obtaining more performance gains over traditional schemes. With a larger tradeoff area, there exist more potential to obtain higher performance gain for the cooperative DPs.

Moreover, the overall D2D content sharing performance is depicted in Fig. 4. With the increasing number of DPs, the performance gap between the proposed cooperative content sharing scheme and the non-cooperation scheme enlarges. This is because, with more DPs deployed, those DPs will have more chances to apply the cooperative sharing scheme to enhance the content sharing services. This feature reveals the great potential of the proposed scheme in improving the

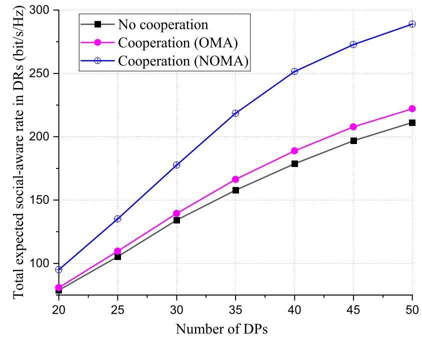


Fig. 4. Total expected social-aware rate in DRs vs. different number of DPs.

content sharing service in future networks where D2D content sharing is commonly used. Besides, we can also find that the performance gain of OMA-based scheme is marginal.

V. Conclusion

In this letter, we propose a cooperative D2D content sharing scheme using NOMA under social ties. To analyze the performance of this scheme, we derive the mathematical expectation of the social-aware rates of underlay D2D links with partial CSI, where the derived results are easy to compute in practice and suitable for distributed implementation. Finally, the feasibility and effectiveness of the proposed scheme are validated with simulations.

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