Performance Analysis of D2D and Cellular Coexisting Networks With Interference Management

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ABSTRACT Integrating device-to-device (D2D) communication into cellular networks is considered as a promising technology to support high data rate and improve spectrum utilization. However, the severe interference issue in D2D and cellular coexisting networks might erode the benefits brought by D2D communications. To address this critical issue, we first propose two exclusion-based D2D activation schemes with hybrid spectrum allocation (named EDAH) and spectrum sharing (named EDAS), where D2D users (DUs) outside the exclusion regions of base stations are active. Based on the activation scheme, cellular users can be classified into central users (CUs) within the exclusion regions and the remaining edge users (EUs). Secondly, we establish a stochastic geometry-based framework to characterize the performance of D2D and cellular coexisting networks, where the distribution of the active D2D pairs follow a bipolar Poisson hole process. Specifically, we provide tight bounds and accurate approximations for the success probabilities of CUs and DUs. Due to the different spectrum allocation, we provide an exact analytical expression for the success probability of EUs in EDAH and a tight bound in EDAS. With these results, we further analyze the area spectral efficiency (ASE) for network-level performance evaluations. The results show that both schemes are effective in suppressing interference. In particular, the EDAH scheme can significantly improve the transmission reliabilities of users anywhere, while the EDAS scheme generally gains higher ASE at the expense of the transmission reliability of EUs.

INDEX TERMS Stochastic geometry, D2D and cellular coexisting network, Poisson hole process, success probability, area spectrum efficiency.

I. INTRODUCTION

A. MOTIVATION

The explosive growth of emerging devices and high-speed applications exacerbates the imbalance between the increasing demand of information transmission rate and the limited available spectrum resources in cellular networks. A promising approach is to introduce D2D communication in cellular networks, which can reduce the burdens of base stations (BSs), improve the spectrum utilization of the network and enable new proximity-based services, such as social networking applications and media sharing [1]–[5]. According to spectrum allocation schemes between D2D and cellular communications, there are D2D overlaid and underlaid cellular networks. In the former, part of cellular spectrum is dedicated for D2D communications, thereby avoiding the mutual interference between D2D and cellular communications but at the cost of low spectrum utilization. In the latter, D2D transmitters reuse the resource blocks of cellular users for direct communications [6]. The underlaid way, though, provides higher spectrum utilization, it introduces serious mutual interference and hence degrades the communication...
transmitter predicts the would-be interference to small cell BSs due to the criteria. In [20], the potential D2D protection, and the active D2D users leave holes around the BSs. For example, the authors in [7]–[9] focus the uplink cellular networks and set exclusion regions around the BSs, in which the interference from D2D transmitters to the BSs is suppressed, but in turn, cellular communication produce severe interference to D2D receivers. Reference [7] maximizes the potential throughput of D2D communication under the condition of ensuring a certain coverage probability of cellular links, and reference [8] searches for the optimal radius to maximize the overall system throughput. In [9], the relationship between the normalized exclusion radius and the average system spectral efficiency is studied. In [21], [22], the authors consider downlink cellular networks and set exclusion regions for cellular users, which only suppresses the interference from D2D communications to users, but does not consider the interference from BSs to DUs. Reference [10] considers a downlink cellular network with exclusion regions around BSs and analyzes the success probabilities and the area spectral efficiency (ASE) without considering edge users, who are strongly interfered by D2D transmitters due to spectrum sharing. Furthermore, besides the corollary 2 in [22] provides a boundary for considering the influence of holes, the point process of the active D2D transmitters in [7]–[10], [19]–[21] are approximated by the PPPs with same densities, which may cause underestimation of interference and the accuracy of approximation will be limited by the system parameters [23]. Therefore, no matter uplink or downlink cellular networks, the existing exclusion-based activation schemes cannot comprehensively suppress the mutual interference between the cellular communications and D2D communications. Moreover, the existing research based on the distribution of correlation between BSs and D2D transmitters is relatively few. Very recently, a hybrid spectrum allocation scheme in [11] between the two extremes of spectrum sharing and spectrum partitioning is applied in heterogeneous cellular networks, which not only has relatively high spectrum efficiency, but also can avoid serious SINR deterioration. Motivated by this, we will fill this gap through integrating hybrid spectrum allocation into the exclusion-based D2D activation scheme and provide insights for the theoretical analysis of cellular and D2D coexisting networks.

C. CONTRIBUTIONS
In this paper, we mainly focus on the interference suppression in D2D and cellular coexisting networks. We establish a stochastic geometry-based framework and analyze the success probabilities of both cellular and D2D users, transmitters and prohibits transmission if the interference exceeds the set threshold. In this way, D2D transmissions form an exclusion region around each small cell transmitter, which is a function of instantaneous channel gain. Recently, a D2D activation scheme based on physical exclusion regions has been widely studied [7]–[10], [21], [22], where each BS or cellular user has an exclusion region and only the D2D transmitters outside the exclusion regions are active. Based on this scheme, the active D2D transmitters also leave holes around the BSs. Therefore, if the D2D link quality is better than the cellular uplink quality, the potential D2D links choose the D2D communication mode, thus the BSs have interference protection, and the active D2D users leave holes around the BSs due to the criteria. In [20], the potential D2D transmitter predicts the would-be interference to small cell

B. RELATED WORK
Because of the capability of stochastic geometry to capture the irregularities and variabilities of node locations in real networks, it has been widely used to characterize the interference for providing theoretical insights in a variety of D2D networks [12]–[18]. To maintain the analytical tractability, most of D2D and cellular coexisting networks based on stochastic-geometry modeling used Poisson point processes (PPPs) to model the spatial distributions of D2D transmitters, the BSs and cellular users. Although the independent PPPs model is convenient for performance analysis and provides some useful insights for network design, this model is obviously not suitable for those scenarios where the spatial distributions of D2D transmitters and BSs exhibit correlations.

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respectively, where the active D2D transmitter-receiver pairs follow a bipolar Poisson hole process (PHP). The specific contributions are summarized as follows.

- We propose two exclusion-based D2D activation schemes with hybrid spectrum allocation (named EDAH) and spectrum sharing (named EDAS). Each BS has an exclusion region, and D2D links outside the exclusion regions are active. Based on the activation scheme, we further give a mathematical definition of cell region classification. The union of the exclusion regions of the BSs is the center region, and the remaining is the edge region. As a consequence, the cellular users located in the center and edge region are central users (CUs) and edge users (EUs), respectively.

- For EDAH, we provide an exact expression of success probability for EUs and bounding and approximative results of success probabilities for DUs and CUs. Based on the results of success probabilities, we further analyze the overall success probability. Different spectrum allocation only change the success probability of EUs, thus we give the bound of the success probability of EUs in EDAS. The simulation results verify the accuracy of exact result, the tightness of bound and the effectiveness of approximations.

- Based on the results of success probabilities, we further derive the ASE of cellular tier and whole networks in both EDAH and EDAS schemes to evaluate network-level performance. In addition, we investigate the influence of systems parameters, such as the exclusion radius, DU density, on the ASE.

- We compare the results of the proposed EDAH, EDAS schemes and no interference suppression. The results show that both schemes can effectively suppress the mutual interference. EDAH can improve the transmission reliabilities of users anywhere and the ASE of cellular tier. In contrast, the EDAS scheme generally has higher ASE of the whole network at the expense of no improvement of the success probability of EUs.

In summary, the theoretical results provide deep insights for the intricate relationships among system parameters, and success probability as well as ASE performance, which is conducive to the parameter selection in system design.

The rest of the paper is organized as follows: Section II introduces the system model. Section III presents the analysis of the success probabilities in EDAH and EDAS schemes. Section IV explores the ASE performance. Section V gives the numerical results, and Section VI offers the concluding remarks.

II. SYSTEM MODEL

A. NETWORK MODEL

We consider a D2D and downlink cellular coexisting network. It is assumed that the BSs are distributed uniformly in the two-dimensional Euclidean space $\mathbb{R}^2$ according to a homogeneous PPP $\Phi_b$ with density $\lambda_b$ and operate at a constant transmit power $\mu_b$. The cellular users follow an independent PPP $\Phi_u$ with density $\lambda_u$. The potential DUs follow another independent PPP $\Phi_D$ with density $\tilde{\lambda}_D$. The independence assumption is made for the spatial distributions of potential D2D pairs, cellular users and BSs, where cellular users indicate the users without target neighbors and should communicate with the BSs, and the potential D2D pairs indicate the users having target neighbors and operating in the D2D mode. We denote by $h_i$ and $\ell(x)$ the small-scale path loss, respectively. We assume that the fading coefficients $h_i$ are i.i.d with exponential distributions (Rayleigh fading) and $\mathbb{E}[h_i] = 1$, and $\ell(x) = ||x||^{-\alpha}$, where $\alpha$ is the path loss exponent and $\alpha > 2$. We focus on an interference-limited network, i.e., ignoring the influence of thermal noise.

B. EXCLUSION-BASED D2D ACTIVATION SCHEME

Whether the potential D2D links are active is determined by the exclusion-based D2D activation scheme where the potential D2D pairs outside the exclusion regions choose the D2D mode and the remaining ones choose the cellular mode. In other words, the proposed scheme acts as the mode selection from the perspective of interference mitigation. Specifically, there is an exclusion region around each BS, and the inclusion model indicates the users without target neighbors and should communicate with the BSs, and the potential DUs outside the exclusion regions become cellular users. We further assume that each DU transmits with a constant power $\mu_D$ and has a dedicated receiver at distance $d$ in a random direction, thus the D2D transmitter-receiver pairs form a bipolar Poisson hole process (BPHP). The specific definition is given as follows.

Definition 1 (Poisson Hole Process [24]): Let $\Phi_b$ and $\Phi_D$ be two independent PPPs with density $\lambda_b$ and $\tilde{\lambda}_D$, respectively. For each $x \in \Phi_b$, remove all the points in $\Phi_D \cap c(x, R)$, where the $c(x, R)$ is a disk centered at $x$ with radius $R$. Then all the remaining points in $\Phi_D$ constitute a Poisson hole process (PHP) $\Phi_D$.

Definition 2 (Bipolar Poisson Hole Process): Each point in Poisson hole process has a dedicated partner located at distance $d$ in a random direction. These pairs form a bipolar PHP.

Based on the above analysis, the active DUs $\Phi_D$ have density of $\lambda_D = \tilde{\lambda}_D \exp(-\lambda_b \pi R^2)$, and communicate with their dedicated receivers without the participation of BSs. The cellular users have two parts: one is the original cellular users with density $\lambda_u$ and the other is inactivated DUs with density $\tilde{\lambda}_D (1 - \exp(-\lambda_b \pi R^2))$, and they all communicate with the nearest BS. Fig. 1 shows a realization of the network.

In the following, we will make a detailed description of the proposed schemes in combination with the adopted spectrum allocation:

- In order to improve the spectrum utilization in the network, we propose EDAS scheme, in which all users share the same spectrum. The scheme reduces the interference from BSs to DUs, and also makes CUs avoid the interference from nearby D2D transmitters.
However, EUs suffer from stronger interference in D2D and cellular coexisting networks than conventional cellular networks alone.

- We further propose EDAH scheme to protect EUs from the interference from D2D transmitters, which improves the transmission reliability of EUs. Specifically, a fraction of the spectrum resources are shared among DUs and CUs, and the remaining resources are used by EUs, and $a_1 + a_2 = 1$. For example, $a_1 = a_2 = 0.5$ means the total bandwidth is divided into two equal parts with 50% of the bandwidth allocated to CUs and DUs and the remaining 50% for the EUs [11].

C. USER CLASSIFICATION

Based on the exclusion regions, the whole plane is divided into two parts and cellular users are further classified into two types. The union of the exclusion regions is the center region, denoted by $C_1$, and the remaining region is the edge region, denoted by $C_2$. Based on the mode selection scheme, the cellular users can be divided into two types: the ones in exclusion regions are CUs and the others are EUs. Next, the mathematical definitions of these two regions are given,

$$C_1 = \bigcup_{x \in \Phi_b} c(x, R),$$
$$C_2 = \mathbb{R}^2 \setminus C_1. \quad (1)$$

Due to the ergodicity of the PPP, the area fraction of two regions are equivalent to the probabilities that the typical user at the origin falls into the two regions, respectively, given by

$$P_{in} = \mathbb{P}(o \in C_1) = 1 - \exp(-\lambda_b \pi R^2),$$
$$P_{eg} = \mathbb{P}(o \in C_2) = \exp(-\lambda_b \pi R^2). \quad (2)$$

Fig. 2 shows the area fraction of the two regions with $R$.

Remark 1: The user classification in [25] is based on the relative distance between the user and the serving BS and the interfering BSs, where the area fraction can be from 0 to 1.

The user classification in this paper is based on the exclusion regions. Note that $R = 0$ results in $C_2 = \mathbb{R}^2$. With the increase of $R$, the area fraction of $C_1$ will only be closer to 1.

Remark 2: Based on the above analysis, there are three kinds of users in the network: CUs, EUs and DUs. Their densities are: $\lambda_c = (\lambda_u + \lambda_D)P_{in}$, $\lambda_e = \lambda_u P_{eg}$, and $\lambda_D = \lambda_D P_{eg}$.

D. SIGNAL-TO-INTERFERENCE RATIO ANALYSIS

Due to the stationarity of PPPs, we assume that the typical user is located at the origin. The signal-to-interference ratio (SIR) of the user is defined as

$$\text{SIR} = \frac{\mu_{x_0} h_{x_0} \ell(x_0)}{I} \quad (3)$$

where $x_0$ is the transmitter corresponding to the typical user, $\mu_{x_0}$ is the transmit power of $x_0$, and $I$ is the total interference power. According to the communication mode, $x_0$ could be the serving BS or a dedicated D2D transmitter, and thus $\mu_{x_0}$ is equal to $\mu_b$ or $\mu_D$. The following is a detailed analysis of the interference to three types of users, and we denote by $I_{CU}$, $I_{EU}$, $I_{DU}$ the interference suffered by CUs, EUs and DUs, respectively.

- The CUs suffer from two types of interference: one is from BSs other than serving BS, denoted by $I_{bc}$, and the other is from D2D transmitters $I_{DC}$. Therefore, we have $I_{CU} = I_{bc} + I_{DC}$, where

$$I_{DC} = \sum_{x \in \Phi_D} \mu_b h_x \ell(x),$$
$$I_{bc} = \sum_{x \in \Phi_b \setminus x_0} \mu_b h_x \ell(x). \quad (4)$$

- The EUs suffer from two types of interference: one is from BSs other than serving BS, denoted by $I_{bc}$, and the other is from D2D transmitters $I_{DE}$. Since the EUs operate in a dedicated frequency band in EDAH, $I_{DE} = 0.$
Therefore, we have $I_{EU} = I_{be} + I_{De}$, where

$$I_{De} = \sum_{x \in \Phi_D} \mu_D h_s \ell(x) \quad \text{for EDAS}$$

$$I_{be} = \sum_{x \in \Phi_b \setminus \Phi_D} \mu_b h_s \ell(x). \quad (5)$$

- The DUs suffer from interference from BSs $I_{BD}$ and other D2D transmitters $I_{DD}$, thus, we have $I_{DU} = I_{BD} + I_{DD}$, where

$$I_{DD} = \sum_{x \in \Phi_D} \mu_D h_s \ell(x),$$

$$I_{BD} = \sum_{x \in \Phi_b} \mu_b h_s \ell(x). \quad (6)$$

The success probability is defined as the complementary cumulative distribution function (CCDF) of the SIR. The general expression of success probabilities for different types of users is

$$p_s(\theta) = \mathbb{P}[\text{SIR} > \theta]$$

$$= \int_0^\infty \mathbb{P}(h_{\Theta} > \theta \mu^{-1} r^2 I)f_{|\Theta|}(r)dr$$

$$= \int_0^\infty L_s(\theta \mu^{-1} r^2 I)f_{|\Theta|}(r)dr, \quad (7)$$

where step (a) is derived from the assumption that $h_{\Theta}$ follows an exponential distribution and $f_{|\Theta|}(r)$ is the probability density function (pdf) of the serving distance for users. According to the user type, $\theta$ is $\theta_c$ for cellular users and $\theta_D$ for DUs.

It should be noted that for the analysis of the success probability, the main difficulty lies in how to obtain $f_{|\Theta|}(r)$ and the Laplace transform of the interference. First, the pdfs $f_{|\Theta|}$ for the three types of users is derived using the conditional pdf, and we have

$$f_{|\Theta|}(r) = \begin{cases} 
  h(r)/P_{in} & 0 < r \leq R \quad \text{for CU} \\
  h(r)/P_{eg} & R < r < \infty \quad \text{for EU} \\
  q(r-d) & 0 < r \leq \infty \quad \text{for DU},
\end{cases} \quad (8)$$

where $h(r)$ is the contact distance function for a PPP, i.e., $h(r) = e^{-\lambda_b \pi r^2 2\pi \lambda_b \ell}$ [26] and $q(r)$ is the Dirac delta function. Second, the Laplace transform of interference is highly related to the spatial distribution of interfering nodes. For the interference from BSs, it is easy to derive the Laplace transform due to the PPP model for BS deployment. However, the PHP model for active D2D transmitters, which does not have an explicit expression of probability generating functional, makes it difficult to derive the exact result of the Laplace transform of interference from D2D transmitters. Hence we turn to the following methods to give the bounds or approximations of the analytical results.

- **Bound**: Considering that potential D2D transmitters in the exclusion regions transmit the dummy signal, this causes an overestimation of the interference and gives a bounding result of the Laplace transform.

- **PPP Approximation**: We approximate the PHP $\Phi_D$ using a PPP $\Phi_{PP}$ with the same density, i.e., $\lambda_{PP} \approx \delta D \exp(-\lambda_b \pi R^2)$ and thus an approximation to the Laplace transform of the interference is obtained.

- **Thomas Cluster Process (TCP) Approximation**: Due to the existence of exclusion regions, the active D2D transmitters exhibit clustered behavior to some extent. Based on this, we use a TCP to approximate PHP by matching first- and second-order statistics. For the TCP, its parent nodes are distributed as PPP with $\lambda_p$ and the daughter nodes of each parent node follow normal distribution with variance $\sigma^2$ around the parent node, and all the daughter nodes form a TCP. The first-order statistic for moment matching is the density

$$\exp(-\lambda_b \pi R^2) = \lambda_p \bar{c}, \quad (9)$$

where $\bar{c}$ is the mean daughter number of each cluster. For motion invariant processes, the second-order statistics are expressed by the pair correlation function $g(r)$ [24]. For the TCP

$$g(r) = 1 + \frac{1}{4\pi \lambda_p \sigma^2} \exp(-\frac{r^2}{4\sigma^2}). \quad (10)$$

For the PHP, there is no expression to represent pair correlation function, so we use non-linear least squares method to fit the curve (nlinfit function in Matlab) and obtain $\lambda_p$ and $\sigma^2$. Then, we get $\bar{c}$ using (9).

The main abbreviations and their full terminology are summarized in Table 1.

### III. SUCCESS PROBABILITY ANALYSIS

In this section, we give the success probabilities of CU, EU and DU in EDAH and EDAS schemes. Then we give comparison of the success probabilities of different types of users without interference suppression.

#### A. SUCCESS PROBABILITY IN EDAH

1) **SUCCESS PROBABILITY OF CELLULAR USERS**

We first give the exact result of success probability for EUs, because EUs merely suffer the interference from BSs.

**Theorem 1**: Letting $\delta = 2/\alpha$, the success probability of the typical EU is

$$p_s^e = \frac{\pi \lambda_b}{P_{eg}} \int_{R^2}^{\infty} L_{EU}(\theta_C \mu_b^{\alpha/2}/\mu_b) \exp(-\lambda_b \pi v)dv, \quad (11)$$

where

$$L_{EU}(s) = \exp \left(-\lambda_b \left( \frac{\pi^2 s}{\sin(\pi \delta)} \int_0^\infty \frac{\pi dz}{1 + (s \mu_b^{-1} z^{1/\delta})} \right) \right). \quad (12)$$

**Proof**: See Appendix A.

- **Bound**: Considering that potential D2D transmitters in the exclusion regions transmit the dummy signal, this causes an overestimation of the interference and gives a bounding result of the Laplace transform.

CUs are interfered by the D2D transmitters, and it is difficult to get an exact expression of the interference, thus we give bound and approximations on the success probabilities of CUs through the three approaches described in Sec. II-D.
In the following theorem, we give the bound on the success probability of CUs.

Theorem 2: The lower bound on success probability for the typical CU is

\[ p_s^c \geq \frac{\pi \lambda_b}{P_{\text{in}}} \int_0^R L_{\text{bc}} \left( \frac{\theta_{\text{CU}} \rho / 2}{\mu_b} \right) L_{\text{tx}} \left( \frac{\theta_{\text{CU}} \rho / 2}{\mu_b} \right) e^{-\lambda_b \pi \rho \theta} \, dv, \quad (13) \]

where

\[ L_{\text{bc}} (s) = \exp \left( -\zeta \lambda_b \left( \frac{\pi^2 \delta (s \mu_d)^{\delta}}{\sin (\pi \delta)} - H_c (s, R) \right) \right). \quad (14) \]

\[ H_c (s, R) = 2 \pi \int_{R - \sqrt{\pi}}^{R + \sqrt{\pi}} \frac{1 + \nu^2 (s \mu_d)^{-1}}{1 + \nu^2 (s \mu_d)^{-1}} \, dv, \quad (15) \]

\[ L_{\text{bc}} (s) = \exp \left( -\lambda_b \left( \frac{\pi^2 \delta (s \mu_d)^{\delta}}{\sin (\pi \delta)} - \int_{0}^{\nu} 1 + (s \mu_d)^{-1} \right) \right). \quad (16) \]

Proof: See Appendix B.

First, the approximation of success probability for CUs can be obtained by approximating \( \Phi_D \) to \( \Phi_{\text{PPP}} \) with the same density \( \lambda_D \). Denote by \( L_{\text{DC,PPP}} \) the interference from the approximate point process \( \Phi_{\text{PPP}} \) to the typical CU. Considering the exclusion region, we also exclude D2D transmitters falling into the region \( \Theta_b \), and we have

\[ L_{\text{DC,PPP}} (s) = \exp \left( -\lambda_D \left( \frac{\pi^2 \delta (s \mu_d)^{\delta}}{\sin (\pi \delta)} - H_c (s, R) \right) \right). \quad (17) \]

We can get the approximation of success probability for CUs

\[ p_s^c \approx \frac{\pi \lambda_b}{P_{\text{in}}} \int_0^R L_{\text{bc}} \left( \frac{\theta_{\text{CU}} \rho / 2}{\mu_b} \right) L_{\text{DC,PPP}} \left( \frac{\theta_{\text{CU}} \rho / 2}{\mu_b} \right) e^{-\lambda_b \pi \rho \theta} \, dv. \quad (18) \]

Then we use a TCP to approximate \( \Phi_D \) by matching first- and second-order statistics. \( L_{\text{DC,PPP}} (s) \) represents the Laplace transform of interference of the typical user at the user, which comes from the transmitters following the TCP. Letting \( \tilde{\ell} (x) = \ell (x) \chi_{x \in \mathbb{R}^2 \setminus \Theta_b}, \) we have [27]

\[ L_{\text{TCP}} (s) = \exp \left( -\lambda_D \int_{\mathbb{R}^2} \left[ 1 - \exp (-\tilde{\tau} w (x, y)) \right] \, dv \right), \quad (19) \]

where

\[ w (s, y) = \int_{\mathbb{R}^2} \left[ 1 + (s \mu_d (x - y) - 1) \, dx, \right. \]

\[ \tilde{\tau} (x) = \frac{1}{2 \pi \sigma^2} \exp \left( \frac{|x|^2}{2 \sigma^2} \right). \quad (20) \]

This quadruple integral needs to be converted into polar coordinates for calculation and can be simplified as

\[ L_{\text{TCP}} (s) = \exp \left( -\lambda_D \int_{0}^{\infty} \left[ 1 - \exp \left( -\tilde{\tau} \rho (r_2, \theta_2) \right) \right] r_2 d r_2 d \theta_2 \right). \quad (21) \]

where

\[ \rho (r_2, \theta_2) = \int_{f_1 (v)}^{2 \pi} \frac{\theta (r_1, r_2, \theta_1, \theta_2)}{1 + s \rho (r_2, \theta_2)} \, dr_1 d \theta_1, \]

\[ \theta (r_1, r_2, \theta_1, \theta_2) = \frac{1}{2 \pi \sigma^2} \exp \left( \frac{r_1^2 + r_2^2 + 2 r_1 r_2 \cos (\theta_1 + \theta_2)}{2 \sigma^2} \right), \]

\[ f_1 (v) = \begin{cases} R - \sqrt{v}, & v \leq R, \\ 0, & \text{otherwise}. \end{cases} \quad (22) \]

Substituting \( L_{\text{TCP}} (s) \) to \( L_{\text{DC,PPP}} (s) \) in (18), the TCP approximate results of success probability for CUs can be obtained.

Combining the results of EUs and CUs, we have the success probability for an arbitrary cellular user, given by

\[ \tilde{p}_c = \frac{\lambda_c}{\lambda_c + \lambda_e} p_s^c + \frac{\lambda_c}{\lambda_c + \lambda_e} p_s^e. \quad (23) \]

2) SUCCESS PROBABILITY OF DUs

We first analyze the fixed distance between the D2D transmitter and receiver. In order to make the results more complete, we then assume that the D2D receiver is distributed in the circle centered as its transmitter with radius \( D \) to supplement the results of fixed transmitting distance.

In general, D2D links occur in a short range, we assume that the link distance is less than the exclusion radius (i.e., \( d < R \)). DUs are also interfered by the D2D transmitters, and similarly to CUs, we give bound and approximations on the success probabilities of DUs.

The bound on the success probability of DUs is given in the following theorem.
\textbf{Theorem 3:} The lower bound of success probability for the typical DU is
\begin{equation}
 p^D_s > L_{\text{hd}} \left( \frac{\theta_D d^a}{\mu_D} \right) L_{\text{hd}} \left( \frac{\theta_D d^a}{\mu_D} \right)
\end{equation}
where
\begin{equation}
 L_{\text{hd}}(s) = \exp \left( -\lambda_h \frac{\pi^2 \delta (s \mu_D)^6}{\sin(\pi \delta)} \right)
\end{equation}

\textbf{Proof:} See Appendix C.

First, we give the success probability of DUs using PPP approximation approach. Denote by $I_{DD, \text{PPP}}$ the interference from the approximate point process $\Phi_{\text{PPP}}$ to the typical DU, and its Laplace transform is
\begin{equation}
 L_{\text{DD,PPP}}(s) = \exp \left( -\lambda_D \frac{\pi^2 \delta (s \mu_D)^6}{\sin(\pi \delta)} \right).
\end{equation}
Regardless of the exclusion between the BSs and the D2D transmitters, the Laplace transform of the interference from BSs to the typical DU is approximately by
\begin{equation}
 L_{\text{hd}}(s) = \exp \left( -\lambda_h \frac{\pi^2 \delta (s \mu_D)^6}{\sin(\pi \delta)} \right).
\end{equation}
Hence, the success probability of DUs can be approximated as
\begin{equation}
 p^D_s \approx L_{\text{hd}} \left( \frac{\theta_D d^a}{\mu_D} \right) L_{\text{DD,PPP}} \left( \frac{\theta_D d^a}{\mu_D} \right).
\end{equation}

Next, we give the success probability of DUs using TCP approximation approach. Similar to the analysis of CUs, we use $L_{\text{hd, TCP}}(s)$ to represent the Laplace transform of interference from other transmitters in the TCP for the typical DU located at $z(d, 0)$. According to [28], we have
\begin{equation}
 L_{\text{hd, TCP}}(s) = \exp \left( -\lambda_p \int_{R^2} \left[ 1 - \exp(-\tilde{v}(s, y)) \right] dy \right)
 \times \int_{R^2} \exp(-\tilde{v}(s, y)) f(y) dy,
\end{equation}
where
\begin{equation}
 v(s, y) = \int_{R^2} \frac{\theta(x)}{1 + (s \mu_D(x - y - z))^{-1}} dx.
\end{equation}
Substituting $L_{\text{hd, TCP}}(s)$ to $L_{\text{DD,PPP}}(s)$ in (28), the TCP approximate results of success probability for DUs can be obtained.

In order to make the results more general, we consider the fact that the transmitting distance of D2D pairs is random and give the success probability of DUs. For instance, we assume that the D2D receiver is located in the circle centered at the its transmitter with radius $D$, i.e., the distance $d$ from the receiver to its transmitter is distributed as $f_d(t) = \frac{2D}{D^2} I_{0 \leq D}$. Hence, the lower bound and PPP approximation of success probability of the typical DU are:
\begin{equation}
 p^D_s > \int_{0}^{D} L_{\text{hd}} \left( \frac{\theta_D d^a}{\mu_D} \right) L_{\text{hd}} \left( \frac{\theta_D d^a}{\mu_D} \right) \frac{2t}{D^2} dt,
\end{equation}
\begin{equation}
 p^D_s \approx \int_{0}^{D} L_{\text{hd}} \left( \frac{\theta_D d^a}{\mu_D} \right) L_{\text{DD,PPP}} \left( \frac{\theta_D d^a}{\mu_D} \right) \frac{2t}{D^2} dt.
\end{equation}
Substituting $L_{\text{hd, TCP}}(s)$ to $L_{\text{DD,PPP}}(s)$ in (32), the TCP approximate results of success probability for DUs in this case can be obtained. Furthermore, it can be easily extended to other random cases with the explicit probability distributions.

3) THE OVERALL SUCCESS PROBABILITY
For an arbitrary user (either cellular or D2D user), the probabilities of being a CU, EU and DU are discussed in previous section. Therefore, the overall success probability is obtained via the total success probability formula, given by
\begin{equation}
 p_s = \frac{\lambda_c}{\lambda_a + \lambda_D} p^C_s + \frac{\lambda_e}{\lambda_u + \lambda_D} p^E_s + \frac{\lambda_D}{\lambda_u + \lambda_D} p^D_s.
\end{equation}

\textbf{B. SUCCESS PROBABILITY IN EDAS}
Since spectrum allocation only affects the success probability of EUs, the success probabilities of CUs and DUs are consistent with those with EDAD. When considering the EDAS scheme, we need to consider the interference from D2D transmitters to EUs, which highly depends on the spatial distribution of D2D transmitters. Hence we give the lower bound on the success probability of EUs.

\textbf{Corollary 1:} The bound on success probability for typical EU with EDAS scheme is
\begin{equation}
 p^E_s > \frac{\pi \lambda_c}{P_{eq}} \int_{R^2} \mathcal{L}_{\text{EU}} \left( \frac{\theta_{C_{y \theta/2}}}{\mu_b} \right) \mathcal{L}_{\text{EU}} \left( \frac{\theta_{C_{y \theta/2}}}{\mu_b} \right) e^{-\tilde{v} \beta \pi v} dv,
\end{equation}
where
\begin{equation}
 \mathcal{L}_{\text{EU}}(s) = \exp \left( -\lambda_D \frac{\pi^2 \delta (s \mu_D)^6}{\sin(\pi \delta)} - H_c(s, R) \right),
\end{equation}
\begin{equation}
 H_c(s, R) = 2 \sqrt{\pi + R} \frac{\arccos(\frac{\sqrt{\pi + R}^2 - R^2}{2s})}{\frac{\sqrt{\pi + R}^2 - R^2}{2s}} dy.
\end{equation}
\textbf{Proof:} See Appendix D.

\textbf{C. COMPARISON WITH NO SCHEME AND OTHER SCHEME}
1) \textbf{COMPARISON WITH NO SCHEME}
In this section, we compare the success probabilities of three kinds of users when no scheme is applied, which shows that three kinds of users benefit from our proposed schemes.
When the EDAH and EDAS schemes are not considered, all D2D links are active and EUs suffer from the interference from D2D transmitters $I_{cD}$. $\mathcal{L}_{hc}(s)$ and $\mathcal{L}_{hb}(s)$ are the same as (44) and (16), and the Laplace transforms of the other types of interference are as follows,

$$\mathcal{L}_{hc}(s) = \mathcal{L}_{hb}(s) = \exp\left(-\frac{\pi^2 \delta (s\mu_D)^\delta}{\sin(\pi \delta)}\right).$$

Substituting the items in (36) into general formulation (7), we obtain the success probabilities of EUs, CUs and DUs in this case, respectively.

**Remark 3:** When the activation scheme is not considered, the exclusion regions are merely used to classify cellular users, and thus we can compare the performance for different types of users with that using the activation scheme.

2) **COMPARISON WITH OTHER SCHEME**

In this section, we compare with the case that the exclusion regions are around the cellular users (ERCU), which is also a common scheme to suppress mutual interference in D2D and cellular coexisting network [21],[22]. We assume that the density of cellular users is the same as that of BSs, i.e., $\lambda_u = \lambda_c$ and each cellular user has an exclusion region. The D2D transmitters outside the exclusion regions are active, and all users share the downlink spectrum. In this case, the lower bounds on the success probabilities of the cellular and D2D users are given by

$$p^c_s > \pi \lambda_b \int_0^\infty \mathcal{L}_{hc} \left(\frac{\theta_c v^{\alpha/2}}{\mu_b}\right) e^{-\lambda_b \pi v} dv, \quad (37)$$

where $\mathcal{L}_{hc}(s)$ is the same as (16), and

$$\mathcal{L}_{hc} = \exp\left(-\lambda_D \left(\frac{\pi^2 \delta (s\mu_b)^\delta}{\sin(\pi \delta)} + \int_0^R \frac{\pi dv}{1+(s\mu_b)^{-1}}\right)\right),$$

$$p^c_s > \mathcal{L}_{hc} \left(\frac{\theta_c d^{\alpha}}{\mu_D}\right) \mathcal{L}_{hc} \left(\frac{\theta_D d^{\alpha}}{\mu_D}\right),$$

where $\mathcal{L}_{hc}(s)$ is the same as (36), and

$$\mathcal{L}_{hc}(s) = \exp\left(-\frac{\pi^2 \delta (s\mu_D)^\delta}{\sin(\pi \delta)}\right).$$

**IV. ASE ANALYSIS**

Since the previous analysis on the success probability merely reflects the link-level performance, in this section, we analyze the network-level performance in terms of ASE for the D2D and cellular coexisting networks.

- The ASE in EDAH: Under a fixed-rate transmission based on the SIR threshold, the ASE is given by

$$\text{ASE} = \lambda_b \log_2(1+\theta_c) + \lambda_D p^D_s \log_2(1+\theta_D),$$

where $p^c_s$ and $p^D_s$ are in the (13), (11) and (24), respectively.

**V. NUMERICAL RESULTS**

In this section, we present numerical results of various performance metrics involved in the framework in Section III and IV for D2D and cellular coexisting networks. How to choose the radius is related to the specific system parameters and the concerned performance. Given the system parameters such as the density of BSs and the path loss exponent, the relationship between success probability (or ASE) and exclusion radius is studied with the explicit expressions and the optimal (or sub-optimal) radius is obtained via plotting the curves or some heuristic algorithms, such as genetic algorithm and particle swarm optimization algorithm. The main symbols and parameters are summarized in Table 2, and default values are given where applicable.

**A. SUCCESS PROBABILITY PERFORMANCE TRENDS**

Fig. 3 illustrates the success probability of CUs as a function of $\theta_c$ in a D2D and cellular coexisting network. Since the success probability of CUs is not affected by the hybrid spectrum allocation we proposed, it is equal under the EDAH and EDAS schemes. The lower bound derived for the success probability is quite tight, and the approximations using independent thinning PPP and the fitted TCP match the simulation

\[\text{FIGURE 3. Success probability of CUs with } R = 35.\]
TABLE 2. Symbols and descriptions.

| Symbol          | Description                                      | Default value |
|-----------------|--------------------------------------------------|---------------|
| $\Phi_{b,\lambda_b}$ | The PPP of BSs and its density                    | $2 \times 10^{-4}$ |
| $\Phi_{D,\lambda_D}$ | The PPP of potential D2D transmitters and its density | 0.01          |
| $\Theta_{D,\lambda_D}$ | The PHP of active D2D transmitters and its density | N/A           |
| $\alpha$       | Path loss exponent                               | 4             |
| $h_f$          | Small-scale fading channel gain                  | N/A           |
| $R$            | The exclusion radius of BSs                      | 35            |
| $\mu_{b,\mu_D}$ | The transmitting power of BSs and D2D transmitters | 40 W/0.5W     |
| $a_1$          | The fraction frequency band allocated to CUs and DUs | 0.9           |
| $d$            | The fixed distance of D2D transmitter-receiver pairs | 3             |
| $\theta_C,\theta_D$ | SIR threshold for cellular user and DU         | 0 dB          |

Fig. 4 shows how exclusion radius $R$ affects the success probability of CUs. It can be seen that the success probability decreases with the increase of exclusion radius. The larger radius means that the distance from CUs to serving BSs will increase, which will reduce the desired signal, thus the success probability will decrease. Furthermore, the gap (SIR gain) between the results with and with no scheme will increase with $R$, that is, the interference suppression is more effective.

Fig. 5 shows the success probability of EUs as a function of threshold $\theta_C$ in a D2D and cellular coexisting network. We can observe that the analytical results obtained with EDAH scheme match the simulation exactly, and the lower bound derived with EDAS scheme can also approximate the simulation results very tightly, which verifies the accuracy of our theoretical derivation and the validity of the bound. Moreover, it can be seen from the plot that the proposed hybrid spectrum allocation significantly improves the success probability of EUs, which verifies the effectiveness of EDAH for EUs. This is because the EDAH protects EUs from the interference from D2D transmitters.

Similar to the CUs, the hybrid spectrum allocation does not affect the success probability of DUs. Fig. 6 and 7 investigate the success probability of DUs as a function of $\theta_D$ for fixed distance and random distance, respectively. The fitting TCP
FIGURE 7. Success probability of DUs with random transmitting distance.

FIGURE 8. Overall success probability in EDAH with $R = 10$.

FIGURE 9. Overall success probability in EDAH.

parameters are $\lambda_p = 2.8997 \times 10^{-4}$, $\sigma^2 = 287.7966$, $\bar{c} = 15.9726$. We can see that the derived bounds are very tight. When the fixed link distance $d$ and radius $D$ increase, the success probability of DUs decrease due to the path loss of the desired signal. The results show that the trends of the success probability with random and fixed transmitting distance are the same, which means the more tractable analysis with fixed distance can be used to analyze and design the D2D networks sufficiently. Compared with the results with no scheme, the success probability of DUs has also been improved. Since the EDAH scheme makes BSs and DUs form spatial separation, the interference from BSs to DUs is reduced.

Fig. 8 illustrates the overall success probability of the network in EDAH scheme as a function of $\lambda_D$ where $\lambda_u = \lambda_D$. It can be observed from the plots that the overall success probability decreases with increase of the density of DUs. The higher the BS density is, the smaller the value decreases. This is because when the densities of DUs or BSs increase, the impact of CUs on the overall success probability increases, while that of DUs and EUs decreases. When the density of DUs is small, the overall success probability decreases with increase in the density of BSs. After the density of DUs increases to a certain value, the CU has a greater influence on the whole network, and the overall success probability increases with the increase of the density of BSs.

Fig. 9 shows the plot of the overall success probability versus $R$ in EDAH for different values of $\lambda_u$. We can see that the overall success probability increases first and then decreases with $R$. When the exclusion radius changes, the proportions of three users in the network have greater impacts on the overall success probability than the changes of their success probabilities. When $R$ increases, the influence of CUs on the overall users increases, while that of EUs or DUs decreases. At the beginning, the influence of CUs increases more, and when the exclusion radius increases to a certain value, the other two users decrease more. When the density of cellular users $\lambda_u$ increases, the proportion of CUs remains unchanged, while the proportions of DUs and EUs decreases and increases, respectively. The success probability of DUs is greater than that of EUs. Therefore, when the $R$ and $\bar{\lambda}_D$ are fixed, the higher the density of cellular users $\lambda_u$, the lower the overall success probability.

B. ASE PERFORMANCE TRENDS

Fig. 10 investigates how the density of potential DUs affects the ASE performance in EDAH for different $\lambda_b$ where $\lambda_u = \bar{\lambda}_D$. From the figure, we can see that the ASE increases first and then decreases with the density of potential DUs. There is an optimal density value that can make the ASE reach the maximum value. As $\bar{\lambda}_D$ increases, the density of BSs $\lambda_b$ increases accordingly, and the interference of the three types of users increases. ASE is initially determined by the increase of the densities of DUs and BSs. However, when the density increases to a certain value, the success probability decreases more, resulting in the decrease of the ASE. When the $\bar{\lambda}_D/\lambda_b$ is large, ASE depends on the DUs to a greater extent, which leads to a larger value of ASE, indicating that D2D communication can improve the ASE of the network.
In Fig. 11, the ASE in EDAH, EDAS, ERCU and no scheme are compared to illustrate the impact of these two schemes on the performance of ASE of the whole network. From the figure, we can clearly observe that both EDAH and EDAS scheme can improve the ASE of the networks, and the larger $R$ results in the more obvious effect. The ERCU scheme is slightly better than the result without no scheme, and worse than the result of our proposed two schemes. When the hybrid spectrum allocation scheme is applied, EUs communicate with the spectrum independent of CUs and DUs. Although this improves the success probability of the EUs, the available frequency band of the CUs and DUs is narrowed, which may lead to the decline of ASE when the exclusion radius is large. Therefore, network operators can reasonably determine whether to apply hybrid spectrum allocation strategy according to the adequacy of existing band resources and the link-level success probability of single user.

Accordingly, in Fig. 12, we study the ASE of the cellular tier in the same cases as in Fig. 11. It is observed that both EDAH and EDAS scheme can significantly improve the ASE of cellular tier. The result of ERCU is close to that of EDAS. As analyzed in Fig. 4, the success probability of cellular users decreases with the increase of exclusion radius, thus, the ASE of cellular tier with EDAH will decrease with $R$. When hybrid spectrum allocation is not applied, the overall success probability of cellular tier is taken into account because we assume that each BS serves only one cellular user at a time. The proportion of CUs in cellular users will increase with $R$, and the overall success probability may increase accordingly, which will lead to the increase of the ASE of cellular tier with no hybrid spectrum allocation. Compared with EDAS, EDAH scheme can obviously improve the ASE of cellular tier because it can improve the success probability of EUs.

VI. CONCLUSION

In this paper, we proposed EDAH and EDAS schemes to suppress the interference in a D2D and cellular coexisting network. Based on stochastic geometry, we not only provided success probability performance analysis for the different types of users and overall users, but also studied the ASE performance. The simulation results confirmed the accuracy of the analytical expressions, the tightness of the bounds and the effectiveness of approximations. The results show that both the schemes can effectively suppress interference, and the success probabilities of both CUs and DUs are significantly improved. Especially, the reliability of EUs can also be significantly improved when the EDAH scheme is applied. When EDAS and EDAH improve the performance of ASE of the whole network almost, EDAH can significantly improve the ASE of cellular tier compared with EDAS, which benefits from the improvement of success probability of EUs. In conclusion, we provided a good interference suppression technique, and the specific application depends on the emphasis of different performance. If network operator more focus on success probabilities, the EDAH scheme should be considered for application. If spectrum utilization is more focused, the EDAS scheme is should be applied. Our results also concretely demonstrate that for an effective interference.
management technique, it is very important to achieve a good balance between the link-level (transmission reliability of a link) and the network-level performance (spectrum utilization).

APPENDIXES

APPENDIX. A: PROOF OF THEOREM 1
Since EUs use the spectrum independent of DUs, they are not interfered by D2D transmitters, and the interference only comes from cellular communications. The Laplace transform of the interference from BSs to the EU is

\[
L_{h_b}(s) = \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_b \setminus \xi_0} \mu_b h_x \ell(x) \right) \right]
\]

\[
= \mathbb{E} \left[ \prod_{x \in \Phi_b \setminus \xi_0} \frac{1}{1 + s \mu_b \ell(x)} \right]
\]

\[
= \exp \left( -\lambda_b \left( \int_{\mathbb{R}^2} \frac{dx}{1 + (s \mu_b \ell(x))^{-1}} - \int_0^r \frac{2\pi x dx}{1 + (s \mu_b)^{-1}} \right) \right)
\]

\[
= \exp \left( -\lambda_b \left( \pi^2 \delta(s \mu_b)^\delta - \int_0^\beta \frac{\pi dz}{1 + (s \mu_b)^{-2z}} \right) \right). \quad (44)
\]

APPENDIX. B: PROOF OF THEOREM 2
Since the D2D transmitters are at least at distance \( R \) from the BSs, \( \hat{I}_{\text{D}} \) stochastically dominates the interference \( I_{\text{Dc}} \), where \( \hat{I}_{\text{Dc}} \) denotes the interference from D2D transmitters in \( \Phi_{\text{D}} \) except those are within the exclusion area of the serving BS. We denote by \( \xi_0 \) the exclusion area of the serving BS and the Laplace transform of \( \hat{I}_{\text{D}} \) is given as,

\[
L_{\text{hD}}(s) = \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_{\text{D}} \setminus \xi_0} \mu_D h_x \ell(x) \right) \right]
\]

\[
= \mathbb{E} \left[ \prod_{x \in \Phi_{\text{D}} \setminus \xi_0} \frac{1}{1 + s \mu_D \ell(x)} \right]
\]

\[
= \exp \left( -\lambda_D \left( \int_{\mathbb{R}^2} \frac{dx}{1 + (s \mu_D \ell(x))^{-1}} - H_{\text{c}}(s, R) \right) \right)
\]

\[
= \exp \left( -\lambda_D \left( \frac{\pi^2 \delta(s \mu_D)^\delta}{\sin(\pi \delta)} - H_{\text{c}}(s, R) \right) \right). \quad (45)
\]

where

\[
H_{\text{c}}(s, R) = \int_0^{2\pi} \int_0^r \frac{\cos x + \sqrt{R^2 - r^2 \sin^2 x}}{1 + \gamma^a(s \mu_D)^{-1}} \frac{y dy d\phi}{1 + \gamma^a(s \mu_D)^{-1}}, \quad (46)
\]

the serving distance of CU is less than the exclusion radius \( r < R \), and \( H_{\text{c}}(s, R) \) is simplified to (15) by exchanging the orders of integration variables.

APPENDIX. C: PROOF OF THEOREM 3
\( I_{\text{D}} \) is stochastically dominated by the interference \( \hat{I}_{\text{D}} \), caused by the transmitters in \( \Phi_{\text{D}} \). The Laplace transform of \( \hat{I}_{\text{D}} \) is:

\[
L_{\hat{I}_{\text{D}}}(s) = \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_{\text{D}}} \mu_D h_x \ell(x) \right) \right]
\]

\[
= \exp \left( -\lambda_D \frac{\pi^2 \delta(s \mu_D)^\delta}{\sin(\pi \delta)} \right). \quad (47)
\]

The Laplace transform of the interference from BSs to the D2D receiver is

\[
L_{h_b}(s) = \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_b \setminus \xi_0} \mu_b h_x \ell(x) \right) \right]
\]

\[
= \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_b \setminus \xi_0} \mu_b h_x \ell(x) \right) - \sum_{x \in \xi_0} \mu_b h_x \ell(x) \right]
\]

\[
= \exp \left( -\lambda_b \frac{\pi^2 \delta(s \mu_b)^\delta}{\sin(\pi \delta)} - H_D(s, R) \right). \quad (48)
\]

where \( \xi_D \) denotes the exclusion region with radius \( R \) and centered at the location of transmitter corresponding to the typical DU, and

\[
H_D(s, R) = \int_0^{2\pi} \int_0^r \frac{\cos x + \sqrt{R^2 - r^2 \sin^2 x}}{1 + \gamma^a(s \mu_b)^{-1}} \frac{y dy d\phi}{1 + \gamma^a(s \mu_b)^{-1}}, \quad (49)
\]

and \( H_D(s, R) \) is simplified to (25) by exchanging the orders of integration variables.

APPENDIX. D: PROOF OF COROLLARY 1
Denote by \( I_{\text{Dc}} \) the interference from D2D transmitters to the typical EU. Similar to the CUs, the interference \( I_{\text{Dc}} \) is stochastically dominated by \( \hat{I}_{\text{Dc}} \), where \( \hat{I}_{\text{Dc}} \) is the interference from D2D transmitters in \( \Phi_{\text{D}} \) except those within the exclusion area of the serving BS. We denote by \( \xi_{\text{D}} \) the exclusion area of the serving BS and the Laplace transform of \( \hat{I}_{\text{D}} \) is given as,

\[
L_{\text{hD}}(s) = \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_{\text{D}} \setminus \xi_0} \mu_D h_x \ell(x) \right) \right]
\]

\[
= \mathbb{E} \left[ \exp \left( -s \sum_{x \in \Phi_{\text{D}} \setminus \xi_0} \mu_D h_x \ell(x) \right) \right]
\]

\[
= \exp \left( -\lambda_D \left( \frac{\pi^2 \delta(s \mu_D)^\delta}{\sin(\pi \delta)} - H_{\text{c}}(s, R) \right) \right), \quad (50)
\]

where

\[
H_{\text{c}}(s, R) = \int_{\arcsin \frac{R}{\sqrt{R^2 - y^2}} - \frac{r \cos x + \sqrt{R^2 - r^2 \sin^2 x}}{1 + \gamma^a(s \mu_D)^{-1}}} \frac{y dy d\phi}{1 + \gamma^a(s \mu_D)^{-1}}, \quad (51)
\]

the serving distance of EU is less than the exclusion radius \( r > R \), and \( H_{\text{c}}(s, R) \) is simplified to (35) by exchanging the orders of integration variables.

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