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The Impact of In-band Emission Interference in D2D-Enabled Cellular Networks

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***Abstract*—The overlay in-band device to device (D2D) scheme can be used by cellular user equipments (CUEs) and D2D user equipments (DUEs) to transmit the uplink and D2D data. The CUEs experience in-band emission interference (IEI) from the DUEs that transmit D2D signals in the adjacent channels. This paper evaluates the IEI impact in D2D-enabled cellular networks in terms of typical CUE outage probability for different DUE densities and DUE transmission powers. Further, the IEI intra-cell and IEI inter-cell are examined separately to determine the dominating part of IEI in the system. The results show the IEI impact has a harmful impact and causes the outage in the system with high probability when the DUE density is high. Also, a remarkable result finds that the IEI intra-cell and IEI inter-cell dominate the typical CUE outage probability similarly when the DUE density is low, whilst at high DUE density the IEI intra-cell does.**

I. INTRODUCTION

Device to device (D2D) communication is one of the technology components of the next generation networks, which enables devices to communicate directly without passing data traffic through a network infrastructure. The potential gains of D2D communication are: user data rate gain, latency gain, extended coverage, and reduced transmission power [1], [2]. D2D communication can also improve the spectral efficiency, where the frequency resources are reused within a cell [3]. The D2D links in the next generation cellular networks are expected to increase significantly [4], where an efficient frequency reused becomes highly demanded to cope with high D2D user equipments (DUE) densities.

By increasing the DUE density and reusing the frequency resources by multiple DUEs, the leakage power among adjacent channels increases and can be a serious problem in D2D-enabled networks. This leakage power is known by the in-band emission interference (IEI) [5]–[9]. Therefore, the IEI alongside with the co-channel interference should be analysed to evaluate accurately the cellular system performance. The IEI analysing also helps to propose new approaches to mitigate the IEI and improve the network performance.

[5]–[8] modelled the IEI in D2D-enabled cellular networks and proposed a power control schemes to alleviate it. [5] introduced the open loop power control to control the IEI. However, in this method, the DUEs experience unnecessary power constraints, which degrades the DUEs data rate. [6] and [7] proposed two new channel structure to relax the power constraints for open loop power control method, where the DUEs can increase the transmission power when the resource blocks in that particular time slot are only allocated to DUEs. [8] and [9] identified addition symbols to relax more the power constraint, where the DUEs can boost the transmission power without affecting the cellular user equipments (CUEs). Despite the aforementioned studies, the lack of IEI analytic study is our motivation to analyse the IEI in D2D-enabled networks performance in terms of the outage probability of cellular system, where the stochastic geometry is used to model the network [10]–[12].

This paper investigates the IEI impact in D2D-enabled cellular networks, where the overlay in-band D2D scheme is used (orthogonal spectrum between CUEs and DUEs). The cellular system performance is theoretically analysed, where the outage probability of a typical CUE at a reference base station (BS) is derived. Our results show the IEI is significant and cause outage with high probability when the DUEs density is high, which implies that the IEI should be taken into account in the case of D2D-enabled networks performance analysing and evaluation. Further, the outage probability is analysed in terms of the IEI intra-cell (IEI from the same cell) and IEI inter-cell (IEI from other cells), separately. The results show that the IEI intra-cell and IEI inter-cell affect the outage probability similarly when the DUEs density is low, whilst the IEI intra-cell dominates when the DUEs density is high. We evaluate the typical CUE outage probability under different DUEs parameters (DUE density and DUE transmission powers). The numerical results in this paper are validated by simulation.

The reminder of the paper is organized as follows. In Section II, the system model of D2D-enabled cellular networks is described. In Section III, the outage probability of cellular system is analysed. Numerical results are provided in Section IV. The conclusion is followed in Section V.

II. SYSTEM MODEL

The IEI impact is investigated under the overlay in-band D2D scheme, using the uplink channel model adopted in 3rd generation partnership project (3GPP) [6]- [8], which is described as follows. The CUEs use uplink cellular resource blocks (CRBs) to transmit the uplink traffic, while DUEs use D2D resource blocks (DRBs) to transmit D2D data. N_C and N_D represent the number of CRBs and DRBs in each time slot t, where $N_C + N_D = N$ and N is the total number of resource blocks (RBs) in the channel.

Consider D2D-enabled cellular orthogonal frequency division multiple access (OFDMA)-based cellular network with multiple cells. The locations of BSs, the active CUEs using the ith CRB, and the active DUEs using the jth DRBs in this network are modeled as independent Poisson point processes (PPPs) Φ, Φ_i, and Φ_j with density of λ, λ_i and Λ_j respectively, where

$$i \in \{1, 2, .., N_C\} \quad \text{and} \quad j \in \{1, 2, .., N_D\}.$$

A full load scenario is assumed, where each CRB is occupied by one CUE in each cell. Meanwhile, each DRB can be reused by different DUEs. The DUEs density using the jth DRB is given by $\Lambda_j = r_d \lambda_j$, where λ_j is the DUEs density using the jth DRB if each DRB is occupied by one DUE in each cell, and r_d is the reuse factor of each DRB in the network. The r_d is defined according to the following facts. Commonly, the RBs are allocated to the DUEs to satisfy the fairness and load balancing among DRBs. To achieve that, the number of DUEs using each DRB should be similar in each cell. Additionally, the expected number of active DUEs in each cell is the same, the uniform distribution of DUEs validate this approximation. For D2D side, we assume r_d satisfies constraint $0 \leq r_d \leq r_{max}$ to guarantee the minimum signal to interference and noise ratio (SINR) threshold requirement for each D2D link in the system, where r_{max} is a maximum reuse factor of each DRB. It is worth noting that λ_i and λ_j have the same value as λ in the network.

In this model, the signals experience distance dependent path loss with a path loss exponent α, and fast fading. The fast fading power gain follows the exponential distribution and it is given by $h \sim \exp(\mu)$, where μ is the average power. A fractional pathloss-inversion based power control is considered of form $x^{\alpha\epsilon}$, where $\epsilon \in [0, 1]$ is the power control factor. The distances are assumed independent and identically distributed (i.i.d) and follow a Rayleigh distribution [3]. Further, IEI from a DUE uses the jth DRB to a uplink CUE uses the ith CRB can be expressed in the form of

$$IeI_i = P_D h_{k,j} x_{k,j}^{-\alpha} \xi_{j,i},$$

where P_D is the transmission power of k DUE, $h_{k,j}$ and $x_{k,j}^{-\alpha}$ denote the channel gain and path-loss between the DUE and the serving BS, and $\frac{1}{\xi_{j,i}}$ is the adjacent channel interference ratio (ACIR)-the ratio of transmission power at the ith CRB to the power measured in the jth DRB [13]).

Since access to CRBs is orthogonal, the active CUEs density is significantly lower than the DUEs' and the impact of the leakage power among the CUEs is dominated by the IEI from the DUEs. Therefore, the leakage power among the CUEs is neglected.

Following the above assumption, we define the typical CUE as the closest uplink user to the serving BS that use ith CRB to transmit data in the typical cell, where the BS is centred at the origin as a reference. The uplink SINR of the typical CUE can be expressed as

$$SINR_i = \frac{P_C h_0 {x_0}^{\alpha(\epsilon-1)}}{I_i + IEI_i + \sigma^2}, \tag{1}$$

where P_C represents the constant baseline transmission power of CUEs. h_0 denotes the distance-independent channel gain between the reference BS and the typical CUE. x_0 is the distances between the reference BS and the typical CUE. R_m is the distance between the co-channel interferer CUEs and their serving BS. I_i denotes the cumulative co-channel interference from interferer CUEs at the reference BS. IEI_i is the cumulative IEI from interferer DUEs at the reference BS. σ^2 is the noise power. I_i is given by

$$I_i = \sum_{m \in \Phi_i / 0} P_C R_m^{\alpha\epsilon} h_m {x_m}^{-\alpha},$$

where R_m is the distance between the co-channel interferer CUEs and their serving BS. h_m denotes the distance-independent channel gain between the reference BS and the co-channel interferer CUEs from other cells. x_m is the distance between the reference BS and the co-channel interferer CUEs from other cells. Further, IEI_i is given by

$$IEI_i = \sum_{j=1}^{N_D} \sum_{k \in \Phi_j} P_D h_{k,j} {x_{k,j}}^{-\alpha} \xi_{j,i},$$

where P_D represents the transmission power of DUEs. $h_{k,j}$ denote the distance-independent channel gain between the reference BS and the typical CUE and the IEI interferer DUEs in the network. $x_{k,j}$ is the distance between the reference BS and the IEI interferer DUEs. $\xi_{j,i}$ represents a multiplicative inverse of ACIR between the ith CRB and jth DRB, which are used by typical CUE and IEI interferer DUEs, respectively.

III. THE CUE LINK OUTAGE PROBABILITY ANALYSIS

In this section, the typical CUE outage probability is derived for the whole network by taking into account the IEI impact, and defined in terms of IEI intra-cell and IEI inter-cell to examine the dominant part of IEI. Worth noting that the outage happens when the desired signals drops below the interference plus the noise power level. Thus, the outage probability in D2D-enabled cellular networks can be defined as the probability that the uplink SINR of the CUE at its serving BS is less than the SINR threshold β. The outage probability is analysed for one time slot, which can be generalized to all time slots.

The outage probability is averaged over the plane conditioned on the closest CUE (typical CUE) being at the distance x_0 from the serving BS as

$$P_{out}^{(i)} = \mathbb{E}_{x_0}\Big[\mathbb{P}(SINR_i \leq \beta \mid x_0)\Big]. \tag{2}$$

Since x_0 is assumed that follows a Rayleigh distribution, the outage probability can be rewritten as

$$\begin{aligned} P_{out}^{(i)} &= 1 - \int_0^\infty \mathbb{P}[SINR_i \geq \beta \mid x_0] f(x_0) dx_0 \\ &= 1 - \int_0^\infty \mathbb{P}[h_0 \geq \beta P_C^{-1} {x_0}^{\alpha(1-\epsilon)} (I_i + IEI_i + \sigma^2) \mid x_0] \\ &\qquad \cdot 2\pi\lambda_i x_0 e^{-\pi\lambda_i {x_0}^2} dx_0. \end{aligned} \tag{3}$$

Using the fact that $h_0 \sim \exp(\mu)$, the outage probability in (3) can be expressed as

$$\begin{aligned} P_{out}^{(i)} = \; & 1 - \int_0^\infty 2\pi\lambda_i x_0 e^{-\pi\lambda_i {x_0}^2} \\ & \cdot \mathbb{E}_{I_i}[\exp(-\beta\mu {P_C}^{-1} {x_0}^{\alpha(1-\epsilon)} I_i)] \\ & \cdot \mathbb{E}_{IEI_i}[\exp(-\beta\mu {P_C}^{-1} {x_0}^{\alpha(1-\epsilon)} IEI_i)] \\ & \cdot \exp(-\beta\mu {P_C}^{-1} {x_0}^{\alpha(1-\epsilon)} \sigma^2) dx_0. \end{aligned} \tag{4}$$

By letting $s = \beta\mu {P_C}^{-1} {x_0}^{\alpha(1-\epsilon)}$, the cumulative CUEs co-channel interference term $\mathbb{E}_{I_i}[\exp(-sI_i)]$ in (4) can be calculated as

$$\mathbb{E}_{I_i}[\exp(-sI_i)] = \exp\Big(-\pi\lambda_i \varrho(\beta, x_0, \epsilon, \alpha)\Big), \tag{5}$$

where

$$\varrho(\beta, x_0, \epsilon, \alpha) = \Big(\frac{\mu}{sP_C \mathbb{E}_{R_m}[R_m^{\alpha\epsilon}]}\Big)^{-\frac{2}{\alpha}} \int_{u(x_0)}^{\infty} \frac{1}{1 + u^{\frac{\alpha}{2}}} du, \tag{6}$$

and

$$u(x_0) = \Big(\frac{\mu}{sP_C \mathbb{E}_{R_m}[R_m^{\alpha\epsilon}]}\Big)^{\frac{2}{\alpha}} {x_0}^2.$$

$\mathbb{E}_{I_i}[\exp(-sI_i)]$ is averaged over h_m and R_m, and by using the probability generating functional (PGFL) of $\phi_{i/0}$ PPP. The integration limits of the PGFL are from x_0 to ∞ since the closest co-channel interferer is at least at a distance x_0. Furthermore, the cumulative IEI of interferer DUEs term $\mathbb{E}_{IEI_i}[\exp(-sIEI_i)]$ in (4) is derived in Appendix A and given by

$$\begin{aligned} & \mathbb{E}_{IEI_i}[\exp(-sIEI_i)] = \\ & \exp\Big(-\frac{\frac{2\pi^2}{\alpha}}{\sin\frac{2\pi}{\alpha}} r_d \lambda_j \big(\frac{\mu}{sP_D}\big)^{-\frac{2}{\alpha}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{2}{\alpha}}]\Big). \end{aligned} \tag{7}$$

The cumulative IEI of interferer DUEs can be also expressed in term of IEI intra-cell $\mathbb{E}_{IEI_i}^{(O)}[\exp(-sIEI_i)]$ and IEI inter-cell $\mathbb{E}_{IEI_i}^{(\hat{O})}[\exp(-sIEI_i)]$, and rewritten as follow

$$\begin{aligned} & \mathbb{E}_{IEI_i}[\exp(-sIEI_i)] = \\ & \mathbb{E}_{IEI_i}^{(O)}[\exp(-sIEI_i)]).\mathbb{E}_{IEI_i}^{(\hat{O})}[\exp(-sIEI_i)]. \end{aligned} \tag{8}$$

The IEI intra-cell presents the cumulative IEI of the interferer DUEs from the typical cell, and the IEI inter-cell presents the cumulative IEI of the interferer DUEs from other cells. By following the derivation in appendix A, the IEI intra-cell and IEI inter-cell can be given by

$$\begin{aligned} & \mathbb{E}_{IEI_i}^{(O)}[\exp(-sIEI_i)] = \\ & \exp\Big(-2\pi r_d \lambda_j \big(\frac{\mu}{sP_D}\big)^{-\frac{2}{\alpha}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{2}{\alpha}}] \int_0^{\mathfrak{R}} \frac{v}{1+v^\alpha} dv\Big), \end{aligned} \tag{9}$$

and

$$\begin{aligned} & \mathbb{E}_{IEI_i}^{(\hat{O})}[\exp(-sIEI_i)] = \\ & \exp\Big(-2\pi r_d \lambda_j \big(\frac{\mu}{sP_D}\big)^{-\frac{2}{\alpha}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{2}{\alpha}}] \int_{\mathfrak{R}}^{\infty} \frac{v}{1+v^\alpha} dv\Big), \end{aligned} \tag{10}$$

where the PGFL of ϕ_j integration limits is taken from 0 to $\mathfrak{R}$ for IEI intra-cell, and from $\mathfrak{R}$ to ∞ for IEI inter-cell, where $\mathfrak{R}$ is the typical cell radius. As a result, the outage probability of typical CUE is obtained by substituting (5) and (7), and plugging $s = \beta\mu P_C^{-1} {x_0}^{\alpha(1-\epsilon)}$ in (4). This gives

$$\begin{aligned} P_{out}^{(i)} = \; & 1 - \int_0^\infty 2\pi\lambda_i x_0 e^{-\pi\lambda_i {x_0}^2} \cdot \exp\Big(-\pi\lambda_i \varrho(\beta, x_0, \epsilon, \alpha)\Big) \\ & \cdot \exp\big(-\psi {x_0}^{2(1-\epsilon)}\big) \cdot \exp(-\beta\mu P_C^{-1} {x_0}^{\alpha(1-\epsilon)} \sigma^2) dx_0, \end{aligned} \tag{11}$$

where

$$\psi = \frac{\frac{2\pi^2}{\alpha}}{\sin\frac{2\pi}{\alpha}} r_d \lambda_j \beta^{\frac{2}{\alpha}} \big(\frac{P_D}{P_C}\big)^{\frac{2}{\alpha}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{2}{\alpha}}],$$

and the outage probability in terms of the IEI intra-call and IEI inter-cell can be obtained by substituting (5) and (8), and plugging $s = \beta\mu P_C^{-1} x^{\alpha(1-\epsilon)}$ in (4). This yields

$$\begin{aligned} P_{out}^{(i)} = \; & 1 - \int_0^\infty 2\pi\lambda_i x_0 e^{-\pi\lambda_i {x_0}^2} \cdot \exp\Big(-\pi\lambda_i \varrho(\beta, x_0, \epsilon, \alpha)\Big) \\ & \cdot \exp\big(-\varpi {x_0}^{2(1-\epsilon)}\big) \cdot \exp\big(-\varsigma {x_0}^{2(1-\epsilon)}\big) \\ & \cdot \exp(-\beta\mu P_C^{-1} {x_0}^{\alpha(1-\epsilon)} \sigma^2) dx_0, \end{aligned} \tag{12}$$

where

$$\varpi = 2\pi r_d \lambda_j \beta^{\frac{2}{\alpha}} \big(\frac{P_D}{P_C}\big)^{\frac{2}{\alpha}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{2}{\alpha}}] \Big(\int_0^{\mathfrak{R}} \frac{v}{1+v^\alpha} dv\Big), \tag{13}$$

and

$$\varsigma = 2\pi r_d \lambda_j \beta^{\frac{2}{\alpha}} \big(\frac{P_D}{P_C}\big)^{\frac{2}{\alpha}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{2}{\alpha}}] \Big(\int_{\mathfrak{R}}^{\infty} \frac{v}{1+v^\alpha} dv\Big). \tag{14}$$

To shed further light on the significance of the expression given by (11), it is instructive to consider a special case. We are able to derive the outage probability closed-form expression for the interference-limited regime $\sigma^2 = 0$, with $\alpha = 4$ and $\epsilon = 0$. The outage probability given by (11) becomes

$$\begin{aligned} P_{out}^{(i)} = \; & 1 - \int_0^\infty 2\pi\lambda_i x_0 \\ & \cdot \exp\Big(-\big(\pi\lambda_i + \pi\lambda_i \bar{\varrho}(\beta, \epsilon=0, \alpha=4) + \hat{\psi}\big) {x_0}^2\Big) dx_0. \end{aligned} \tag{15}$$

This follows from substituting $\varrho(\beta, x_0, \epsilon, \alpha)$ and ψ in (11) by

$$\varrho(\beta, x_0, \epsilon, \alpha) = \bar{\varrho}(\beta, \epsilon = 0, \alpha = 4) {x_0}^2,$$

and

$$\hat{\psi} = \frac{\frac{\pi^2}{2}}{\sin\frac{\pi}{2}} r_d \lambda_j \beta^{\frac{1}{2}} \big(\frac{P_D}{P_C}\big)^{\frac{1}{2}} \sum_{j=1}^{N_D} \xi_{j,i}^{\frac{1}{2}}.$$

From (6), we can calculate $\bar{\varrho}(\beta, \epsilon = 0, \alpha = 4)$ as

$$\begin{aligned} \bar{\varrho}(\beta, \epsilon = 0, \alpha = 4) = \; & \beta^{\frac{1}{2}} \int_{\beta^{-\frac{1}{2}}}^{\infty} \frac{1}{1+u^2} du \\ = \; & \beta^{\frac{1}{2}} [\frac{\pi}{2} - tan^{-1}(\beta^{-\frac{1}{2}})]. \end{aligned} \tag{16}$$

By substituting (16) and letting $z = {x_0}^2$ in (15), we get the closed-form of outage probability as

$$\begin{aligned} P_{out}^{(i)} = \; & 1 - \int_0^\infty \pi\lambda_i \\ & \cdot \exp(-(\pi\lambda_i + \pi\lambda_i \bar{\varrho}(\beta, \epsilon = 0, \alpha = 4) + \hat{\psi}) z) dz \\ = \; & \frac{\beta^{\frac{1}{2}}[\frac{\pi}{2} - tan^{-1}(\beta^{-\frac{1}{2}})] + \frac{\hat{\psi}}{\pi\lambda_i}}{1 + \beta^{\frac{1}{2}}[\frac{\pi}{2} - tan^{-1}(\beta^{-\frac{1}{2}})] + \frac{\hat{\psi}}{\pi\lambda_i}}. \end{aligned} \tag{17}$$

TABLE I: System Parameters

Parameters	Values
Path loss exponent α	4
Power control factor ϵ	0
Transmission power P_C, P_D	23 dBm, 20 dBm
DUE Transmission power P_D	20 dBm
Density $\lambda_i = \lambda_j = \lambda$	0.25 (CUEs,DUEs)/km^2
Number of D2D resources N_D	44 [15], [16]
Number of Uplink resources N_C	6 [15], [16]
D2D resources indices j	4 to 47 [15], [16]
Uplink resources indices i	from 1 to 3,48 to 50

By following the same approach in (17), we find the outage probability in term of IEI intra-cell and IEI inter-cell as

$$P_{out}^{(i)} = \frac{\beta^{\frac{1}{2}}[\frac{\pi}{2} - tan^{-1}(\beta^{-\frac{1}{2}})] + \frac{\hat{\varpi}+\hat{\varsigma}}{\pi\lambda_i}}{1 + \beta^{\frac{1}{2}}[\frac{\pi}{2} - tan^{-1}(\beta^{-\frac{1}{2}})] + \frac{\hat{\varpi}+\hat{\varsigma}}{\pi\lambda_i}}, \qquad (18)$$

where

$$\hat{\varpi} = 2\pi r_d \lambda_j \beta^{\frac{1}{2}} (\frac{P_D}{P_C})^{\frac{1}{2}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{1}{2}}] \Big(\int_0^{\mathfrak{R}} \frac{v}{1+v^4} dv \Big),$$

and

$$\hat{\varsigma} = 2\pi r_d \lambda_j \beta^{\frac{1}{2}} (\frac{P_D}{P_C})^{\frac{1}{2}} \sum_{j=1}^{N_D} [\xi_{j,i}^{\frac{1}{2}}] \Big(\int_{\mathfrak{R}}^{\infty} \frac{v}{1+v^4} dv \Big).$$

It is worth noting that the IEI impact changes according to the location of CRB [14]. Thereby, the expected value of outage probability over the given CRBs can be calculated as

$$\bar{P}_{out} = \sum_{i}^{N_c} \frac{P_{out}^{(i)}}{N_C}. \qquad (19)$$

IV. NUMERICAL RESULTS

This section provides the numerical results for D2D-enabled cellular networks, which are all averaged over all CRBs by using (19). The system parameters are given in Table. I, and the leakage power model is given by $\xi_{j,i} = -21 - 5\,|j - i|$ in dB [14].

Fig. 1 shows the IEI impact on the typical CUE outage probability for different values of SINR threshold at the reference BS. We compare the results with no-IEI scenario in [11], [17], and [18]. The performance without considering the IEI is better than the case where the IEI is considered. The former case gives inaccurate results about the real cellular system performance, especially under high DUE density scenario. The typical CUE outage is caused mainly by co-channel interference, where the DUE density is small. However, under the high DUE density scenario, the dominating interference becomes the IEI, as shown in the figure, where the outage probability increases significantly if the reuse factor $r_d > 5$.

Fig. 2 depicts the effect of the distance between the typical CUE and the reference BS x_0 on the outage probability for different DUE densities and transmission powers. Logically, the outage probability increases when the CUE distance from the BS is increased. Increasing the DUE transmission power for the same DUE density increases the outage probability of typical CUE. Interestingly, we note the gap between the outage curves that have different DUEs transmission powers becomes larger when the density increases. This implies that the outage probability increases rapidly when the density of DUEs increases. Additionally, the outage probability for the same DUE density and different transmission powers is almost the same when the distance x_0 is small. For instance, the outage probability is small and almost the same when the distance x_0 is less than 200 meter. This because, the path loss between the typical CUE and the BS is less and the desired signal at the BS is stronger, then the outage probability is lower. On contrary for the edge CUEs, the outage probability increases dramatically and becomes worse by increasing the DUE density and DUE transmission power.

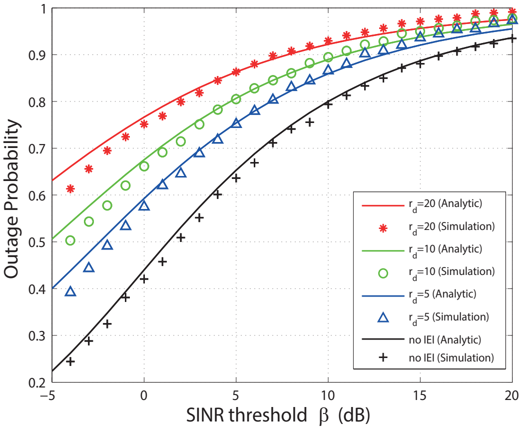

Fig. 1: Performance comparison: IEI and no-IEI scenarios.

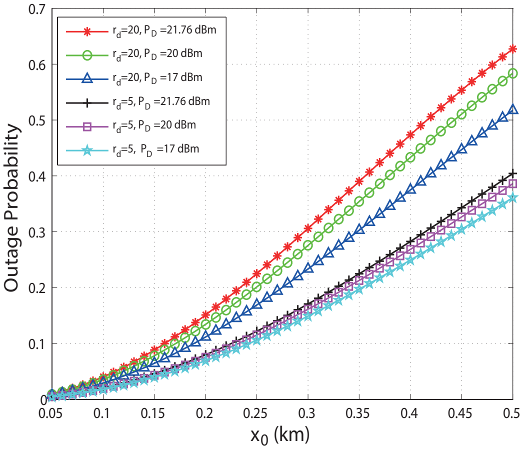

Fig. 2: The effect of typical CUE distance on the CUE performance.

Fig. 3 shows the IEI impact for three cases: only IEI intra-cell, only IEI inter-cell, and where both IEI intra-cell and IEI inter-cell are considered. Three cases are defined for two different RBs setting, $N_C = 6, N_D = 44$, and $N_C = 20, N_D = 30$. We note that the typical CUE outage probability can be reduced by controlling and reducing the number of DRBs in the channel. Considering full load scenario, by assigning less number of DRBs, less number of DUEs can be served in t, thus the leakage power to the CRBs becomes less. Interestingly, the IEI intra-cell is significantly high and affects the outage probability of typical CUE for $N_C = 6, N_D = 44$ case. Unlike $N_C = 20, N_D = 30$ case, IEI intra-cell and IEI inter-cell similarly impact the outage probability of typical CUE. However, the IEI inter-cell is not negligible especially at high DUEs density. As a result,

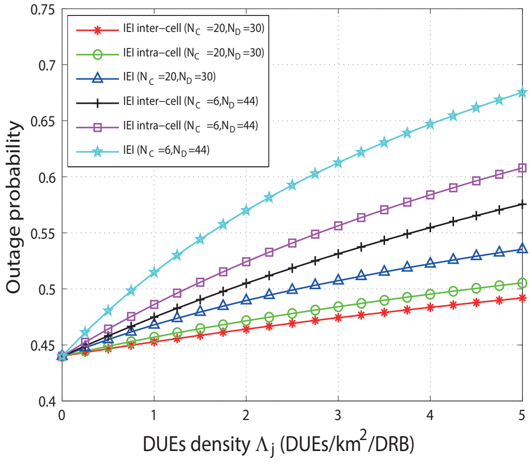

Fig. 3: The IEI intra-cell and IEI inter-cell.

the IEI intra-cell dominates the performance at high DUEs density. At low DUEs density, both similarly affect the outage probability. This implies, considering only IEI intra-cell at high DUEs density can help to evaluate approximately the cellular system performance.

V. CONCLUSION

This work has investigated the IEI impact in D2D-enabled cellular networks, where the overlay D2D in-band scheme is used. The outage probability of the typical cellular user are derived to evaluate the cellular system performance, where the IEI alongside the co-channel interference are considered. The results show the IEI is significant and causes outage with high probability, especially at high DUE density. Furthermore, we have examined the IEI intra-cell and IEI inter-cell impact, separately. From the results, the IEI intra-cell has larger outage probability when the DUE density is high. On the other hand, the IEI intra-cell and IEI inter-cell outage probabilities are similar when the DUE density is low. This implies, considering only IEI intra-cell when the DUE density is high can help to evaluate approximately the real cellular system performance.

APPENDIX A

$$\mathbb{E}\Big[\exp(-sIEI_i)\Big]=$$

$$\overset{(a)}{=}\mathbb{E}_{\Phi_j}\Big[\prod_{j=1}^{N_D}\prod_{k\in\Phi_j}\mathbb{E}_{h_{k,j}}\exp(-sP_D h_{k,j}{x_{k,j}}^{-\alpha}\xi_{j,i})\Big]$$

$$\overset{(b)}{=}\mathbb{E}_{\Phi_j}\Big[\prod_{j=1}^{N_D}\prod_{k\in\Phi_j}\int_0^\infty \mu e^{(-h(\mu+sP_D x_{k,j}^{-\alpha}\xi_{j,i}))}dh\Big]$$

$$\overset{(c)}{=}\prod_{j=1}^{N_D}\exp\Big(-2\pi r_d\lambda_j\int_0^\infty(1-\frac{\mu}{\mu+sP_D x^{-\alpha}\xi_{j,i}})xdx\Big)$$

$$\overset{(d)}{=}\prod_{j=1}^{N_D}\exp\Big(-2\pi r_d\lambda_j(\frac{\mu}{sP_D\xi_{j,i}})^{-\frac{2}{\alpha}}\int_0^\infty\frac{v}{1+v^\alpha}dv\Big)$$

$$\overset{(e)}{=}\exp\Big(-\frac{\frac{2\pi^2}{\alpha}}{\sin\frac{2\pi}{\alpha}}r_d\lambda_j(\frac{\mu}{sP_D})^{-\frac{2}{\alpha}}\sum_{j=1}^{N_D}[\xi_{j,i}^{\frac{2}{\alpha}}]\Big),$$

where (a) follows from the i.i.d distribution of $h_{k,j}$, and the independence from PPP Φ_j, (b) follows from $h \sim \exp(\mu)$, (c) follows from the independence of PPP Φ_j and from the PGFL of PPP Φ_j, where the integration limits are from 0 to ∞ since the closest DUEs using the jth DRB are at least at a distance 0 from the reference BS, and the density of DUEs using the jth DRB is $r_d\lambda_j$, (e) follows from substitution $v^\alpha = \frac{\mu z^\alpha}{sP_D\xi_{j,i}}$ and from using [19, 3.241-2].

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