Transmission Capacity Analysis of Relay-Assisted Device-to-Device Overlay/Underlay Communication

Yang Yang, *Member, IEEE*, Yuan Zhang, *Member, IEEE*, Linglong Dai, *Senior Member, IEEE*, Jianjun Li, Shahid Mumtaz, *Senior Member, IEEE*, and Jonathan Rodriguez, *Senior Member, IEEE*

***Abstract*—Device-to-device (D2D) communication can effectively meet the demanding high data rate by providing direct links among mobile users in cellular networks. In this paper, we analyze the transmission capacity of relay-assisted D2D communication coexisting with cellular networks in both overlay and underlay modes. D2D users can use the delicate spectrum resources in the overlay mode, while reuse the cellular resources in the underlay mode. Based on stochastic geometry, cellular users, D2D transmitters, and relay nodes (RNs) in the networks are all modeled as Poisson point process. Then, we calculate the RN existence probability and the expectation of relay link distance to obtain the successful transmission probabilities for D2D communication. According to two relay mechanisms for enhancing D2D transmission distance, we further obtain the transmission capacities of D2D communication with the assistance of RNs in both two modes, which reflect the influence from D2D density and power. In addition, the D2D transmission capacities with variable D2D link distance are also analyzed in two modes. Simulation results verify that D2D transmission capacity can be enhanced by relay transmission and influenced by a multitude of factors, including the user density, power, the D2D link distance, and the way of using RNs.**

***Index Terms*—Device-to-device (D2D) communication, relay, stochastic geometry, transmission capacity.**

Manuscript received August 9, 2016; revised September 30, 2016; accepted October 8, 2016. Date of publication October 18, 2016; date of current version February 6, 2017. This work was supported in part by the National Key Basic Research Program of China under Grant 2013CB329203, in part by the National Natural Science Foundation of China under Grant 61571270 and Grant 61271266, in part by the China Postdoctoral Science Foundation under Grant 2016M591177, and in part by the British Telecom and Tsinghua SEM Advanced ICT LAB. Paper no. TII-16-0630. *(Corresponding author: L. Dai.)*

Y. Yang, Y. Zhang, and L. Dai are with the Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China (e-mail: yy0553@mail.tsinghua.edu.cn; zhang.yuan0313@163.com; daill@tsinghua.edu.cn).

J. Li is with the School of Electric and Information Engineering, Zhongyuan University of Technology, Zhengzhou 450007, China (e-mail: jianjun.li@tsinghua.org.cn).

S. Mumtaz and J. Rodriguez are with the Instituto de Telecomunicações, Aveiro 1049-001, Portugal (e-mail: smumtaz@av.it.pt; jonathan@av.it.pt).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TII.2016.2617921

I. Introduction

THE fast development of wireless communications leads to the shortage of spectrum resource, which becomes a bottleneck for the further explosive of wireless services [1]. The fifth generation (5G) networks have included a lot of new promising technologies such as nonorthogonal multiple access [2], massive MIMO [3], device-to-device (D2D) communication, and so on. As one of the key 5G technologies, D2D communication enables wireless transmission between users over the direct link, which brings a lot of advantages such as enhancing the transmission capacity, reducing the transmission power, improving spectrum, and so on [4]. Nevertheless, as D2D communication reuses the frequency resources, so it causes harmful interference to the existing network, which may lower the expected performance of the system [5]–[7].

As one of the fundamental performance index of the communication system, D2D transmission capacity has already been analyzed in some previous literature [8]–[11]. In order to enhance the capacity of cellular and D2D system, an interference-limited area control scheme to manage interference in the networks was proposed in [8]. Further, Yu *et al.* [9] investigated the resource allocation and power control between cellular and D2D users, which proposed an optimization method to improve the system capacity. Consider the complexity of the networks, the network capacity by a bidirectional data transmission was studied in [10]. In addition, with the extended consideration of cooperation communication in D2D, an optimal D2D transmission capacity was presented in [11], where D2D transmission can be assisted by cellular users in the networks.

On the other hand, relay technology [12] has been proposed as a way to enhance the capacity and coverage of wireless networks due to its spatial diversity. This technology can also be introduced into D2D communication to improve the system performance [13]. Hasan *et al.* [14] extended the analysis in a multirelay network and proposed a robust distributed resource allocation for D2D communication. Consider the spectrum sharing system, the outage probability with interference power constraints, and the outage probability of cognitive amplify-and-forward relay were analyzed in [15] and [16], respectively, where both of them indicate the large enhancement of the relay transmission. Moreover, a D2D retransmission scheme was applied in an intracluster D2D networks in [17], where D2D can adaptively select the number of cooperative relays to perform multicast retransmissions. Similar works are also shown in [18] and [19]. However, when the spatial isolation is sufficient, most existing works have not considered the important case that the relay links are allowed to reuse the same resources of the cellular network, which is indeed helpful to further improve the spectrum efficiency.

In this paper, the scenario that D2D communication can use potential relay nodes (RNs) to perform relay transmission in the network coexisting with cellular system is considered.[1] Those potential RNs are the mobile terminals, which are able to provide relay services for D2D communication. By utilizing the stochastic geometry, the cellular user, D2D transmitters, and RNs in the network are modeled by Poisson point process (PPP) with different densities. Then, the following two modes are analyzed in detail: 1) Overlay mode: Dedicated resources are allocated to D2D communication, cellular users and D2D users use orthogonal resources, thus, the interference does not exist between cellular users and D2D users; 2) Underlay mode: D2D communication reuses the same resources with cellular system, i.e., cellular users and D2D users share the resources, thus the interference is not only existed among the D2D users, but also between cellular and D2D communications.

For each mode, the effect of relay transmission is divided into two cases: transmission distance extension and transmission capacity improvement, which are analyzed, respectively. First, for the relay existence probability, the expectation of the relay link distance and the general form of successful transmission probability are derived. Then, the expressions of D2D transmission capacity in different modes with different mechanisms are obtained, which show the influence from D2D RNs. Furthermore, we derive the D2D transmission capacity gain with the assistance of D2D RNs. In addition, the transmission capacities with variable D2D link distance are analyzed in all cases. Finally, simulation results verify that D2D transmission capacity can be enhanced by the relay transmission, and such D2D transmission capacity is affected by some important factors including the user density, variable D2D link distance, and the way of using the relay in D2D transmission.

The rest of the paper is organized as follows. Section II describes the scenario and the system model. Section III presents the RN existence probability, the expectation of the relay link distance, and the general form of successful transmission probability. Sections IV and V analyze the D2D transmission capacity in overlay mode and underlay mode, respectively. Then, the simulation results are illustrated in Section VI. Finally, the conclusions are summarized in Section VII.

II. Scenario Description and System Model

In this section, we first explain the scenario of the relay-assisted D2D communication coexisting with cellular network, and then present the network and channel model in detail.

[1]Simulation codes are provided to reproduce the results presented in this paper: http://oa.ee.tsinghua.edu.cn/dailinglong/.

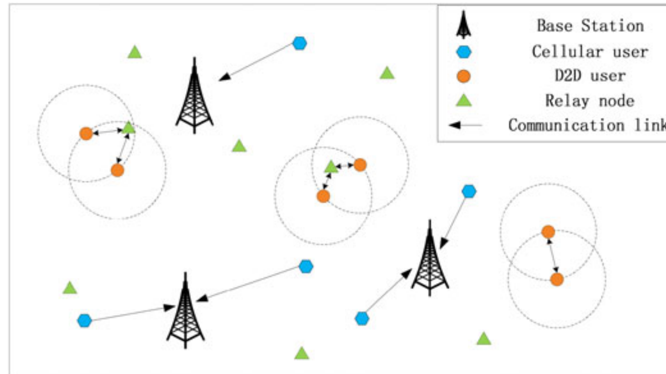

Fig. 1. Scenario of relay-assisted D2D communication in cellular networks.

A. Scenario Description

As shown in Fig. 1, the basic scenario contains cellular networks, D2D users, and potential RNs, which are denoted as S_0, S_1, and S_2, respectively. Cellular networks are deployed on the cellular frequency spectrum, and D2D communication reuses the uplink resources. The networks work in time division duplex (TDD) mode, and the cellular uplink frequency spectrum is divided into K frequency-flat subchannels by using orthogonal frequency division multiplexing technology. Both cellular and D2D users use full set of the subchannels in the networks.

B. Network Models

Based on the theory of stochastic geometry, the following assumptions are made:

Assumption 1: The cellular users form a stationary PPP on the two-dimensional plane $\Re$, which is denoted as Π_0 with density λ_0. The cellular transmission power is denoted as P_0.

Assumption 2: The transmitters of D2D users form a PPP which is denoted as Π_1 with density λ_1 on $\Re$. Each D2D transmitter is associated with a D2D receiver located at a distance R. The D2D transmission power is denoted as P_1.

Assumption 3: The potential RNs form a stationary PPP which is denoted as Π_2 with density λ_2 on $\Re$. The transmission power of RN is denoted as P_2. D2D communication can be forwarded by one of the RNs under the condition that the distances between the RN and either the D2D transmitter or the receiver are shorter than R. If more than one RN is available, the D2D pair randomly chooses one to the forward signals.

Assumption 4: According to Palm theory [20], a typical receiver of system S_j, $j \in \{0, 1, 2\}$ is assumed to be located in the origin, which does not influence the statistics of the PPP.

C. Channel Models

The propagation channel model can be expressed as

$$P_{rx} = \delta P_{tx} |D|^{-\alpha} \quad (1)$$

where P_{tx} and P_{rx} represent the transmitter and receiver power, respectively. δ stands for Rayleigh fading coefficient, which obeys an independent exponential distribution with unit mean

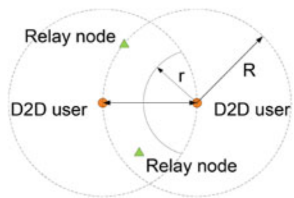

Fig. 2. D2D communication assisted by RNs.

for every communication link in the system, i.e., $\delta \sim exp(1)$. α is the path loss exponent, and $|D|$ is the distance between the transmitter and the receiver.

When D2D communication reuses the cellular resources, the typical receiver suffers from the interference generated by cellular users, D2D users, and RNs. In order to complete the subsequent deduction, we define δ_{jk} and X_{jk} to represent the Rayleigh fading coefficient and the distance from the origin to the interfering node k, $(k \in \Pi_j)$ in S_j, $j \in \{0, 1, 2\}$, respectively.

III. RN Existence Probability, the Expectation of Relay Link Distance and the General Form of Successful Transmission Probability

In this section, first, the RN existence probability and the expectation of relay link distance between two D2D users are deduced. Next, the general form of successful transmission probability of the receiver in system S_n, (n is 0, 1, or 2) is obtained.

A. RN Existence Probability and the Expectation of Relay Link Distance

According to assumption 3, D2D users utilize RNs to forward signals when RNs are located in the shadow region as shown in Fig. 2. The area of this region is given by

$$S = \left(2\pi/3 - \sqrt{3}\Big/2\right) R^2. \tag{2}$$

Because the density of potential RNs is λ_2, the RN existence probability $\Pr_e$ in the shadow region is

$$\Pr_e = 1 - e^{-\lambda_2 S} = 1 - e^{-\lambda_2 \left(\frac{2\pi}{3} - \frac{\sqrt{3}}{2}\right) R^2}. \tag{3}$$

The average link distance between D2D user and RN can be obtained by calculating the mathematical expectation. Let the distance between D2D user and RN is r, $(0 < r \leq R)$, we get the following lemma.

Lemma 1: The expectation of relay link distance $E(r)$ satisfies

$$E(r) = AR \tag{4}$$

where $A = (4\pi - 36\sqrt{3} + 64)\Big/(12\pi - 9\sqrt{3})$.

Proof: As the black arc showed in Fig. 2, the arc length $l(r)$ with D2D user as center and r as radius cross the shadow region is $l(r) = 2r \arccos(\frac{r}{2R})$. Because the RN is uniform-distributed in the shadow region, the probability density function (pdf) of r is $f(r) = \frac{l(r)}{S} = \frac{2r \arccos(\frac{r}{2R})}{(\frac{2\pi}{3} - \frac{\sqrt{3}}{2})R^2}$. Then, the expectation of distance between D2D user and RN is

$$\begin{aligned} E(r) &= \int_0^R r f(r)\, dr = \int_0^R \frac{12r^2 \arccos\left(\frac{r}{2R}\right)}{\left(4\pi - 3\sqrt{3}\right) R^2} dr \\ &\overset{(a)}{=} \frac{96R}{4\pi - 3\sqrt{3}} \int_0^{\frac{1}{2}} x^2 \arccos(x)\, dx \\ &\overset{(b)}{=} \frac{4\left(\pi - 9\sqrt{3} + 16\right) R}{12\pi - 9\sqrt{3}} \end{aligned} \tag{5}$$

where (a) is the substitution of $x = \frac{r}{2R}$, (b) is the result according to [21, eq. (2.833)]. Make $A = \frac{4(\pi - 9\sqrt{3} + 16)}{12\pi - 9\sqrt{3}}$, the result (4) is obtained. ∎

B. General Form of Successful Transmission Probability

In order to obtain the general form of successful transmission probability, all three kinds of interferences from cellular users, D2D users, and RNs are considered. Because the spectrum sharing of D2D users and RNs are the main consideration, which means the whole networks are interference-limited and the thermal noise is negligible. The signal-to-interference ratio (SIR) of system S_n, (n is 0, 1, or 2) at the typical receiver can be expressed

$$\mathrm{SIR}_n = \frac{P_n \delta_{n0} R_{n0}^{-\alpha}}{\sum_{j \in \{0,1,2\}} I_j} \tag{6}$$

where $I_j = (P_j \big/ P_n) \sum_{k \in \Pi_j} \delta_{jk} |X_{jk}|^{-\alpha}$, δ_{n0} and R_{n0} are the Rayleigh fading and the distance from the desired transmitter to the typical receiver of S_n, respectively.

In order to guarantee the reliability of the transmission, the SIR of the receiver in S_n, (n is 0, 1, or 2) should satisfy $\mathrm{SIR}_n \geq T_n$, where T_n is the SIR threshold of S_n. Then, the following lemma shows the general form of successful transmission probability.

Lemma 2: The general form of successful transmission probability of a typical receiver in S_n, (n is 0, 1, or 2) satisfies

$$\Pr(SIR_n \geq T_n) = e^{-C_\alpha T_n^{\frac{2}{\alpha}} R_{n0}^2 \sum_{j \in \{0,1,2\}} \lambda_j \left(\frac{P_j}{P_n}\right)^{\frac{2}{\alpha}}} \tag{7}$$

where $C_\alpha = \pi \Gamma(1 + \frac{2}{\alpha}) \Gamma(1 - \frac{2}{\alpha})$.

Proof: From (6), the successful transmission probability satisfies

$$\begin{aligned} \Pr(\mathrm{SIR}_n \geq T_n) &= \Pr\left(\delta_{n0} \geq T_n R_{n0}^\alpha (I_0 + I_1 + I_2)\right) \\ &= \int_0^\infty e^{-s T_n R_{n0}^\alpha} d\left[\Pr(I_0 + I_1 + I_2 \leq s)\right] \\ &= \psi_{I_0}(T_n R_{n0}^\alpha)\, \psi_{I_1}(T_n R_{n0}^\alpha)\, \psi_{I_2}(T_n R_{n0}^\alpha) \end{aligned} \tag{8}$$

where $\psi_{I_0}(\cdot)$, $\psi_{I_1}(\cdot)$ and $\psi_{I_2}(\cdot)$ are Laplace transformation of I_0, I_1, and I_2, respectively. Because δ_{n0} satisfies independent exponential distribution, we have [22]

$$\psi_{I_0}(s) = e^{-\lambda_0 \pi \left(\frac{s P_0}{P_n}\right)^{\frac{2}{\alpha}} \Gamma\left(1 + \frac{2}{\alpha}\right) \Gamma\left(1 - \frac{2}{\alpha}\right)} \tag{9}$$

where $\Gamma(\cdot)$ is the gamma function with the form $\Gamma(z) = \int_0^\infty e^{-t}t^{z-1}dt$. Similarly

$$\psi_{I_1}(s) = e^{-\lambda_1\pi\left(\frac{sP_1}{P_n}\right)^{\frac{2}{\alpha}}\Gamma\left(1+\frac{2}{\alpha}\right)\Gamma\left(1-\frac{2}{\alpha}\right)} \quad (10)$$

$$\psi_{I_2}(s) = e^{-\lambda_2\pi\left(\frac{sP_2}{P_n}\right)^{\frac{2}{\alpha}}\Gamma\left(1+\frac{2}{\alpha}\right)\Gamma\left(1-\frac{2}{\alpha}\right)}. \quad (11)$$

Substitute (9), (10), and (11) into (8), and let $C_\alpha = \pi\Gamma(1+\frac{2}{\alpha})\Gamma(1-\frac{2}{\alpha})$, the result (7) is obtained. ∎

IV. Transmission Capacity Analysis of D2D Communication With RNs in the Overlay Mode

In this section, the performance of D2D communication with RNs is analyzed in the overlay mode, i.e., the influence of cellular system is not considered because D2D users and RNs reuse the dedicated spectrum resources.

A. D2D Transmission Capacity With RN Assistance in the Overlay Mode

The relay transmission is divided into following two cases:

Case 1: The D2D pair is able to launch transmission only if there is an available RN in the shadow region shown in Fig. 2.

Case 2: If the RN is in the shadow region, the D2D pair utilizes this RN to forward signals, else, transmits signals by the direct link.

Then the two cases are analyzed as follows:

Case 1: Transmission Distance Extension

In this case, the D2D pairs cannot transmit signals if there is no available RN. Because of the relay transmission in TDD way, transmission time of D2D users is same as that of RNs. So, the density of activated D2D transmitter or RN is $(1/2)\lambda_1\mathrm{Pr}_e$. The transmission capacity is defined as the product of user density and the successful transmission probability [22]. The successful transmission probabilities from D2D to RN and from RN to D2D of case 1 in the overlay mode are

$$\Pr\left(\mathrm{SIR}_{\mathrm{D2RN,ov1}} \geq T_2\right) = e^{-\frac{1}{2}\lambda_1\mathrm{Pr}_e C_\alpha T_2^{\frac{2}{\alpha}}A^2R^2\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}+1\right]} \quad (12)$$

$$\Pr\left(\mathrm{SIR}_{\mathrm{RN2D,ov1}} \geq T_2\right) = e^{-\frac{1}{2}\lambda_1\mathrm{Pr}_e C_\alpha T_2^{\frac{2}{\alpha}}A^2R^2\left[\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}+1\right]}. \quad (13)$$

The D2D transmission capacity of case 1 in the overlay mode is given by

$$C_{\mathrm{relay,ov1}} = \frac{1}{2}\lambda_1\Pr_e \times \Pr\left(\mathrm{SIR}_{\mathrm{D2RN,ov1}} \geq T_2\right) \times \Pr\left(\mathrm{SIR}_{\mathrm{RN2D,ov1}} \geq T_2\right). \quad (14)$$

Case 2: Transmission Capacity Improvement

In this case, the D2D pair needs to transmit signals over the direct link without the RN appearing in the overlap region. The D2D density with direct transmission link is $(1-\mathrm{Pr}_e)\lambda_1$. And the densities of transmission from D2D transmitter to RN and from RN to D2D receiver are both $\frac{1}{2}\lambda_1\mathrm{Pr}_e$. From *Lemma 1* and *Lemma 2*, the successful transmission probability of D2D with direct link in the overlay mode is

$$\Pr\left(\mathrm{SIR}_{\mathrm{D2D,ov2}} \geq T_1\right) = e^{-\lambda_1 C_\alpha T_1^{\frac{2}{\alpha}}R^2\left[1-\frac{1}{2}\mathrm{Pr}_e+\frac{1}{2}\mathrm{Pr}_e\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}\right]}. \quad (15)$$

The successful probabilities from D2D to RN and from RN to D2D of case 2 in the overlay mode are

$$\Pr\left(\mathrm{SIR}_{\mathrm{D2RN,ov2}} \geq T_2\right) = e^{-\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}}A^2R^2\left[1-\frac{1}{2}\mathrm{Pr}_e+\frac{1}{2}\mathrm{Pr}_e\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}\right]}, \quad (16)$$

$$\Pr\left(SIR_{\mathrm{RN2D,ov2}} \geq T_2\right) = e^{-\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}}A^2R^2\left[\left(1-\frac{1}{2}\mathrm{Pr}_e\right)\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}+\frac{1}{2}\mathrm{Pr}_e\right]}. \quad (17)$$

The D2D transmission capacity of case 2 in the overlay mode is given by

$$C_{\mathrm{relay,ov2}} = \lambda_1\left(1-\mathrm{Pr}_e\right)\Pr\left(\mathrm{SIR}_{\mathrm{D2D,ov2}} \geq T_1\right) + \frac{1}{2}\lambda_1\Pr_e\Pr\left(\mathrm{SIR}_{\mathrm{D2RN,ov2}} \geq T_2\right)\Pr\left(\mathrm{SIR}_{\mathrm{RN2D,ov2}} \geq T_2\right). \quad (18)$$

B. Transmission Capacity Gain from RNs in the Overlay Mode

In order to analyze the transmission capacity gain from RN, first the D2D transmission capacity without RN in the overlay mode is calculated. From *Lemma 2*, the D2D transmission capacity without RN is

$$C_{\mathrm{D2DnoRN,ov}} = \lambda_1\Pr\left(\mathrm{SIR}_{\mathrm{D2DnoRN,ov}} \geq T_1\right) = \lambda_1 e^{\left(-\lambda_1 C_\alpha T_1^{\frac{2}{\alpha}}R^2\right)}. \quad (19)$$

Then the following proposition is obtained:

Proposition 1: In the overlay mode, the D2D transmission capacity gains from RNs of case 1 and case 2 are indicated by (20) and (21), respectively.

$$G_{\mathrm{case1,ov}} = C_{\mathrm{relay,ov1}}/C_{\mathrm{D2DnoRN,ov}} = \frac{1}{2}\mathrm{Pr}_e e^{\lambda_1 C_\alpha R^2\left\{T_1^{\frac{2}{\alpha}}-\frac{1}{2}\mathrm{Pr}_e T_2^{\frac{2}{\alpha}}A^2\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}+\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}+2\right]\right\}} \quad (20)$$

$$G_{\mathrm{case2,ov}} = C_{\mathrm{relay,ov2}}/C_{\mathrm{D2DnoRN,ov}} = \left(1-\mathrm{Pr}_e\right)e^{\frac{\mathrm{Pr}_e\lambda_1 C_\alpha T_1^{\frac{2}{\alpha}}R^2}{2}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}\right]} + \frac{\mathrm{Pr}_e}{2} \times e^{\lambda_1 C_\alpha T_1^{\frac{2}{\alpha}}R^2-\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}}A^2R^2\left\{1+\frac{1}{2}\mathrm{Pr}_e\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}-\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}\right]+\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}\right\}}. \quad (21)$$

When $G_{\mathrm{case1,ov}}$ or $G_{\mathrm{case2,ov}}$ is greater than 1, the RN can bring benefit to the D2D transmission. Otherwise, the D2D transmission with direct link is better.

C. Relay Transmission Capacity With Variable D2D Link Distance

From above analysis, the link distance of D2D transmission R is a fixed value. While in the practice networks, the link distance is a random variable. To bridge the gap between theoretical models and practical situations, the relay transmission capacity with variable D2D link distance is analyzed below. Since the influence of RN is always considered, the density of potential RN is assumed to be large enough so that D2D transmission can always be assisted by RN, i.e., the condition that $\mathrm{Pr}_e = 1$ is established. Denote $R_{\max}$ and $R_{\min}$ as the maximum and the minimum transmission distance between D2D transmitter and receiver, and the distance R obeys uniform distribution in $[R_{\min}, R_{\max}]$, $(0 \le R_{\min} < R_{\max})$. Then the pdf of R is

$$f_R(r) = \frac{1}{R_{\max} - R_{\min}}; r \in [R_{\min}, R_{\max}]. \tag{22}$$

Theorem 1: When D2D link distance R satisfies the uniform distribution in $[R_{\min}, R_{\max}]$, the D2D transmission capacity with RN in the overlay mode is

$$\begin{aligned} C_{\text{relay,ov}} = & \frac{\lambda_1 \pi}{2\sqrt{B_1 D_1}(R_{\max} - R_{\min})^2} \\ & \times \left[\Phi\left(\sqrt{2B_1} R_{\max}\right) - \Phi\left(\sqrt{2B_1} R_{\min}\right)\right] \\ & \times \left[\Phi\left(\sqrt{2D_1} R_{\max}\right) - \Phi\left(\sqrt{2D_1} R_{\min}\right)\right] \end{aligned} \tag{23}$$

where $B_1 = \frac{1}{2}\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}} A^2 [(\frac{P_2}{P_1})^{\frac{2}{\alpha}} + 1]$, $D_1 = \frac{1}{2}\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}} A^2 [(\frac{P_1}{P_2})^{\frac{2}{\alpha}} + 1]$, and $\Phi(\bullet)$ is the cumulative distribution function (cdf) of standard normal distribution.

Proof: Because the condition of RN is always available, the transmission capacity expressions of case 1 and 2 in the overlay mode are the same, which can be written as $C_{\text{relay,ov}} = \frac{1}{2}\lambda_1 \,\mathrm{Pr}_{\text{ov}}^{\text{D2RN}}\, \mathrm{Pr}_{\text{ov}}^{\text{RN2D}}$, where $\mathrm{Pr}_{\text{ov}}^{\text{D2RN}}$ and $\mathrm{Pr}_{\text{ov}}^{\text{RN2D}}$ are the successful transmission capacities from D2D transmitter to RN and from RN to D2D receiver, respectively.

Denote $B_1 = \frac{1}{2}\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}} A^2 [(\frac{P_2}{P_1})^{\frac{2}{\alpha}} + 1]$ and $D_1 = \frac{1}{2}\lambda_1 C_\alpha T_2^{\frac{2}{\alpha}} A^2 [(\frac{P_1}{P_2})^{\frac{2}{\alpha}} + 1]$. Since R satisfies uniform distribution in $[R_{\min}, R_{\max}]$, the equation becomes

$$\begin{aligned} C_{\text{relay,ov}} &= \frac{1}{2}\lambda_1 E_R\left(e^{-B_1 R^2}\right) E_R\left(e^{-D_1 R^2}\right) \\ &= \frac{1}{2}\lambda_1 \frac{1}{R_{\max} - R_{\min}} \sqrt{\frac{\pi}{B_1}} \int_{R_{\min}}^{R_{\max}} \sqrt{\frac{B_1}{\pi}} e^{\frac{-r^2}{2\left(\sqrt{\frac{1}{2B_1}}\right)^2}} dr \\ &\cdot \frac{1}{R_{\max} - R_{\min}} \sqrt{\frac{\pi}{D_1}} \int_{R_{\min}}^{R_{\max}} \sqrt{\frac{D_1}{\pi}} e^{\frac{-r^2}{2\left(\sqrt{\frac{1}{2D_1}}\right)^2}} dr \\ &= \frac{\lambda_1 \pi}{2\sqrt{B_1 D_1}(R_{\max} - R_{\min})^2} \left[\Phi\left(\sqrt{2B_1} R_{\max}\right)\right. \\ &\left. -\Phi\left(\sqrt{2B_1} R_{\min}\right)\right] \left[\Phi\left(\sqrt{2D_1} R_{\max}\right) - \Phi\left(\sqrt{2D_1} R_{\min}\right)\right] \end{aligned} \tag{24}$$

where $\Phi(\bullet)$ is the cdf of standard normal distribution. ∎

V. Transmission Capacity Analysis of D2D Communication With RNs in the Underlay Mode

In this section, the performance of D2D communication with RNs is analyzed in the underlay mode, i.e., the influence of cellular system is considered because D2D users and RNs share the cellular spectrum resources.

A. D2D Transmission Capacity With RN Assistance in the Underlay Mode

When D2D users and RNs work in the underlay mode, the transmission is interfered by the cellular system. Similar to the analysis in the overlay mode, the following two cases are still considered:

Case 1: Transmission Distance Extension

In this case, the successful transmission probabilities from D2D to RN and from RN to D2D of case 1 in the underlay mode can be written as

$$\begin{aligned} &\Pr\left(\text{SIR}_{\text{D2RN,un1}} \ge T_2\right) \\ &= e^{-C_\alpha T_2^{\frac{2}{\alpha}} A^2 R^2 \left[\lambda_0 \left(\frac{P_0}{P_1}\right)^{\frac{2}{\alpha}} + \frac{1}{2}\lambda_1 \mathrm{Pr}_e + \frac{1}{2}\lambda_1 \mathrm{Pr}_e \left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}}\right]} \end{aligned} \tag{25}$$

$$\begin{aligned} &\Pr\left(\text{SIR}_{\text{RN2D,un1}} \ge T_2\right) \\ &= e^{-C_\alpha T_2^{\frac{2}{\alpha}} A^2 R^2 \left[\lambda_0 \left(\frac{P_0}{P_2}\right)^{\frac{2}{\alpha}} + \frac{1}{2}\lambda_1 \mathrm{Pr}_e \left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}} + \frac{1}{2}\lambda_1 \mathrm{Pr}_e\right]}. \end{aligned} \tag{26}$$

The D2D transmission capacity of case 1 in the underlay mode is given by

$$\begin{aligned} C_{\text{relay,un1}} = & \frac{1}{2}\lambda_1 \Pr_e \Pr\left(SIR_{\text{D2RN,un1}} \ge T_2\right) \\ & \times \Pr\left(\text{SIR}_{\text{RN2D,un1}} \ge T_2\right). \end{aligned} \tag{27}$$

Case 2: Transmission Capacity Improvement

In this case, there are cellular users in the system and D2D users should use the direct link to transmit signals when no RN in the overlap region. First, the successful transmission probability of D2D with direct link in the underlay mode is

$$\begin{aligned} &\Pr\left(\text{SIR}_{\text{D2D,un2}} \ge T_1\right) \\ &= e^{-C_\alpha T_1^{\frac{2}{\alpha}} R^2 \left[\lambda_0 \left(\frac{P_0}{P_1}\right)^{\frac{2}{\alpha}} + \lambda_1 + \frac{1}{2}\lambda_1 \mathrm{Pr}_e \left(\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}} - 1\right)\right]}. \end{aligned} \tag{28}$$

Second, the successful probabilities from D2D to RN and from RN to D2D of case 2 in the underlay mode are

$$\begin{aligned} &\Pr\left(SIR_{\text{D2RN,un2}} \ge T_2\right) \\ &= e^{-C_\alpha T_2^{\frac{2}{\alpha}} A^2 R^2 \left\{\lambda_0 \left(\frac{P_0}{P_1}\right)^{\frac{2}{\alpha}} + \lambda_1 + \frac{1}{2}\lambda_1 \mathrm{Pr}_e \left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\alpha}} - 1\right]\right\}} \end{aligned} \tag{29}$$

$$\begin{aligned} &\Pr\left(\text{SIR}_{\text{RN2D,un2}} \ge T_2\right) \\ &= e^{-C_\alpha T_2^{\frac{2}{\alpha}} A^2 R^2 \left\{\lambda_0 \left(\frac{P_0}{P_2}\right)^{\frac{2}{\alpha}} + \lambda_1 \left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}} + \frac{\lambda_1}{2} \mathrm{Pr}_e \left[1 - \left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}\right]\right\}}. \end{aligned} \tag{30}$$

The D2D transmission capacity of case 2 in the underlay mode is given by

$$\begin{aligned} C_{\text{relay,un2}} = & \lambda_1 \left(1 - \mathrm{Pr}_e\right) \Pr\left(\text{SIR}_{\text{D2D,un2}} \ge T_1\right) + \frac{1}{2}\lambda_1 \mathrm{Pr}_e \\ & \times \Pr\left(\text{SIR}_{\text{D2RN,un2}} \ge T_2\right) \Pr\left(\text{SIR}_{\text{RN2D,un2}} \ge T_2\right). \end{aligned} \tag{31}$$

Remark 1: Compared the expression of D2D transmission capacity in the overlay mode, the influence of cellular system is added. It is obvious that the D2D transmission capacity of the underlay mode is less than the overlay mode under the same system parameter configurations.

B. Transmission Capacity Gain From RNs in the Underlay Mode

In the underlay mode, the interference in the system is more complex than the overlay mode. In order to obtain D2D transmission capacity gain from RNs, first the D2D successful transmission probability without RN in the underlay mode can be written as

$$\Pr\left(\mathrm{SIR}_{\mathrm{D2DnoRN,un}} \geq T_1\right) = e^{-C_\alpha T_1^{\frac{2}{\alpha}} R^2 \left[\lambda_0 \left(\frac{P_0}{P_1}\right)^{\frac{2}{\alpha}} + \lambda_1\right]}. \quad (32)$$

$$C_{\text{relay,un}} = \frac{1}{2}\lambda_1 E_R\left(e^{-B_2 R^2}\right) E_R\left(e^{-D_2 R^2}\right)$$
$$= \frac{\lambda_1 \pi}{2\sqrt{B_2 D_2}(R_{\max} - R_{\min})^2}\left[\Phi\left(\sqrt{2B_2}R_{\max}\right)\right.$$
$$\left. - \Phi\left(\sqrt{2B_2}R_{\min}\right)\right]\left[\Phi\left(\sqrt{2D_2}R_{\max}\right) - \Phi\left(\sqrt{2D_2}R_{\min}\right)\right]. \quad (33)$$

The D2D transmission capacity without RN in the underlay mode is $C_{\mathrm{D2DnoRN,un}} = \lambda_1 e^{-C_\alpha T_1^{\frac{2}{\alpha}} R^2 [\lambda_0 (\frac{P_0}{P_1})^{\frac{2}{\alpha}} + \lambda_1]}$. Then the following proposition is obtained:

Proposition 2: In the underlay mode, the D2D transmission capacity gains from RNs of case 1 and case 2 are presented as $G_{\text{case1,un}} = \frac{C_{\text{relay, un1}}}{C_{\text{D2DnoRN, un}}}$ and $G_{\text{case2,un}} = \frac{C_{\text{relay, un2}}}{C_{\text{D2DnoRN, un}}}$, respectively. If $G_{\text{case1,un}}$ or $G_{\text{case2,un}}$ is greater than 1, the RN can bring benefit to D2D transmission. Otherwise, the D2D transmission with direct link is better.

Remark 2: Based on **Proposition 2**, it is known that the bigger D2D density brings more influence to the system because more RNs can be used to assist D2D users to transmit signals. Particularly, when the density of potential RN is big enough and the RN transmission power equals D2D power, i.e., $\Pr_e \approx 1$ and $P_1 = P_2$, from the expressions of $G_{\text{case1,un}}$ and $G_{\text{case2,un}}$ we can conclude that if $T_1^{\frac{2}{\alpha}} > 2T_2^{\frac{2}{\alpha}} A^2$, the D2D transmission capacity gains increase when D2D density λ_1 increases, but when $T_1^{\frac{2}{\alpha}} < 2T_2^{\frac{2}{\alpha}} A^2$, $G_{\text{case1,un}}$ and $G_{\text{case2,un}}$decrease when λ_1 increases.

C. Relay Transmission Capacity With Variable D2D Link Distance

In this part, the relay transmission capacity with variable D2D link distance in the underlay mode is analyzed. The same as the situation in the overlay mode, the density of potential RN λ_2 is assumed to be large enough and D2D transmission can be assisted by RN all the time because the influence of RN is always considered. So, $\Pr_e = 1$ and the random variable R is supposed to obey uniform distribution in $[R_{\min}, R_{\max}]$, $(0 \leq R_{\min} < R_{\max})$. Then the following theorem is obtained:

TABLE I
SIMULATION PARAMETERS

Parameter	Connotation	Value
λ_0	Cellular user density	0.0001 m^{-2}
$\lambda_{,1}$	D2D density	0.0003 m^{-2}
λ_2	Potential RN density	0.0004 m^{-2}
P_0	Cellular transmission power	24 dBm
P_1	D2D transmission power	15 dBm
P_2	RN transmission power	15 dBm
T_0	Cellular SIR threshold	0 dB
T_1	D2D SIR threshold	2 dB
T_2	SIR threshold of relay transmission	2 dB
α	Path loss coefficient	4
R	D2D link distance	35 m

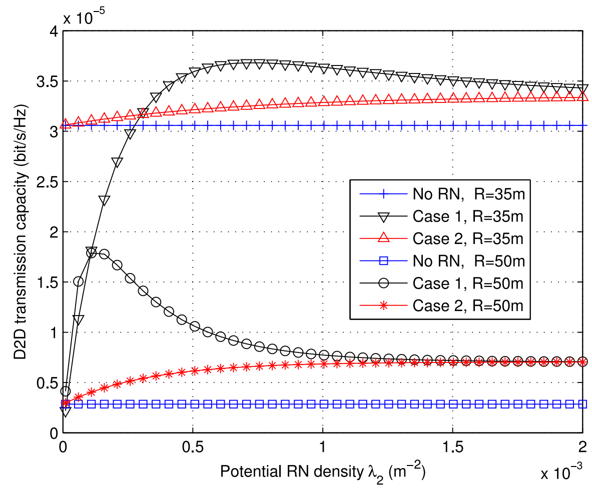

Fig. 3. D2D transmission capacity versus potential RN density in the overlay mode under different D2D direct link distance.

Theorem 2: When D2D link distance R satisfies the uniform distribution in $[R_{\min}, R_{\max}]$, $(0 \leq R_{\min} < R_{\max})$, the D2D transmission capacity with RN in the underlay mode is as (33) shown, where $B_2 = C_\alpha T_2^{\frac{2}{\alpha}} A^2 \{\lambda_0 (\frac{P_0}{P_1})^{\frac{2}{\alpha}} + \frac{\lambda_1}{2}[(\frac{P_2}{P_1})^{\frac{2}{\alpha}} + 1]\}$, $D_2 = C_\alpha T_2^{\frac{2}{\alpha}} A^2 \{\lambda_0 (\frac{P_0}{P_2})^{\frac{2}{\alpha}} + \frac{\lambda_1}{2}[1 + (\frac{P_1}{P_2})^{\frac{2}{\alpha}}]\}$. $\Phi(\bullet)$ is the cdf of standard normal distribution.

Proof: Following same steps as the proof of *Theorem 1*, we can reach the result. ■

VI. SIMULATION RESULTS AND DISCUSSIONS

In this section, the results of D2D transmission capacity are evaluated when D2D users and RNs share the cellular spectrum in the overlay mode and the underlay mode, respectively. The key parameters in the simulation are listed in Table I.

A. Simulation Analysis of D2D Transmission Capacity in the Overlay Mode

Fig. 3 illustrates the relationship between D2D transmission capacity and potential RN density in the overlay mode. The horizontal line stands for the capacity of D2D transmission without RNs. We can know that the capacity value of case 2

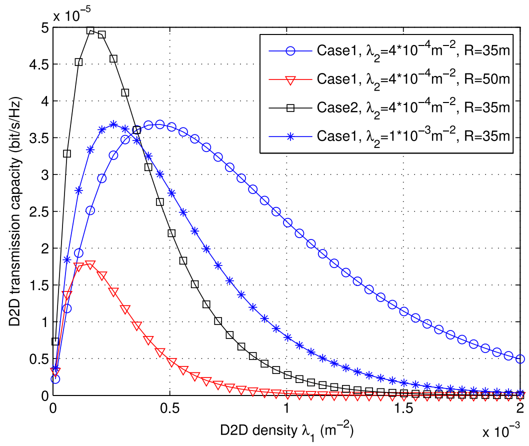

Fig. 4. D2D transmission capacity versu. D2D density in the overlay mode.

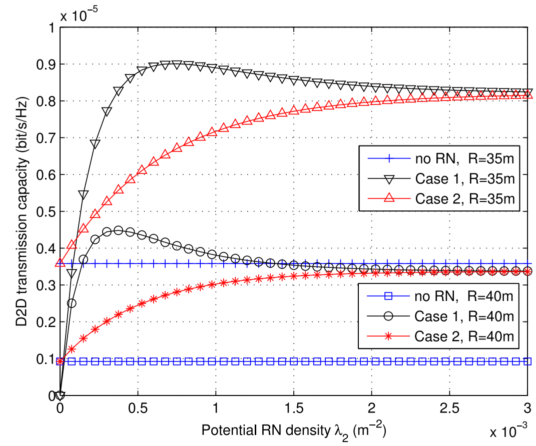

Fig. 5. D2D transmission capacity versus potential RN density in the underlay mode under different D2D direct link distance.

is always greater than the case without RNs because D2D direct link can be used to transmit signals when there are no RNs in the overlap region. When λ_2 is small, the D2D network can obtain the capacity gain from relay transmission which can further improve the D2D transmission capacity, the capacity rises rapidly at the beginning when the potential RN density increases. When the potential RN density continues increasing, the D2D network capacity suffers from the loss caused by the excessive interference which leads to the decline of capacity.

In Fig. 4, when D2D density is small, it can be observed that the D2D transmission capacity increases as D2D density increases because large D2D density can bring enhancement to network performance. But if the D2D density continues increasing, the interference can not be ignored and leads to a decrease of capacity. Under the same λ_2, D2D transmission capacity of case 2 is larger than case 1 when λ_1 is low, but if λ_1 increases, the capacity value of case 1 becomes larger than case 2. The reason is that D2D users of case 1 can not only get benefits from RNs, but also from the D2D direct link under a low value of λ_1.

B. Simulation Analysis of D2D Transmission Capacity in the Underlay Mode

Fig. 5 demonstrates the relationship between D2D transmission capacity and potential RN density in the underlay mode. Similar to the overlay mode, the capacity of case 2 is larger than the case without RN because D2D direct link can be used in case 2. Besides, the D2D transmission capacities of case 1 and 2 are equal under a large λ_2 because D2D users can always find RNs to assist the transmission in both two cases. Compared with Fig. 3, the D2D transmission capacities in Fig. 5 are lower than the capacities in the overlay mode because cellular users also interfere D2D transmission. From Fig. 5, the curves of case 1 rise first and then decline because the gains from the RNs are dominated at first but then the harmful interference becomes dominated as λ_2 increases.

In Fig. 6, the D2D transmission capacity increases at the beginning as D2D density increases because the D2D can bring capacity enhancement to the whole system. When D2D density

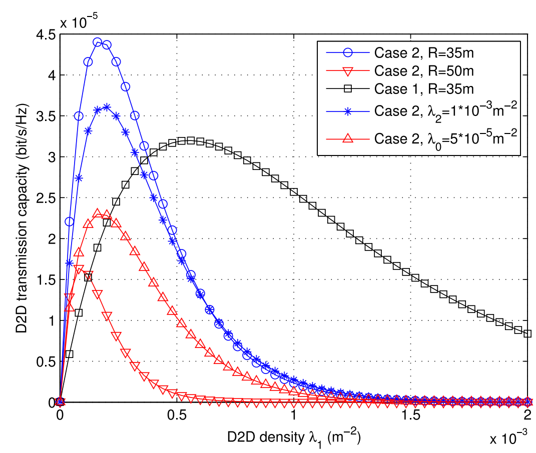

Fig. 6. D2D transmission capacity versus D2D density in the underlay mode.

continues increasing, the interference caused by D2D system becomes more and more serious, which leads to a reduction of D2D transmission capacity. Furthermore, compared with case 1, the D2D transmission capacity of case 2 is higher at first but lower later. The reason is D2D users in case 2 can benefit more from direct link when λ_1 is small but suffers from interference when λ_1 becomes large. Next, it can be seen that the D2D transmission capacity is lower when $R = 50$ m because longer D2D direct link brings more propagation loss to the D2D system. In addition, the interference from cellular users is considered when D2D users share the spectrum in the underlay mode. D2D transmission capacity decreases when λ_0 increases to 5×10^{-5} m^{-2} because big cellular user density brings more interference to the D2D system. Last, when λ_2 is small, the benefits D2D users get from RNs decrease, so the reduction of D2D transmission capacity can be observed in the figure.

C. Simulation Analysis of Boundaries of the D2D Direct Link Distance

Fig. 7 demonstrates the trend of D2D transmission capacity with different $R_{\min}$ in the overlay mode. Here, the maximum

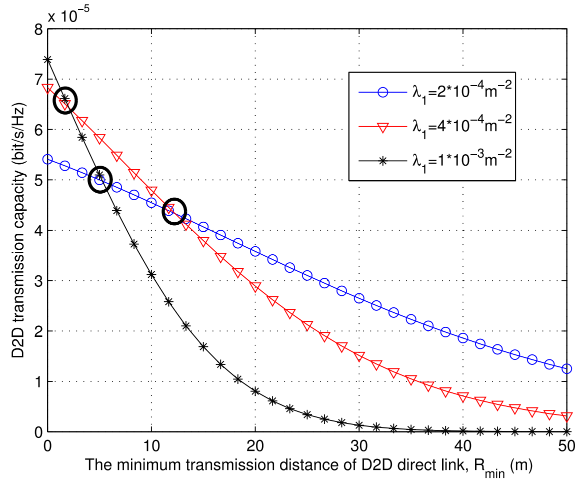

Fig. 7. D2D transmission capacity under different D2D density in the overlay mode with variable minimum transmission distances of D2D direct link.

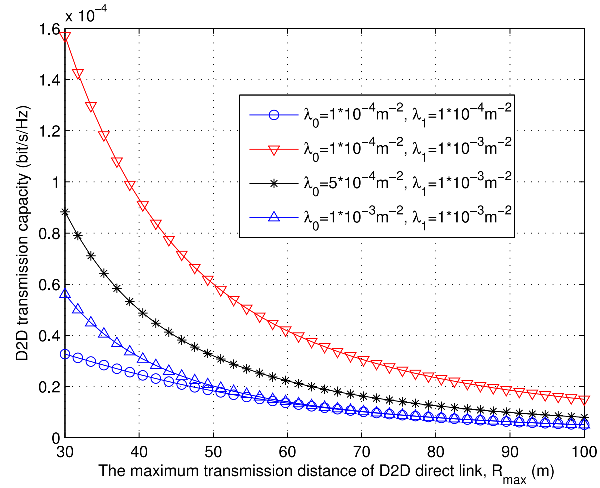

Fig. 9. D2D transmission capacity under different cellular and D2D density in the underlay mode with variable maximum transmission distances of D2D direct link.

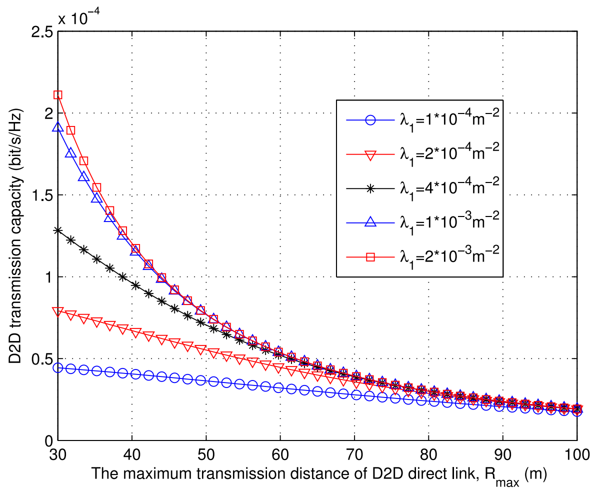

Fig. 8. D2D transmission capacity under different D2D density in the overlay mode with variable maximum transmission distances of D2D direct link.

D2D direct link distance is fixed at 50 m. Since, the average D2D direct link distance is extended under a high $R_{\min}$, the D2D transmission capacity decreases as $R_{\min}$ increases. According to the black circles in the figure, it is known that the large D2D density is more conducive to the D2D system when $R_{\min}$ is small. However, for the curve of low D2D density, both the reduction of D2D users and the interference among the system are smaller when the same increment is added to $R_{\min}$, so the decline trend of the curve with high D2D density is faster.

Fig. 8 illustrates the influence of maximum transmission distance of D2D direct link in the overlay mode. Here, the minimum D2D direct link distance is set at 0. The D2D transmission capacity decreases as $R_{\max}$ increases; this is because the extension of $R_{\max}$ leads to the longer average D2D direct link distance, which causes more propagation loss during the signal transmission.

Fig. 9 reveals D2D transmission capacity decreases as $R_{\max}$ increases due to long $R_{\max}$ causes long average D2D direct link distance, which makes the large propagation loss. We can see low D2D density brings little benefit to the networks, which causes a low D2D transmission capacity. Besides, D2D transmission capacity is decreasing as the increasing of cellular user density, which causes more and more serious interference to the D2D system.

VII. Conclusion

In this paper, the transmission capacities of D2D communication with the assistance of RNs are analyzed in both overlay and underlay modes. Based on stochastic geometry, the network is modeled by the heterogeneous PPP. The D2D transmission capacity expressions with RNs for transmission distance extension and capacity improvement are obtained in closed-form, which leads to the transmission capacity gains in both modes. Besides, the influences of the variable D2D direct link in two modes are considered, which can be used in the evaluation of practical network design. Furthermore, simulation results illustrate that the transmission capacity is influenced by the way of how to use RNs. In addition, the results demonstrate that D2D transmission capacity is impacted by the D2D direct link distance as well as the cellular, D2D and RN density, which introduce interference to the D2D system in different degrees.

References

[1] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, “Device-to-device communication in 5G cellular networks: Challenges, solutions, and future directions,” *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 86–92, May. 2014.

[2] L. Dai, B. Wang, Y. Yuan, S. Han, C.-L. I, and Z. Wang, “Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends,” *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015.

[3] X. Gao, L. Dai, S. Han, C.-L. I, and R. W. Heath, “Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays,” *IEEE J. Sel. Commun.*, vol. 34, no. 4, pp. 998–1009, Apr. 2016.

[4] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity service," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 40–48, Apr. 2014.
[5] P. Phunchongharn, E. Hossain, and D. I. Kim, "Resource allocation for device-to-device communications underlaying LTE-Advanced networks," *IEEE Commun. Mag.*, vol. 20, no. 4, pp. 91–100, Aug. 2013.
[6] D. Karvounas, A. Georgakopoulos, K. Tsagkaris, V. Stavroulaki, and P. Demestichas, "Smart management of D2D constructs: An experiment-based approach," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 82–89, Apr. 2014.
[7] G. Fodor *et al.*, "Design aspects of network assisted device-to-device communications," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 170–177, Mar. 2012.
[8] H. Min, J. Lee, S. Park, and D. Hong, "Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 3995–4000, Dec. 2011.
[9] C. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2752–2763, Aug. 2011.
[10] R. Vaze, K. T. Truong, S. Weber, and R. W. Heath, "Two-way transmission capacity of wireless ad-hoc networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 6, pp. 1966–1975, Jun. 2011.
[11] Y. Yang, Z. Liu, Z. Fu, T. Peng, and W. Wang, "Transmission capacity of device-to-device communication under heterogeneous networks with cellular users assisted," in *Proc. IEEE Globecom Workshops*, Atlanta, GA, USA, Dec. 2013, pp. 335–341.
[12] L. Chen *et al.*, "Mobile relay in LTE-advanced systems," *IEEE Commun. Mag.*, vol. 51, no. 11, pp. 144–151, Nov. 2013.
[13] H. Nishiyama, M. Ito, and N. Kato, "Relay-by-smartphone: Realizing multihop device-to-device communications," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 56–65, Apr. 2014.
[14] M. Hasan, E. Hossain, and D. I. Kim, "Resource allocation under channel uncertainties for relay-aided device-to-device communication underlaying LTE-A cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2322–2338, Apr. 2014.
[15] J. Lee *et al.*, "Outage probability of cognitive relay networks with interference constraints," *IEEE Trans. Wireless Commun.*, vol. 10, no. 2, pp. 390–395, Feb. 2011.
[16] T. Q. Duong, V. N. Q. Bao, and H.-J. Zepernick, "Exact outage probability of cognitive AF relaying with underlay spectrum sharing," *Electron. Lett.*, vol. 47, no. 17, pp. 1001–1002, Aug. 2011.
[17] B. Zhou, H. Hu, S. Huang, and H.-H. Chen, "Intracluster device-to-device relay algorithm with optimal resource utilization," *IEEE Trans. Veh. Technol.*, vol. 62, no. 5, pp. 2315–2326, Jun. 2014.
[18] Z. Gao, L. Dai, Z. Lu, C. Yuen, and Z. Wang, "Super-resolution sparse MIMO-OFDM channel estimation based on spatial and temporal correlations," *IEEE Commun. Lett.*, vol. 18, no. 7, pp. 1266–1269, Jul. 2014.
[19] L. Dai, J. Wang, Z. Wang, P. Tsiaflakis, and M. Moonen, "Time domain synchronous OFDM based on simultaneous multi-channel reconstruction," in *Proc. IEEE Int. Conf. Commun.*, Budapest, Hungary, Jun. 2013, pp. 1–5.
[20] F. Baccelli and B. Blaszczyszyn, *Stochastic Geometry and Wireless Networks*, Vol. 1. Delft, the Netherlands: NOW, 2010.
[21] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. New York, NY, USA: Academic, 2000.
[22] M. Haenggi, *Stochastic Geometry for Wireless Networks.* Cambridge, U.K.: Cambridge Univ. Press, 2013.

Yang Yang (M'13) received the Ph.D. degree in electronic engineering from the School of Telecommunications Engineering, Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in June 2015.

He was a Core Member of the team in D2D communication research in the Wireless Signal Processing and Network Lab, BUPT. Since July 2015, he has been a Postdoctoral Research Fellow with the Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing, China. His research interests include D2D communication, cognitive radio networks, and heterogeneous networks based on stochastic geometry and convex optimization.

Yuan Zhang (M'16) is currently working toward the B.E. degree in electronic engineering at Tsinghua University, Beijing, China, since 2013.

He joined the Tsinghua National Laboratory for Information Science and Technology as a Research Student in 2015. He has participated in the science fair with two research projects at College Student Innovation and Entrepreneurship Education of Beijing (top 3%). He has received the Student Award for Research and Innovation (top 2%), the First-class Scholarship of Tsinghua University four times, and others. His research interests include device-to-device communication based on stochastic geometry, convex optimization, and nonlinear programming.

Linglong Dai (M'11–SM'14) received the B.S. degree in electronic engineering from Zhejiang University, Hangzhou, China, in 2003, the M.S. degree in electronic engineering (with the highest honors) from the China Academy of Telecommunications Technology, Beijing, China, in 2006, and the Ph.D. degree in electronic engineering (with the highest honors) from Tsinghua University, Beijing, China, in 2011.

From 2011 to 2013, he was a Postdoctoral Research Fellow with the Department of Electronic Engineering, Tsinghua University, where he has been an Assistant Professor since July 2013 and then an Associate Professor since June 2016. He has published more than 50 IEEE journal papers and more than 30 IEEE conference papers. He also holds 13 granted patents. He co-authored the book *mmWave Massive MIMO: A Paradigm for 5G* (Academic Press). His current research interests include massive MIMO, millimeter-wave communications, multiple access, and sparse signal processing. Particularly, he is dedicated to reproducible research and has made a large amount of simulation codes publicly available (refer to his homepage for more details: http://oa.ee.tsinghua.edu.cn/dailinglong/).

Dr. Dai received the IEEE ICC Best Paper Award in 2013, the IEEE ICC Best Paper Award in 2014, the IEEE TRANSACTIONS ON BROADCASTING Best Paper Award in 2015, the URSI AP-RASC 2016 Young Scientist Award in 2016, and the WCSP Best Paper Award in 2016. He currently serves as an editor of the IEEE TRANSACTIONS ON COMMUNICATIONS, an editor of the IEEE COMMUNICATIONS LETTERS, a guest editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (Special Issue on Millimeter Wave Communications for Future Mobile Networks), and the co-chair of the IEEE Special Interest Group (SIG) on Signal Processing Techniques in 5G Communication Systems.

Jianjun Li received the B.S. and M.S. degrees in electronic engineering from Xidian University, Xi'an, China, and the Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China, in 1996, 1999, and 2002, respectively.

From 2002 to 2007, he was a Senior Researcher on 4G wireless communication with the Beijing Samsung Telecom R&D Center in Beijing. From 2007 to 2015, he was with Posdata, Pantech and Innovative technology Lab. Co. in South Korea as a Senior Researcher. During this period, his research mainly focused on Wimax and 3GPP LTE standard including MIMO, CoMP, small cell, and LAA. Since 2016, he has been an Associate Professor at Zhongyuan University of Technology, Zhengzhou, China. His current research interests include 5G wireless communication including massive MIMO, NOMA, new waveform and application of digital signal processing in communication systems.

Shahid Mumtaz (SM'16) received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from Blekinge Institute of Technology, Karlskrona, Sweden, and University of Aveiro, Aveiro, Portugal, in 2006 and 2011, respectively.

He has more than seven years of wireless industry experience and is currently working as a Senior Research Scientist and a Technical Manager at Instituto de Telecomunicações, Aveiro, Portugal, under 4Tell group. Prior to his current position, he was a Research Intern at Ericsson and Huawei Research Labs at Karlskrona, Sweden, in 2005. He has several years of experience in 3GPP radio systems research with experience in HSPA/LTE/LTE-A and a strong track-record in relevant technology fields, especially physical layer technologies, LTE cell planning and optimization, protocol stack, and system architecture. He has more than 80 publications in international conferences, journal papers, and book chapters.

Dr. Mumtaz has been on the technical program committee of several IEEE conferences, including Globecom, ICC, and VTC, and chaired some of their symposia, and was the workshop chair in many conferences. He received the 2006 IITA Scholarship, South Korea.

Jonathan Rodriguez (SM'13) received the Master degree in electronic and electrical engineering and the Ph.D. degree in electronic engineering from the University of Surrey, Guildford, U.K., in 1998 and 2004, respectively.

In 2002, he became a Research Fellow at the Centre for Communication Systems Research and was responsible for coordinating Surrey involvement in European research projects under framework 5 and 6. Since 2005, he has been a Senior Researcher at the Instituto de Telecomunicações, Aveiro, Portugal, where he founded the 4TELL Wireless Communication Research Group in 2008. He was the project coordinator and technical manager of the FP7 C2POWER and the FP7 COGEU projects, respectively, and currently acts as a coordinator of several national and international projects. He is the author of more than 250 scientific publications, has served as the general chair for several prestigious conferences and workshops, and has carried out consultancy for major manufacturers participating in DVB-T/H and HS-UPA standardization. His research interests include green communications, network coding, cognitive radio, cooperative networking, radio resource management, and cross-layer design.

Dr. Rodriguez is a Chartered Engineer.