Deployment Model and Performance Analysis of Clustered D2D Caching Networks under Cluster-Centric Caching Strategy

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Abstract

Device-to-Device (D2D) communication has become a promising candidate in future cellular networks to improve spectrum efficiency and energy efficiency, while reducing the latency. As the capacity of D2D user equipments (DUEs) increases, it makes DUEs caching possible, and it can offload traffic from macro base stations, perform computation-intensive and latency-critical tasks. In this paper, in-band communication is considered, and the Poisson cluster process is utilized to model and analyze the clustered D2D networks under cluster-centric caching strategy. Firstly, we use the Thomas cluster process to model cellular user equipments (CUEs) and DUEs, and give a deployment scheme of clustered D2D caching networks. Secondly, the aggregated interference of the typical D2D receiver is analyzed in the clustered D2D networks. Then the Laplace transform of the aggregated interference is analyzed, and the expressions of coverage probability, average achievable rate and cache hit probability of the typical D2D receiver are deduced. The simulation results show that we can adjust the path loss exponent, densities of DUEs and CUEs, transmitting power of CUEs, mean of simultaneously active transmitters in each cluster and Zipf exponent to improve the performance of clustered D2D caching networks.

Index Terms

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D2D; Poisson cluster process; coverage probability; cache hit probability; average achievable rate

I. Introduction

In recent years, local communication services, such as social networks, online game, and video sharing, have been extensively applied in wireless networks. In order to support the real time and high throughput requirement of these services, researchers and engineers have proposed the Device-to-Device (D2D) communication underlaying cellular networks, which can increase spectral efficiency and energy efficiency, reduce transmission delay, and help offload traffic from cellular networks. All these advantages motivate the D2D communication as one of the key technologies in future networks [1], [2]. D2D user equipments (DUEs) transmit data to each other over a direct link by sharing the spectrum of cellular user equipments (CUEs). In hotspots (such as residential areas, offices, stadiums, shopping malls, etc.), operators can deploy media servers at the macro base stations (MBSs) or DUEs to cache popular contents, from where other DUEs can directly access them. At the edge of cell (blind zone), when the information propagations between CUEs and MBSs fail, the D2D communication mode is activated after an authorization is achieved from the macro base station (MBS), which thus improves the coverage probability [3]. In these scenarios, DUEs will form D2D clusters, which not only can greatly offload traffic from MBSs and increase system throughput, but also can achieve higher data rates. However, the complex conflict of resource usage among CUEs and D2D pairs needs to be efficiently handled for D2D underlaying cellular networks. Developing a comprehensive framework to facilitate the analysis of such setups is the goal of this paper.

A. Related Work

Nowadays, the D2D communication has attracted much attentions, especially in the aspects of modeling and caching strategies. The received desired and interfering signals are closely related to the spatial locations of the interfering sources. To obtain interference characteristics of the wireless networks, it is necessary to accurately model the locations of the network nodes and provide powerful mathematical tools to analyze them.

As a powerful mathematical tool, stochastic geometry has been successfully applied in modeling and performance analysis of cellular and Ad Hoc networks in the past decades [4]–[8]. In addition, the impact of D2D mode selection on networks' performance was also studied in [9] and [10]. In D2D communication mode, traffic can be offloaded from cellular networks to D2D networks. It can also greatly improve the throughput and the QoS of edge DUEs [11]. But the positions of D2D transmitters are usually modeled as homogeneous Poisson Point Process (PPP), fixing the distances between D2D receivers and the corresponding transmitters [12], [13]. For the convenience of analysis, cellular networks were modeled by Poisson Hole Process (PHP), in which the D2D receivers were located at fixed distances from D2D transmitters. This is a good model, but the assumption of fixed distances is quite limited. In [14], H. Kim, et al. studied resource allocation policies to avoid interference between cellular and D2D links. In [15], J. Du, et al. proposed a novel mobile data offloading method based on an external-infrastructure-free approach. Although PPP is a good model, it is obviously inaccurate to use PPP to model DUEs when they cluster together. Because of the clustering distribution of DUEs, the distances between DUEs are usually close. At this time, the locations of active DUEs no longer obey the standard homogeneous PPP, while fixing the distance between D2D communication links is a strict condition, which does not meet the real communication scenario. Using Poisson cluster process (PCP) in stochastic geometry to model D2D networks will be nearer to the real scenario [16]. Newman-Scott cluster process is a kind of PCP, and it can also be divided into Thomas cluster process (TCP) and Matern cluster process. There were relatively few papers to use PCP to model wireless networks, and fewer papers to use PCP to model D2D networks. L. Zhang, et al. modeled CUEs as PPP and Neyman-Scott cluster processes, respectively [17]. In [18], the self-organized D2D clustering was proposed to mitigate physical random access channel congestion. In [19], TCP was first used to model both D2D transmitters and receivers in clustered D2D networks. Based on this model, device-centric content placement strategy was studied. And the authors also deduced the Laplace transform of aggregated interference and quantified the coverage probability of the typical D2D receiver and the area spectrum efficiency of the D2D networks. But the authors only studied the out-band D2D communication without considering the interference caused by CUEs.

Mobile data traffic is growing exponentially, which makes backhaul data rate becoming the main bottleneck to decrease operational expenditure and improve operational benefits. Most of the backhaul traffic is generated by MBSs transmitting duplicate data to multiple DUEs. To solve this problem, cache technologies have attracted great attention, because they can reduce the backhaul traffic of the D2D networks effectively by eliminating duplicate transmission of popular data. The data include popular contents can be cached in the DUEs in advance, so that if other DUEs request the pre-cached data, the DUEs can directly communicate with each other in D2D communication mode to transmit the requested data, thus it can decrease the backhaul traffic. There are many researches on the caching strategy of D2D networks modeled by PPP but few researches modeled by PCP [20]–[22]. Z. Chen, et al. used PPP to model and compare the difference between the DUE cache and the cellular cache in the D2D networks. It was found that caching contents on DUEs can improve the cache hit probability and energy efficiency of D2D networks when the density of DUEs was relatively large [23]. For the purpose of maximizing the cache hit probability, N. Deng, et al. proposed a probabilistic caching placement in [24]. To compare the performances of different content delivery strategies, the success probability and per-user capacity had been derived for single-point caching, two-point cooperative caching with joint transmission or multi-stream transmission, respectively. In [25], an incentive mechanism for pricing the contributions of D2D transmitters in cache-enabled D2D-underlaid cellular networks was proposed. In [26], M. Afshang, et al. defined and analyzed the performance of three common situations: k-Tx situation, k-Rx situation and baseline situation. For all three situations, easy-to-use expressions of coverage probability and area spectrum efficiency for the whole network system were derived. In [27], S. Zhang, et al. studied delay-optimal joint edge caching in user-centric large-scale mobile networks. They exploited the stochastic information of network topology, traffic distribution, channel quality, and file popularity to optimize the content placement and cluster size. A caching strategy based on content clustering and popularity prediction was proposed in [28], and it was a distributed caching management method, which can be implemented without centralized controller. K. S. Khan, et al. proposed an agglomerative clustering hierarchical algorithm for cache-enabled D2D networks, which considered users preferences and set them into the same cluster according to their contents of interest. They applied an optimal caching strategy and optimized the cache hit probability within each cluster [29]. W. Yi, et al. investigated the performance of mmWave communications in clustered D2D networks where devices were equipped with multiple antennas [30], and the locations of DUEs were modeled by PCP. But they didn't consider in-band communications.

B. Contributions and Outcomes

When considering in-band D2D communication, DUEs use the same bandwidth of legacy CUEs. In this case, due to the coexistence of CUEs and DUEs, co-frequency interference in the D2D networks becomes a key problem that cannot be ignored. To the best of our knowledge, in-band D2D communication has not been considered when modeling the D2D networks as PCP. This shortcoming was addressed in our very recent work [31] and [32], where we use PCP to model and analyze the in-band heterogeneous cellular and D2D networks, and only analyze the coverage probability. In contrast, the current work takes DUE cache in clustered D2D caching networks into consideration. It not only considers the analysis of the coverage probability, but also the analysis of the average achievable rate and the cache hit probability. In such a case, how to effectively use PCP to model and analyze the clustered D2D caching networks and how to cache data carrying popular contents have become a growing concern. More details along with other main contributions are explained as follows.

- Considering the scenario where CUEs and DUEs are both clustered together, we present an analytical framework for analyzing clustered D2D caching networks considering in-band communication. TCP is used to model DUEs and CUEs respectively, and a deployment scheme of clustered D2D caching networks is given.
- The aggregated interferences received by the typical D2D receiver and corresponding Laplace transforms in the clustered D2D caching networks are analyzed. Using the analysis results, the expressions of the coverage probability and average achievable rate of the typical D2D receiver are deduced.
- Assuming the contents of interest for the typical D2D receiver are pre-cached on the D2D transmitter located at the representative cluster center, which is of limited caching capacity, we propose a cluster-centric caching strategy and derive the expressions of the cache hit probability of the typical D2D receiver.
- Simulation results show that we can adjust the path loss exponent, densities of DUEs and

CUEs, transmitting power of CUEs, mean of simultaneously active transmitters in each cluster and Zipf exponent to improve the performance of clustered D2D caching networks.

The rest of the paper are structured as follows. In Section II, the doenlink system model is proposed. In Section III, interferences of clustered D2D networks under cluster-centric caching strategy are analyzed. Section IV presents the coverage probability, average achievable rate and cache hit probability of the typical D2D receiver. Section V discusses the simulation results. Finally, the paper is concluded in Section VI.

II. Downlink System Model

In this paper, TCP is utilized to model clustered D2D caching networks. Because the distances between DUEs from different clusters are farther than the ones between DUEs in the same cluster, we assume that DUEs from different clusters do not communicate with each other when in-band D2D communication is considered. The locations of DUEs and CUEs are both modeled by TCP. The parent process of the CUEs, MBS, is drawn from PPP ϕ_{c} with density λ_{c}. Meanwhile, the parent process of the DUEs, D2D cluster center, is drawn from PPP ϕ_{d} with density λ_{d}. The offspring points of TCP are independent identical distributed (i.i.d) around each parent point, and the union of all the offspring points constitute a PCP. Using Thomas cluster process, the offspring process of the CUEs is drawn from an i.i.d. symmetric Gaussian distribution with variance σ_{c}^2 around the cluster center at $x_{\mathrm{c}} \in \phi_{\mathrm{c}}$, and the offspring process of the DUEs is drawn from an i.i.d. symmetric Gaussian distribution with variance σ_{d}^2 around the cluster center at $x_{\mathrm{d}} \in \phi_{\mathrm{d}}$. Assume that the maximum number of DUEs in each cluster is N. The number of simultaneously active transmitters in each cluster is different, which provides sufficient versatility for modeling analysis. The set of all DUEs in the cluster around the center at $x_{\mathrm{d}} \in \phi_{\mathrm{d}}$ is denoted by $N^{x_{\mathrm{d}}}$, which is randomly divided into two subsets including transmitting set and receiving set, and denoted by $N_{\mathrm{t}}^{x_{\mathrm{d}}}$ and $N_{\mathrm{r}}^{x_{\mathrm{d}}}$, respectively. The set of simultaneously active transmitters in each cluster is denoted by $B^{x_{\mathrm{d}}} \subseteq N_{\mathrm{t}}^{x_{\mathrm{d}}}$, where $B^{x_{\mathrm{d}}}$ is assumed to be Poisson distribution with mean $\bar{m}$ conditioned on $|B^{x_{\mathrm{d}}}| \leq |N_{\mathrm{t}}^{x_{\mathrm{d}}}|$. We assume that each D2D transmitter has an intended D2D receiver, so that the maximum number of D2D transmitters is $M = N/2$. For each element $y_{\mathrm{d}} \in N^{x_{\mathrm{d}}} \in \mathbb{R}^2$ which means the distances of the cluster member DUEs relative to their cluster center, its probability density function(PDF) can be denoted as

$$f_{Y_{\rm d}}(y_{\rm d}) = \frac{1}{2\pi\sigma_{\rm d}^2} \exp\left(-\frac{\|y_{\rm d}\|^2}{2\sigma_{\rm d}^2}\right), \tag{1}$$

For each element $y_{\rm c} \in \mathbb{R}^2$ which means the distances of the the cluster member CUEs relative to their cluster center, its PDF is similar to that for $y_{\rm d}$.

Without loss of generality, the performances of randomly chosen DUE (termed typical D2D receiver) in randomly chosen cluster of DUEs(termed representative D2D cluster) are analyzed in this paper. The distribution of proposed clustered D2D networks is illustrated in Fig. 1. The red circles represent the MBSs, green triangles represent the CUEs and blue cross symbols represent the DUEs. For quick reference, the notations used in this paper are summarized in Table I.

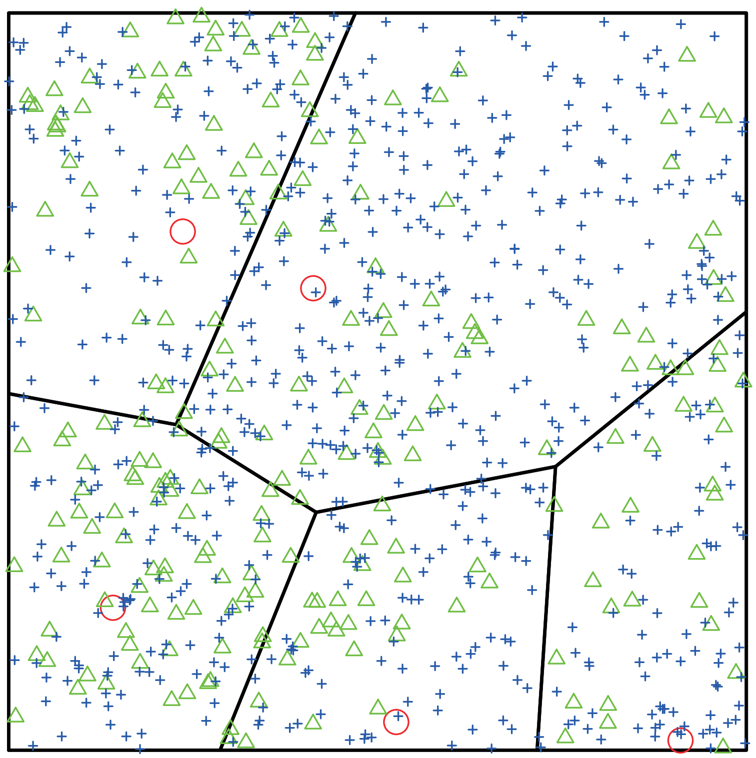

Fig. 1. Illustration of proposed clustered D2D networks.

III. Interference Analysis of Clustered D2D Networks

Owing to the coexistence of CUEs and DUEs, the co-frequency interference in the clustered D2D networks becomes a challenging problem. Because the useful signal intensity and interfer-

TABLE I

SUMMARY OF NOTATIONS

Notation	Description
$\phi_{\mathrm{c}};\ \lambda_{\mathrm{c}}$	Independent PPP modeling the parent process of the CUEs; density of ϕ_{c}
$\phi_{\mathrm{d}};\ \lambda_{\mathrm{d}}$	Independent PPP modeling the parent process of the DUEs; density of ϕ_{d}
$\sigma_{\mathrm{c}}^2\ (\sigma_{\mathrm{d}}^2)$	Scattering variance of the CUE (DUE) locations around each cluster center
$x_{\mathrm{c}}\ (x_{\mathrm{d}})$	Cluster center location of the CUEs(DUEs)
$N\ (M)$	The maximum number of DUEs(D2D transmitters) in each cluster
$N^{x_{\mathrm{d}}}$	Set of all DUEs in the cluster around the center x_{d}
$N_{\mathrm{t}}^{x_{\mathrm{d}}};\ N_{\mathrm{r}}^{x_{\mathrm{d}}}$	Transmitting set and receiving set of all DUEs in the cluster around the center at x_{d}
$B^{x_{\mathrm{c}}}(B^{x_{\mathrm{d}}})$	Set of simultaneously active transmitters in each cluster centered at x_{c} and x_{d}
$y_{\mathrm{c}}\ (y_{\mathrm{d}})$	The distances of the cluster member CUEs(DUEs) relative to their cluster center
$x_{\mathrm{c0}}\ (x_{\mathrm{d0}})$	Cluster center location of the representative cluster of CUEs(DUEs)
P_0; P_{c}	Transmit power of each DUE; transmit power of each CUE
P_{d}; k	The received power at the typical D2D receiver; power ratio
h; α	Channel power gain under Rayleigh fading; path loss exponent
ψ_{m}	The set of simultaneously active D2D transmitters
$\bar{c}$; $\bar{m}$	Mean of $B^{x_{\mathrm{c}}}$ and $B^{x_{\mathrm{d}}}$ distribution
I_{cd}; $\mathcal{L}_{I_{\mathrm{cd}}}$	The interference caused by CUEs and its Laplace transform
$I_{\mathrm{dd}}^{\mathrm{intra}}$; $\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{intra}}}$	Intra-cluster interference and its Laplace transform
$I_{\mathrm{dd}}^{\mathrm{inter}}$; $\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{inter}}}$	Inter-cluster interference and its Laplace transform
I_{dd}; $\mathcal{L}_{I_{\mathrm{dd}}}$	Aggregate interference caused by all interfering DUEs and its Laplace transform
I_{ϕ}	The aggregate interference received by the typical D2D receiver
$\gamma(x_{\mathrm{d0}})$; γ_0	The SIR of the typical D2D receiver; SIR threshold
$Ri\left(r\|v,\sigma^2\right)$; $Ra\left(r\|\sigma^2\right)$	Rice distribution; Rayleigh distribution
r; w; u	The serving distance; intra-cluster interference distance; inter-cluster interference distance
v_{d0}; v_{d}	The distance between the representative or non-representative D2D cluster center and the typical D2D receiver
p_{c}; R_{d}; p_{hit}	Coverage probability; the average achievable rate; cache hit probability
F; C_{d}; I	File library; caching capacity of DUEs; total number of cache files
f_j; q_j	The j^{th} File cached in the D2D transmitter and its cache probability
p_j; $B\left(\cdot,\cdot\right)$	The probability that the file f_j will be requested; Beta function
γ; β	The the Zipf exponent; cache probability coefficient

ence signal intensity received by the D2D receivers are closely related to the spatial locations of the interfering sources, so interference analysis is the basis of performance analysis.

A. Aggregated Interference Received by the Typical D2D Receiver

We assume that the representative cellular cluster is centered at $x_{\mathrm{c}0} \in \phi_{\mathrm{c}}$, the representative D2D cluster is centered at $x_{\mathrm{d}0} \in \phi_{\mathrm{d}}$, where the contents of interest for the typical receiver are pre-cached, and the typical D2D receiver by definition is in $N_{\mathrm{r}}^{x_{\mathrm{d}0}}$. Due to the stationarity of PCP, we assume that the typical D2D receiver is located at the origin and the intended D2D transmitter(termed serving D2D transmitter) is same location with the representative D2D cluster center. Then the distance between the D2D transmitter of interest and the typical D2D receiver can be expressed as $r = \|x_{\mathrm{d}0}\|$. We assume that transmit power of each DUE is P_0 and transmit power of each CUE is $P_{\mathrm{c}} = kP_0\,(k \geq 1)$ in this paper. The received power at the typical D2D receiver is given by:

$$P_{\mathrm{d}} = P_0 h r^{-\alpha}, \tag{2}$$

where the random variable h is the fading coefficient on the link. It is subject to Rayleigh fading and $h \sim \exp(1)$. Assuming Rayleigh fading on the link between the typical D2D receiver and its serving D2D transmitter, we can gert an expression for the complementary cumulative distribution function(CCDF) of the SIR at the typical D2D receiver in terms of the Laplace transform of the interference power. $\alpha > 2$ is the path loss exponent. Shadow fading is ignored in this paper. The set of simultaneously active D2D transmitters is denoted by $\psi_{\mathrm{m}} = \cup_{x_{\mathrm{d}} \in \phi_{\mathrm{d}}} B^{x_{\mathrm{d}}}$. Because the DUEs from different clusters do not communicate, the aggregated interference seen at the typical D2D receiver originates from three sources:

1) Interference caused by CUEs: When the typical D2D receiver multiplexes spectrum with CUEs, The interference caused by CUEs can be defined as

$$I_{\mathrm{cd}} = \sum_{y_{\mathrm{c}} \in \phi_{\mathrm{c}}} kP_0 h \|x_{\mathrm{c}0} + y_{\mathrm{c}}\|^{-\alpha}. \tag{3}$$

2) Intra-cluster interference: The interference at the typical D2D receiver caused by the D2D transmitters except the serving D2D transmitter in the representative cluster can be defined as

$$I_{\mathrm{dd}}^{\mathrm{intra}} = \sum_{y_{\mathrm{d}} \in B^{x_{\mathrm{d}0}}} P_0 h \|x_{\mathrm{d}0} + y_{\mathrm{d}}\|^{-\alpha}. \tag{4}$$

3) Inter-cluster interference: The interference at the typical D2D receiver caused by simultaneously active D2D transmitters outside the representative cluster can be defined as

$$I_{\mathrm{dd}}^{\mathrm{inter}} = \sum_{x_{\mathrm{d}} \in \phi_{\mathrm{d}} \setminus x_{\mathrm{d0}}} \sum_{y_{\mathrm{d}} \in B^{x_{\mathrm{d}}}} P_0 h \| x_{\mathrm{d}} + y_{\mathrm{d}} \|^{-\alpha}. \tag{5}$$

The aggregate interference caused by all interfering DUEs is given by:

$$I_{\mathrm{dd}} = I_{\mathrm{dd}}^{\mathrm{intra}} + I_{\mathrm{dd}}^{\mathrm{inter}}. \tag{6}$$

Thus the aggregate interference received by the typical D2D receiver can be given from equations (3) and (6):

$$I_{\phi} = I_{\mathrm{cd}} + I_{\mathrm{dd}}. \tag{7}$$

The equations in (3) (4) (5) depend on the distance between the typical D2D receiver and other interfering sources. More details on the distance distributions will be given later.

The distribution of SI(N)R is the single most important quantity in design and analysis of clustered D2D networks. We assume the system is interference-limited, so the additive white Gaussian noise is ignored. As a result, the SIR of the typical D2D receiver can be denoted as:

$$\gamma(x_{\mathrm{d0}}) = \frac{P_{\mathrm{d}}}{I_{\phi}}. \tag{8}$$

B. Distance Distributions from D2D Transmitters to the Typical D2D Receiver

Before discussing the distance distributions from intra-cluster and inter-cluster D2D transmitters to the typical D2D receiver, Rice distribution needs to be introduced in advance.

Definition 1. *Rice distribution: In the 2D plane, pick a fixed point at distance v from the origin. Generate a distribution of 2D points centered around the fixed point, where the x and y coordinates are chosen independently from a gaussian distribution with standard deviation σ. If r is the distance from these points to the origin, then r has a Rice distribution and its PDF is:*

$$Ri\left(r|v,\sigma^2\right) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2+v^2}{2\sigma^2}\right) I_0\left(\frac{rv}{\sigma^2}\right), r > 0, \tag{9}$$

where $I_0(.)$ is the modified Bessel function of the first kind with order zero.

When the correlation that both r and v is ignored and $v = 0$, the Rice distribution will degenerate into a Rayleigh distribution.

Definition 2. *Rayleigh distribution: The PDF of the random variable r sampled from Rayleigh distribution is:*

$$Ra\left(r|\sigma^2\right) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right), r > 0, \tag{10}$$

1) Distance Distribution from Intra-cluster D2D Transmitters to the Typical D2D Receiver: According to the previous assumption, the center of the representative cluster(similar to the fixed point) is located at $x_{\mathrm{d}0} \in \phi_{\mathrm{d}}$, the typical D2D receiver is located at the origin, other DUEs(serving DUE and interference DUEs) are drawn from an i.i.d. symmetric Gaussian distribution with variance σ_{d}^2 around the representative cluster center, the distances from serving DUE and interference DUEs to the typical D2D receiver are independent of each other and obey Rice distribution. The distance between the representative D2D cluster center and the typical D2D receiver is $v_{\mathrm{d}0} = \|x_{\mathrm{d}0}\|$, the serving distance between the D2D transmitter of interest and the typical D2D receiver is defined as $r = \|x_{\mathrm{d}0}\|$, then the PDF of the serving distance is $Ri\left(r|v_{\mathrm{d}0}, \sigma_{\mathrm{d}}^2\right)$. Meanwhile, the distance between the interfering D2D transmitters in the representative D2D cluster and the typical D2D receiver can be expressed as $\{w = \|x_{\mathrm{d}0} + y_{\mathrm{d}}\|, \forall y_{\mathrm{d}} \in B^{x_{\mathrm{d}0}}\}$ and the PDF of the intra-cluster interference distance is defined as $Ri\left(w|v_{\mathrm{d}0}, \sigma_{\mathrm{d}}^2\right)$. This setup is illustrated in Fig. 2.

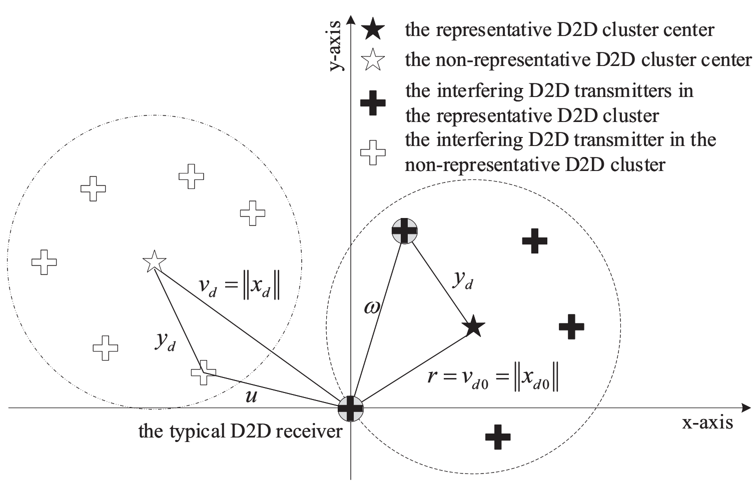

Fig. 2. Illustration of distance distributions from D2D transmitters to the typical D2D receiver.

2) Distance Distribution from Inter-cluster D2D Transmitters to the Typical D2D Receiver: It is assumed that the clusters except the representative cluster are centered at $x_{\mathrm{d}} \in \phi_{\mathrm{d}}$, the distance from the cluster centers outside the representative cluster to the typical D2D receiver is $v_{\rm d} = \|x_{\rm d}\|$, and the distance from the interfering D2D transmitters outside the representative cluster to the typical D2D receiver is defined as $\{u = \|x_{\rm d} + y_{\rm d}\|, \forall y_{\rm d} \in B^{x_{\rm d}}\}$. As a result, the PDF of the inter-cluster interfering distance can be expressed as $Ri\left(u|v_{\rm d}, \sigma_{\rm d}^2\right)$.

C. Laplace Transform of Aggregated Interference

Because the CCDF of SIR can be given in terms of the Laplace transform of interference at the typical D2D receiver [33], [34], we next discuss the circumstances under which Laplace transform of aggregated interference can be derived analytically.

According to equation (6) and (7), Laplace transform of aggregated interference can be derived as:

$$\mathcal{L}_{I_\phi}(s) = \mathbb{E}\left[\exp\left(-s\left(I_{\rm cd} + I_{\rm dd}^{\rm intra} + I_{\rm dd}^{\rm inter}\right)\right)\right] \tag{11}$$

$$= \mathbb{E}\left[\exp\left(-sI_{\rm cd}\right)\right] \cdot \mathbb{E}\left[\exp\left(-sI_{\rm dd}^{\rm intra}\right)\right] \cdot \mathbb{E}\left[\exp\left(-sI_{\rm dd}^{\rm inter}\right)\right] \tag{12}$$

$$= \mathcal{L}_{I_{\rm cd}}\left(s\right) \cdot \mathcal{L}_{I_{\rm dd}^{\rm intra}}\left(s\right) \cdot \mathcal{L}_{I_{\rm dd}^{\rm inter}}\left(s\right). \tag{13}$$

Equation (13) shows that Laplace transform of aggregated interference depends on $\mathcal{L}_{I_{\rm cd}}(s)$, $\mathcal{L}_{I_{\rm dd}^{\rm intra}}(s)$ and $\mathcal{L}_{I_{\rm dd}^{\rm inter}}(s)$, so we will derive them respectively.

Theorem 1. *The Laplace transform of interference distribution from CUEs to the typical D2D receiver is:*

$$\mathcal{L}_{I_{\rm cd}}(s) = \exp\left\{-\lambda_{\rm c}\pi\bar{c}(skP_0)^{\frac{2}{\alpha}}B\left(1-\frac{2}{\alpha}, \bar{c}+\frac{2}{\alpha}\right)\right\}. \tag{14}$$

where $\bar{c}$ is mean of $B^{x_{\rm c}}$, and $B\left(1-\frac{2}{\alpha}, \bar{c}+\frac{2}{\alpha}\right)$ is the Beta function.

Proof: See Appendix A. ■

Theorem 2. *The Laplace transform of intra-cluster interference at the typical D2D receiver is:*

$$\mathcal{L}_{I_{\rm dd}^{\rm intra}}(s|v_{\rm d0}) = \exp\left(-\bar{m}\int_0^\infty \frac{sP_0w^{-\alpha}}{1+sP_0w^{-\alpha}}Ri\left(w\left|v_{\rm d0}, \sigma_{\rm d}^2\right.\right){\rm d}w\right). \tag{15}$$

Proof: See Appendix B. ■

For the convenience of analysis, the correlation that both the serving distance and intra-cluster distance is ignored, and is condition on $v_{\rm d0} = \|x_{\rm d0}\|$, then the approximate expression of the Laplace transform of intra-cluster interference can be given by the following Lemma.

Lemma 1. *Without considering the correlation of the serving distance and intra-cluster distance, the approximate lower bound on Laplace transform of intra-cluster interference at the typical D2D receiver is*

$$\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{intra}}}(s) \geq \exp\left(-\frac{\bar{m}}{4\sigma_{\mathrm{d}}^2}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right). \tag{16}$$

Proof: See Appendix C. ■

Theorem 3. *The Laplace transform of inter-cluster interference at the typical D2D receiver is:*

$$\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{inter}}}(s) = \exp\left(-2\pi\lambda_{\mathrm{d}}\int_0^{\infty}\left(1-\exp[-\bar{m}\left(1-\rho\left(v_{\mathrm{d}}\right)\right)]\right)v_{\mathrm{d}}\mathrm{d}v_{\mathrm{d}}\right). \tag{17}$$

where $\rho\left(v_{\mathrm{d}}\right) = \int_0^{\infty}\frac{1}{1+sP_0u^{-\alpha}}Ri\left(u\left|v_{\mathrm{d}},\sigma_{\mathrm{d}}^2\right.\right)\mathrm{d}u$.

Proof: See Appendix D. ■

Lemma 2. *Without considering the correlation of the serving distance and inter-cluster distance, the approximate lower bound on Laplace transform of inter-cluster interference at the typical D2D receiver is*

$$\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{inter}}}(s) \geq \exp\left(-\pi\lambda_{\mathrm{d}}\bar{m}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right). \tag{18}$$

Proof: See Appendix E. ■

According to the equation (6), Lemma 1 and Lemma 2, we can get

$$\begin{aligned}\mathcal{L}_{I_{\mathrm{dd}}}(s) &= \exp\left(-\frac{\bar{m}}{4\sigma_{\mathrm{d}}^2}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right)\cdot\exp\left(-\pi\lambda_{\mathrm{d}}\bar{m}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right) &(19)\\ &= \exp\left(-\left(\frac{1}{4\sigma_{\mathrm{d}}^2}+\pi\lambda_{\mathrm{d}}\right)\bar{m}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right). &(20)\end{aligned}$$

IV. Coverage Probability, Average Achievable Rate and Cache Hit Probability

A. Coverage Probability of the Clustered D2D Networks

In this paper, coverage probability refers to the probability that the SIR at the typical D2D receiver in the representative cluster is greater than a certain threshold γ_0, and it can be formally defined as the CCDF of SIR as: $p_{\mathrm{c}} = \mathbb{P}\{\gamma(x_{\mathrm{d0}}) > \gamma_0\}$. An exact expression for the coverage probability of the typical D2D receiver in the clustered D2D networks under cluster-centric caching strategy is derived in the following Theorem.

Theorem 4. *The coverage probability of the typical D2D receiver in the clustered D2D networks under cluster-centric caching strategy is*

$$p_{\mathrm{c}} = \int_0^{\infty} \mathcal{L}_{I_{\mathrm{cd}}}\left(\frac{\gamma_0 r^{\alpha}}{P_0}\right) \mathcal{L}_{I_{\mathrm{dd}}}\left(-\frac{\gamma_0 r^{\alpha}}{P_0}\right) Ra\left(r|2\sigma_{\mathrm{d}}^2\right) \mathrm{d}r. \tag{21}$$

Proof: See Appendix F. ■

Lemma 3. *The approximate coverage probability of the typical D2D receiver in the clustered D2D networks is*

$$p_{\mathrm{c}} = \frac{1}{\left[4\pi\lambda_{\mathrm{c}}\sigma_{\mathrm{d}}^2\bar{c}k^{\frac{2}{\alpha}}B(1-\frac{2}{\alpha},\bar{c}+\frac{2}{\alpha}) + (4\pi\lambda_{\mathrm{d}}\sigma_{\mathrm{d}}^2+1)\bar{m}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right]\gamma_0^{\frac{2}{\alpha}}+1}. \tag{22}$$

Proof: See Appendix G. ■

B. Average Achievable Rate of the Clustered D2D Networks

In addition, the average achievable rate is also derived. Average achievable rate can be calculated based upon the Shannon capacity expression as:

$$R_{\mathrm{d}} = \mathbb{E}[\log_2(1+\gamma(x_{\mathrm{d}0}))]. \tag{23}$$

Theorem 5. *According to (8) and (23), the average achievable rate of the typical D2D receiver in the clustered D2D caching networks under cluster-centric caching strategy can be calculated as follows:*

$$R_{\mathrm{d}} = \int_0^{\infty} \mathcal{L}_{I_{\mathrm{cd}}}\left(\frac{r^{\alpha}(2^{R_0}-1)}{P_0}\right) \cdot \mathcal{L}_{I_{\mathrm{dd}}}\left(\frac{r^{\alpha}(2^{R_0}-1)}{P_0}\right) Ra\left(r|2\sigma_{\mathrm{d}}^2\right) \mathrm{d}r. \tag{24}$$

Proof: See Appendix H. ■

Lemma 4. *According to Theorem 5, and by substituting (14), (20) and* $s = \frac{r^{\alpha}(2^{R_0}-1)}{P_0}$ *into (24), the approximate average achievable rate of the typical D2D receiver in the clustered D2D networks can be calculated as:*

$$R_{\mathrm{d}} = \frac{1}{\left[4\pi\lambda_{\mathrm{c}}\sigma_{\mathrm{d}}^2\bar{c}k^{\frac{2}{\alpha}}B(1-\frac{2}{\alpha},\bar{c}+\frac{2}{\alpha}) + (4\pi\lambda_{\mathrm{d}}\sigma_{\mathrm{d}}^2+1)\bar{m}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right](2^{R_0}-1)^{\frac{2}{\alpha}}+1}. \tag{25}$$

Proof: The proof follows on the same line as Lemma 3 and is hence skipped. ■

C. Cache Hit Probability of the Typical D2D Receiver in the Clustered D2D Networks

In this paper, cache hit probability refers to the probability that the typical D2D receiver can find the contents requested by itself in the representative cluster. With the rapid increase of high traffic consumption applications, people are increasingly demanding for network latency and QoE. Therefore, the content placement strategy is considered as a key technology to improve networks' performance. In this way, DUEs do not need to communicate through MBSs or core network, so it can reduce backhaul traffic and latency, and improve QoE. There are many cache placement strategies are available such as first-in-first-out (FIFO), least recently used (LRU), least frequently used (LFU) [35], equal probability random cache (EPRC) and so on. LRU caches new contents by eliminating the least recently used contents, while LFU eliminates contents with the least frequently used. In this paper, cluster-centric caching strategy is proposed, and it is assumed that the contents of interest are cached in the caching space of D2D transmitter located at the cluster center, and communications among different clusters are not considered. It is assumed that popular contents follow Zipf distribution and users request contents from file library $F=\{f_1, f_2, ...f_I\}$ [24], where all files are indexed in descending order of popularity. For the convenience of analysis, normalization size of each file in the file library to 1, so that the size of the file library becomes I. In this library with I files, the probability that the file f_j will be requested can be expressed as:

$$p_j = \frac{j^{-\gamma}}{\sum_{i=1}^{I} i^{-\gamma}}, \tag{26}$$

where $\sum_{j=1}^{I} p_j = 1$, and $\gamma > 0$ is the Zipf exponent. The larger γ, the fewer files will be requested from the file library. Due to the limited capacity of the DUEs, only a small portion of the files in file library can be cached in the D2D transmitter located at the cluster center. It is assumed that size of the D2D transmitters' caching capacity is $C_{\mathrm{d}} \leq I$, that is to say, the D2D transmitter located at the cluster center can cache C_{d} files at most. Thus, the cache hit probability of the typical D2D receiver in the clustered D2D networks can be calculated as:

$$p_{\mathrm{hit}} = \sum\nolimits_{j=1}^{C_{\mathrm{d}}} p_j q_j, \tag{27}$$

where q_j is the probability that the file f_j is cached in the D2D transmitter located at the cluster center. It is assumed that the popularity of files follows Zipf distribution, so the popularity of files decrease with the increase of file index j, leading to the decrease of cache probability of files with increase of j. Due to such characteristic of cache probability of files, the cache probability of the file f_j can be written as follows:

$$q_j = \frac{j^{-\beta\gamma}}{\sum_{i=1}^{I} i^{-\beta\gamma}}, \tag{28}$$

where β is cache probability coefficient. Substituting (26) and (28) into (27), the cache hit probability of the typical D2D receiver in the clustered D2D networks can be deduced as:

$$p_{\text{hit}} = \sum_{j=1}^{C_{\text{d}}} \frac{j^{-\gamma}}{\sum_{i=1}^{I} i^{-\gamma}} \cdot \frac{j^{-\beta\gamma}}{\sum_{i=1}^{I} i^{-\beta\gamma}}. \tag{29}$$

V. Simulation Analysis

In this section, MATLAB is used to simulate and analyze key performance indicator of the proposed clustered D2D caching networks. The specific simulation parameters are shown in Table II.

TABLE II

Simulation Parameters

Description	Value	Description	Value
SIR threshold γ_0	10dB	Density of CUEs λ_c	30×10^{-6} clusters$/m^2$
Total number of cache files I	100		100×10^{-6} clusters$/m^2$
Caching capacity of DUEs C_d	20		400×10^{-6} clusters$/m^2$
Cache probability coefficient β	3		800×10^{-6} clusters$/m^2$
Path loss exponent α	3	Density of DUEs λ_d	100×10^{-6} clusters$/m^2$
	4		500×10^{-6} clusters$/m^2$
	5		900×10^{-6} clusters$/m^2$
Mean $\bar{m}$	5	Power ratio k	100
	100		400
	500		900

A. Analysis of Coverage Probability and Average Achievable Rate with Different Path Loss Exponents

Fig. 3 and Fig. 4 show the impact of different path loss exponents on coverage probability and average achievable rate of clustered D2D networks, respectively. It can be found from the Fig. 3

and Fig. 4 that the coverage probability and average achievable rate of clustered D2D networks increases with the increase of path loss exponent when $\alpha > 2$. This is because the useful power received by the typical D2D receiver from D2D transmitter of interest in clustered D2D networks suffers less loss, while the path loss of interfering CUEs and DUEs is relatively large due to their relatively long distance to the typical D2D receiver. The increase of path loss exponent can restrain the interference signal to some extent, thus it can improve coverage probability and average achievable rate of the typical D2D receiver in clustered D2D networks.

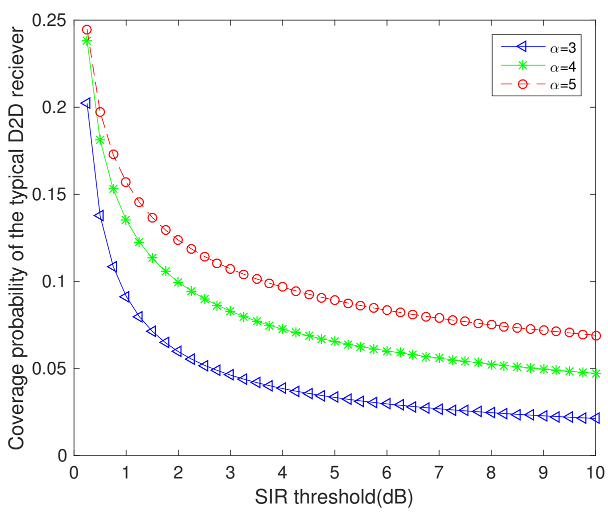

Fig. 3. Coverage probability of the typical D2D receiver for different path loss exponent α.

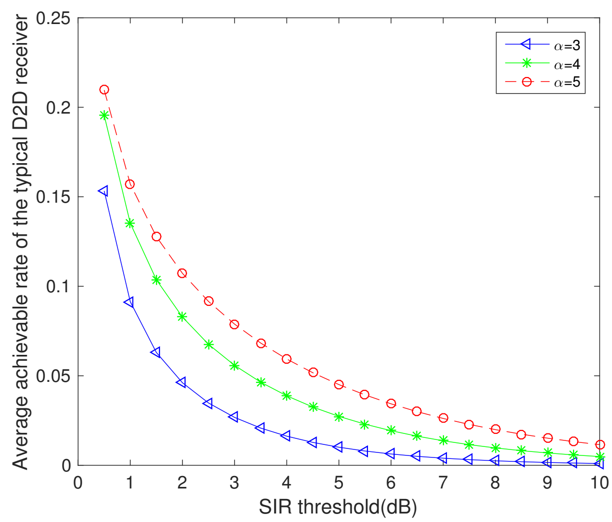

Fig. 4. Average achievable rate of the typical D2D receiver for different path loss exponent α.

B. Analysis of Coverage Probability and Average Achievable Rate with Different Densities of DUEs and CUEs

Fig. 5 and Fig. 6 show the impact of different densities of DUEs and CUEs on coverage probability and average achievable rate of clustered D2D networks, respectively. It can be found from the Fig. 5 and Fig. 6 that the coverage probability and average achievable rate of the typical D2D receiver in clustered D2D networks decreases with the increase of densities of DUEs and CUEs. This is because the increase of densities of DUEs and CUEs leads to a relative increase in the number of interfering devices in clustered D2D networks.

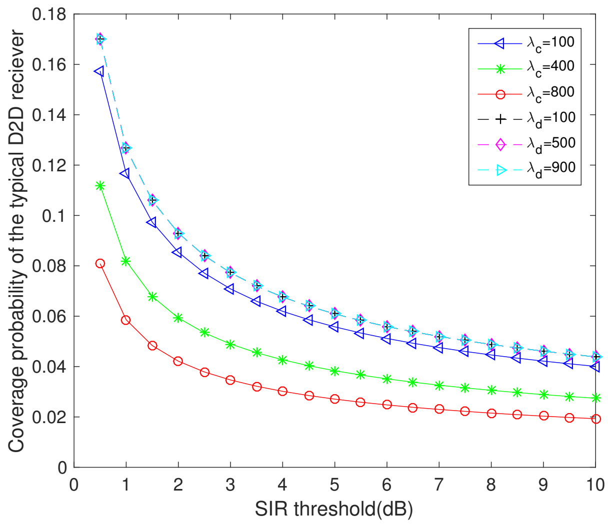

Fig. 5. Coverage probability of the typical D2D receiver for different value of λ_{d} and λ_{c}.

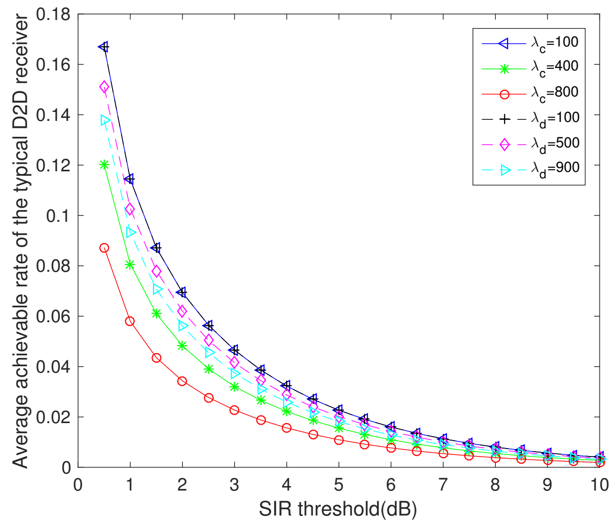

Fig. 6. Average achievable rate of the typical D2D receiver for different value of λ_{d} and λ_{c}.

C. Analysis of Coverage Probability and Average Achievable Rate with Different Transmitting Power of CUEs

Fig. 7 and Fig. 8 show the impact of different transmitting power of CUEs on coverage probability and average achievable rate of clustered D2D networks. It can be found from the Fig. 7 and Fig. 8 that the coverage probability and average achievable rate of the typical D2D receiver in clustered D2D networks decreases with the increase of power ratio k. That is to say, the coverage probability and average achievable rate of the typical D2D receiver in clustered D2D networks decreases with the increase of the transmitting power of CUEs. This is because CUEs are the interfering devices for the typical D2D receiver in clustered D2D networks. The higher the transmitting power of CUEs is, the higher the interfering power is. This increases the aggregated interfering power in clustered D2D networks, and suppresses useful signals to a certain extent, thus reducing the coverage probability and average achievable rate of typical D2D receiver in clustered D2D networks. We can know from above simulation results that the performance of clustered D2D networks under cluster-centric caching strategy can be optimized by controlling the transmitting power of CUEs properly.

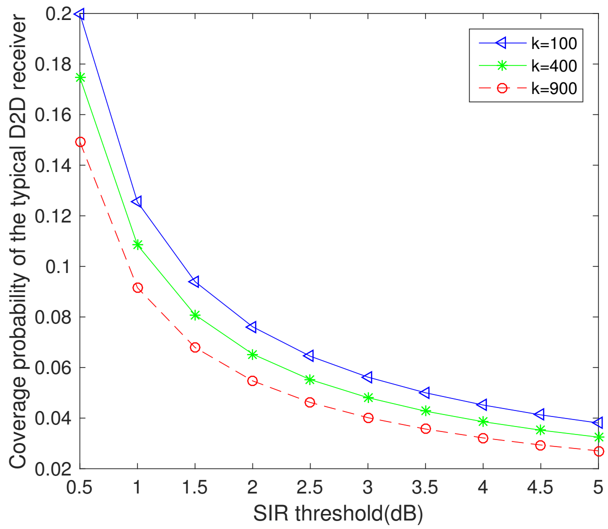

Fig. 7. Coverage probability of the typical D2D receiver for different power ratio k.

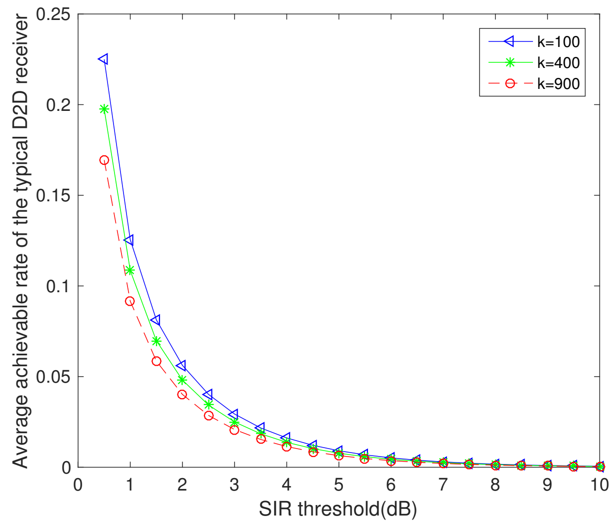

Fig. 8. Average achievable rate of the typical D2D receiver for different power ratio k.

D. Analysis of Coverage Probability and Average Achievable Rate with Different Mean $\bar{m}$

Fig. 9 and Fig. 10 show the impact of different mean $\bar{m}$ of set of simultaneously active transmitters in each cluster on coverage probability and average achievable rate of clustered D2D networks. It can be found from the Fig. 9 and Fig. 10 that the coverage probability and average achievable rate of the typical D2D receiver decreases with the increase of mean $\bar{m}$. This is because D2D transmitters except for the serving D2D transmitter are the interfering devices to the typical D2D receiver. With the increase of $\bar{m}$, the number of simultaneously active D2D transmitters in each cluster increases, leading to the increase of number of interfering D2D transmitters and aggregated interference, thereby reducing the coverage probability and average achievable rate of typical D2D receiver in clustered D2D networks.

E. Comparison of Cache Hit Probability with Different Zipf Exponents and Number of Requests

In this section, we evaluate the performance of the proposed cluster-centric caching strategy and compare it with two traditional cache strategies, LRU and EPRC. Fig. 11 shows the impact of different Zipf exponents on cache hit probability of the typical D2D receiver in clustered D2D caching networks for the path loss exponent $\alpha = 4$, total number of cache files $I = 100$, caching capacity of DUEs $\mathrm{C}_d = 20$, cache probability coefficient $\beta = 3$, and density of DUEs

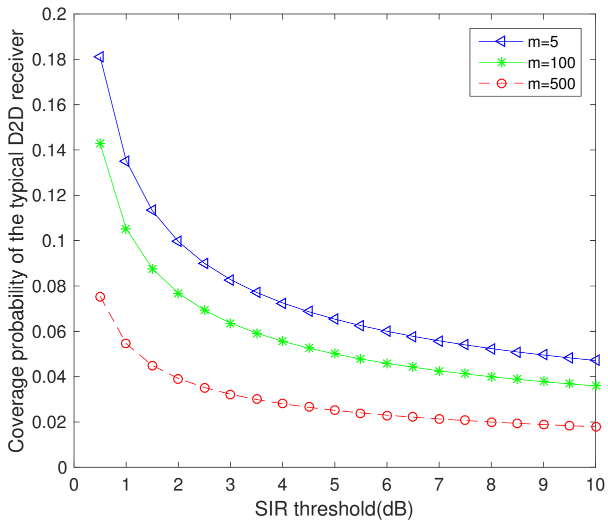

Fig. 9. Coverage probability of the typical D2D receiver for different mean $\bar{m}$.

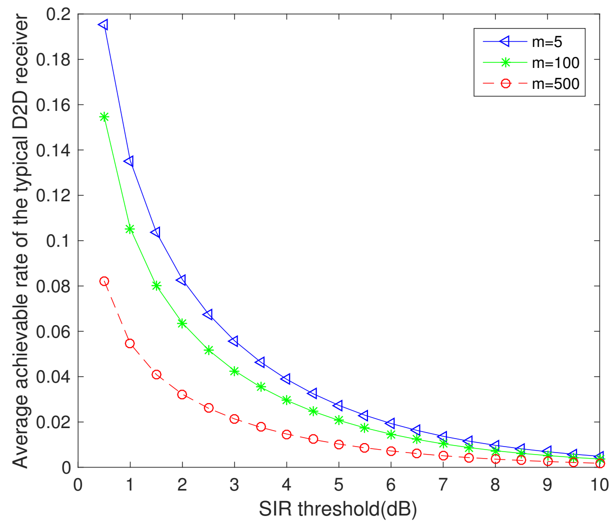

Fig. 10. Average achievable rate of the typical D2D receiver for different mean $\bar{m}$.

$\lambda_d = 500 \times 10^{-6}$ clusters$/m^2$. It can be found from the Fig. 11 that the cache hit probability of the typical D2D receiver increases with the increase of Zipf exponent. This is because the larger Zipf exponent is, the more user requests are concentrated on the most popular files, the lower the diversity of file requests, thus it can increase the cache probability of D2D transmitter located at the cluster center, and improve the cache hit probability of the typical D2D receiver in the clustered D2D caching networks. When $\gamma < 2.5$, the cache hit probability of cluster-centric caching strategy is less than the one of LRU, because limited caching capacity is not enough to cache lower popularity contents. Clearly, EPRC caches content randomly with equal probability, its cache hit probability is low. Therefore, the popularity of contents is important for the cache hit probability. When $\gamma > 2.5$, the cache hit probability of cluster-centric caching strategy is greatly improved.

We randomly generate 10000 requests, and assume Zipf exponent $\gamma = 3$, cache probability coefficient $\beta = 3$, the path loss exponent $\alpha = 4$, total number of cache files $I = 100$, and caching capacity of DUEs $\mathrm{C}_d = 20$. Fig. 12 shows cache hit probability versus number of requests for the proposed cluster-centric caching, LRU and EPRC strategies. As the number of requests increases, the cache hit probability of DUEs becomes gradually stable. From Fig. 11, we can know that cache hit probability of our proposed cluster-centric caching strategy is nearly

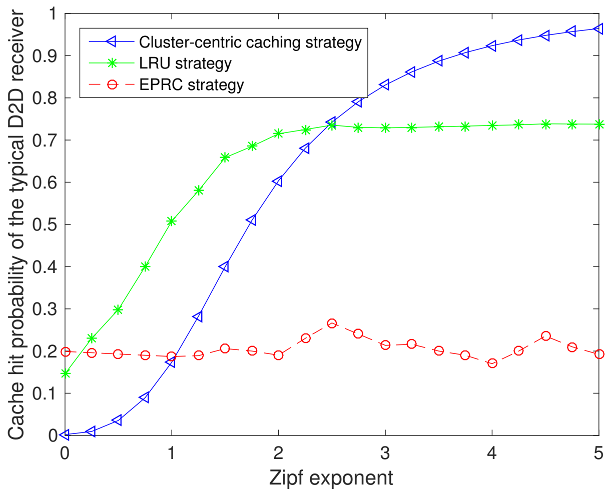

Fig. 11. Cache hit probability of the typical D2D receiver for varying Zipf exponent γ.

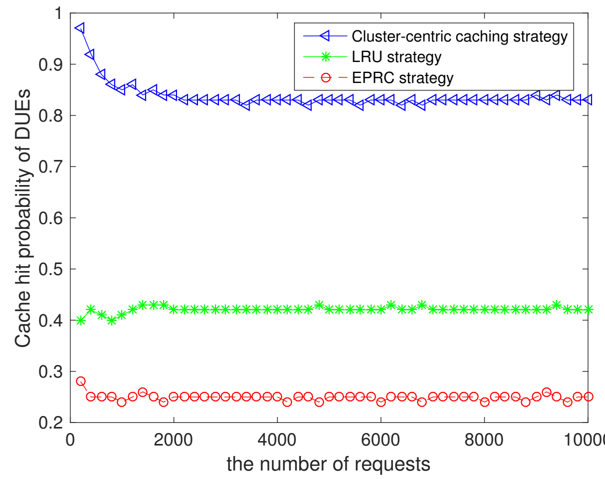

Fig. 12. Cache hit probability of DUEs with varying number of requests.

41% and 60% higher than the one of LRU and EPRC strategies, respectively.

VI. Conclusion

In this paper, we study the application of clustered D2D networks in data sharing under cluster-centric caching strategy. Assuming that no communication is carried out among different clusters, the contents of interest for the typical D2D receiver are pre-cached on the D2D transmitter located at cluster center. Firstly, TCP is used to model and analyze DUEs and CUEs, then the distances between the typical D2D receiver and other devices (serving devices and interfering devices) are characterized, assuming that they are independent and obey the Rice distribution. Secondly, the aggregated interference of the typical D2D receiver and corresponding Laplace transform are characterized. Finally, the expressions of coverage probability, average achievable rate and cache hit probability of the typical D2D receiver under cluster-centric caching strategy are derived, and the performance of the system is verified by simulating with MATLAB. It is found that the system performance can be optimized by properly controlling corresponding parameters of the clustered D2D networks.

APPENDIX

A. Proof of Theorem 1

According to formula (3), the Laplace transform of interference caused by CUEs can be derived as follows:

$$\begin{aligned}
\mathcal{L}_{I_{\rm cd}}(s) &\overset{(a)}{=} \mathbb{E}[\exp(-sI_{\rm cd})] \\
&\overset{(b)}{=} \mathbb{E}[\exp(-s\sum_{y_{\rm c}\in\phi_{\rm c}} kP_0h\left\|x_{\rm c0}+y_{\rm c}\right\|^{-\alpha})] \\
&\overset{(c)}{=} \mathbb{E}[\prod_{y_{\rm c}\in\phi_{\rm c}} \exp(-skP_0h\|x_{\rm c0}+y_{\rm c}\|^{-\alpha})]
\end{aligned}$$

$$\begin{aligned}
&\overset{(d)}{=} \mathbb{E}[\prod_{y_{\rm c}\in\phi_{\rm c}} \mathcal{L}_h(skP_0\|x_{\rm c0}+y_{\rm c}\|^{-\alpha})] \\
&\overset{(e)}{=} \exp\{-\lambda_{\rm c}\pi\bar{c}(skP_0)^{\frac{2}{\alpha}}B(1-\frac{2}{\alpha},\bar{c}+\frac{2}{\alpha})\},
\end{aligned}$$

where equation (d) is derived from the definition of Laplacian transform and the equation (e) is derived from the probability generating functional(PGFL) of PPP.

B. Proof of Theorem 2

According to the intra-cluster aggregation interference formula (4), the Laplace transform of intra-cluster interference can be deduced as follows:

$$\begin{aligned}
\mathcal{L}_{I_{\rm dd}^{\rm intra}}\left(s\left|v_{\rm d0}\right.\right) &\overset{(a)}{=} \mathbb{E}\left[\exp\left(-s\sum_{y_{\rm d}\in B^{x_{\rm d0}}} P_0h\|x_{\rm d0}+y_{\rm d}\|^{-\alpha}\right)\right] \\
&\overset{(b)}{=} \mathbb{E}_{B^{x_{\rm d0}}}\left[\prod_{y_{\rm d}\in B^{x_{\rm d0}}} \mathbb{E}\left[\exp\left(-sP_0h\|x_{\rm d0}+y_{\rm d}\|^{-\alpha}\right)\right]\right] \\
&\overset{(c)}{=} \mathbb{E}_{B^{x_{\rm d0}}}\left[\prod_{y_{\rm d}\in B^{x_{\rm d0}}} \frac{1}{1+sP_0\|x_{\rm d0}+y_{\rm d}\|^{-\alpha}}\right] \\
&\overset{(d)}{=} \sum_{l=0}^{M}\left(\int_{\mathbb{R}^2}\frac{1}{1+sP_0\|x_{\rm d0}+y_{\rm d}\|^{-\alpha}}f_Y\left(y_{\rm d}\right){\rm d}y_{\rm d}\right)^l\frac{\bar{m}^l e^{-\bar{m}}}{l!\xi},
\end{aligned}$$

where equation (a) is derived from the definition of Laplace transform, the equation (c) is due to Rayleigh fading $h \sim \exp(1)$, and in the equation (d), $\xi = \sum_{j=0}^{M} \frac{\bar{m}^j e^{-\bar{m}}}{j!}$. Now under the assumption $\bar{m} \ll M$, the Laplace transform of intra-cluster interference reduces to

$$\begin{aligned}\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{intra}}}\left(s\left|v_{\mathrm{d}0}\right.\right) &\overset{(a)}{=} \exp\left(-\bar{m}\int_{\mathbb{R}^2}\frac{sP_0\|x_{\mathrm{d}0}+y_{\mathrm{d}}\|^{-\alpha}}{1+sP_0\|x_{\mathrm{d}0}+y_{\mathrm{d}}\|^{-\alpha}}f_Y(y_{\mathrm{d}})\mathrm{d}y_{\mathrm{d}}\right)\\ &\overset{(b)}{=} \exp\left(-\bar{m}\int_0^{\infty}\frac{sP_0 w^{-\alpha}}{1+sP_0 w^{-\alpha}}Ri\left(w\left|v_{\mathrm{d}0},\sigma_{\mathrm{d}}^2\right.\right)\mathrm{d}w\right),\end{aligned}$$

the equation (a) is because the set of simultaneous transmitters in the cluster obeys a Poisson distribution with mean $\bar{m}$, and equation (b) follows from the change of variable $\|x_{\mathrm{d}0}+y_{\mathrm{d}}\| \to w$, and converting coordinates from Cartesian to polar.

C. Proof of Lemma 1

According Theorem 2, the Laplace transform of intra-cluster interference can be independently de-conditioned as follows:

$$\begin{aligned}\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{intra}}}(s) &\overset{(a)}{=} \int_{\mathbb{R}^2}\exp\left(-\bar{m}\int_{\mathbb{R}^2}\frac{sP_0\|x_{\mathrm{d}0}+y_{\mathrm{d}}\|^{-\alpha}}{1+sP_0\|x_{\mathrm{d}0}+y_{\mathrm{d}}\|^{-\alpha}}f_Y\left(y_{\mathrm{d}}\right)\mathrm{d}y_{\mathrm{d}}\right)\times f_Y(x_{\mathrm{d}0})\mathrm{d}x_{\mathrm{d}0}\\ &\overset{(b)}{=} \int_{\mathbb{R}^2}\exp\left(-\bar{m}\int_{\mathbb{R}^2}\frac{sP_0\|z\|^{-\alpha}}{1+sP_0\|z\|^{-\alpha}}f_Y\left(z-x_{\mathrm{d}0}\right)\mathrm{d}z\right)\times f_Y(x_{\mathrm{d}0})\mathrm{d}x_{\mathrm{d}0}\\ &\overset{(c)}{\geq} \exp\left(-\bar{m}\int_{\mathbb{R}^2}\int_{\mathbb{R}^2}\frac{sP_0\|z\|^{-\alpha}}{1+sP_0\|z\|^{-\alpha}}f_Y\left(z-x_{\mathrm{d}0}\right)\times f_Y(x_{\mathrm{d}0})\mathrm{d}z\mathrm{d}x_{\mathrm{d}0}\right)\\ &\overset{(d)}{\geq} \exp\left(-\bar{m}\int_{\mathbb{R}^2}\frac{sP_0\|z\|^{-\alpha}}{1+sP_0\|z\|^{-\alpha}}\sup\left(f_Y * f_Y\right)(z)\mathrm{d}z\right)\\ &\overset{(e)}{\geq} \exp\left(-\frac{\bar{m}}{4\pi\sigma^2}\int_{\mathbb{R}^2}\frac{sP_0\|z\|^{-\alpha}}{1+sP_0\|z\|^{-\alpha}}\mathrm{d}z\right)\\ &\overset{(f)}{=} \exp\left(-\frac{\bar{m}}{4\sigma^2}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right),\end{aligned}$$

where equation (b) follows from the change of variable $\|x_{\mathrm{d}0}+y_{\mathrm{d}}\| \to w$, (c) is based on Jensen's inequality, (d) is based on the definition of convolution, and the equation (e) is based on Young's inequality.

D. Proof of Theorem 3

According to the inter-cluster aggregation interference formula (5) and the definition of Laplace transformation, the Laplace transform of intra-cluster interference can be derived as follows:

$$\begin{aligned}
\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{inter}}}(s) &\overset{(a)}{=} \mathbb{E}\left[\exp\left(-s\sum_{x_{\mathrm{d}}\in\phi_{\mathrm{d}}\backslash x_{\mathrm{d}0}}\sum_{y_{\mathrm{d}}\in B^{x_{\mathrm{d}}}} P_0 h\|x_{\mathrm{d}}+y_{\mathrm{d}}\|^{-\alpha}\right)\right]\\
&\overset{(b)}{=} \mathbb{E}\left[\prod_{x_{\mathrm{d}}\in\phi_{\mathrm{d}}\backslash x_{\mathrm{d}0}} \mathbb{E}_{B^{x_{\mathrm{d}}}}\left[\prod_{y_{\mathrm{d}}\in B^{x_{\mathrm{d}}}} \mathbb{E}_h\left[\exp\left(-sP_0 h\|x_{\mathrm{d}}+y_{\mathrm{d}}\|^{-\alpha}\right)\right]\right]\right]\\
&\overset{(c)}{=} \mathbb{E}\left[\prod_{x_{\mathrm{d}}\in\phi_{\mathrm{d}}\backslash x_{\mathrm{d}0}} \mathbb{E}_{B^{x_{\mathrm{d}}}}\left[\prod_{y_{\mathrm{d}}\in B^{x_{\mathrm{d}}}} \frac{1}{1+sP_0\|x_{\mathrm{d}}+y_{\mathrm{d}}\|^{-\alpha}}\right]\right]\\
&\overset{(d)}{=} \mathbb{E}\left[\prod_{x_{\mathrm{d}}\in\phi_{\mathrm{d}}\backslash x_{\mathrm{d}0}} \sum_{k=0}^{M}\left(\int_{\mathbb{R}^2}\frac{1}{1+sP_0\|x_{\mathrm{d}}+y_{\mathrm{d}}\|^{-\alpha}} f_Y\left(y_{\mathrm{d}}\right)\mathrm{d}y_{\mathrm{d}}\right)^k \frac{\bar{m}^k e^{-\bar{m}}}{k!\eta}\right]\\
&\overset{(e)}{=} \exp\left(-2\pi\lambda_{\mathrm{d}}\int_0^\infty (1-\sum_{k=0}^{M}\left(\rho\left(v_{\mathrm{d}}\right)\right)^k\frac{\bar{m}^k e^{-\bar{m}}}{k!\eta})v_{\mathrm{d}}\mathrm{d}v_{\mathrm{d}}\right),
\end{aligned}$$

where (a) is based on Laplacian transform, (c) is based on $h\sim\exp(1)$, and (d) is derived from the PGFL of PPP. (e) follows by converting from Cartesian to polar coordinates where $\rho\left(v_{\mathrm{d}}\right)=\int_0^\infty \frac{1}{1+sP_0u^{-\alpha}}Ri\left(u\left|v_{\mathrm{d}},\sigma_{\mathrm{d}}^2\right.\right)\mathrm{d}u$. Under the assumption $\bar{m}\ll M$, the equation (e) can be written as follows:

$$\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{inter}}}(s)=\exp\left(-2\pi\lambda_{\mathrm{d}}\int_0^\infty(1-\exp[-\bar{m}\left(1-\rho\left(v_{\mathrm{d}}\right)\right)])v_{\mathrm{d}}\mathrm{d}v_{\mathrm{d}}\right).$$

E. Proof of Lemma 2

According Theorem 3, the Laplace transform of intra-cluster interference can be independently de-conditioned as follows:

$$\begin{aligned}
\mathcal{L}_{I_{\mathrm{dd}}^{\mathrm{inter}}}(s) &\overset{(a)}{\geq} \exp\left(-2\pi\lambda_{\mathrm{d}}\int_0^\infty\left(\bar{m}\int_0^\infty\frac{sP_0u^{-\alpha}}{1+sP_0u^{-\alpha}}Ri\left(u\left|v_{\mathrm{d}},\sigma_{\mathrm{d}}^2\right.\right)\mathrm{d}u\right)v_{\mathrm{d}}\mathrm{d}v_{\mathrm{d}}\right)\\
&\overset{(b)}{=} \exp\left(-2\pi\lambda_{\mathrm{d}}\left(\bar{m}\int_0^\infty\frac{sP_0u^{-\alpha}}{1+sP_0u^{-\alpha}}u\mathrm{d}u\right)\right)\\
&\overset{(c)}{=} \exp\left(-\pi\lambda_{\mathrm{d}}\bar{m}\left(sP_0\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right),
\end{aligned}$$

where (a) is derived from exponential Taylor series expansion and satisfies the following inequality $1-\exp(-ax) \leq a, a \geq 0$, and (b) follows from the Rice distribution property that $\int_0^\infty Ri(u|v_\mathrm{d}, \sigma_\mathrm{d}^2)v_\mathrm{d}\mathrm{d}v_\mathrm{d} = u$.

F. Proof of Theorem 4

The coverage probability of the typical D2D receiver in the clustered D2D networks can be derived as follows:

$$\begin{aligned}
p_\mathrm{c} &\overset{(a)}{=} \mathbb{E}\left[\mathbb{P}\left(\gamma(x_{\mathrm{d}0}) > \gamma_0\right)\right] \\
&\overset{(b)}{=} \mathbb{E}\left[\mathbb{P}\left(\frac{P_0 h r^{-\alpha}}{I_\mathrm{cd}+I_\mathrm{dd}} > \gamma_0\right)\right] \\
&\overset{(c)}{=} \mathbb{E}\left[\mathbb{P}\left(h > \frac{\gamma_0 r^\alpha (I_\mathrm{cd}+I_\mathrm{dd})}{P_0}\right)\right] \\
&\overset{(d)}{=} \mathbb{E}\left[1-\int_0^{[\gamma_0 r^\alpha (I_\mathrm{cd}+I_\mathrm{dd})]/P_0} \exp\left(-x\right) dx\right] \\
&\overset{(e)}{=} \mathbb{E}\left[\exp\left(-\frac{\gamma_0 r^\alpha}{P_0}\right)\left(I_\mathrm{cd}+I_\mathrm{dd}\right)\right] \\
&\overset{(f)}{=} \mathbb{E}\left[\exp\left(-\frac{\gamma_0 r^\alpha}{P_0}\cdot I_\mathrm{cd}\right)\cdot \exp\left(-\frac{\gamma_0 r^\alpha}{P_0}\cdot I_\mathrm{cd}\right)\right] \\
&\overset{(g)}{=} \int_0^\infty \mathcal{L}_{I_\mathrm{cd}}\left(\frac{\gamma_0 r^\alpha}{P_0}\right)\mathcal{L}_{I_\mathrm{dd}}\left(\frac{\gamma_0 r^\alpha}{P_0}\right) Ra\left(r|2\sigma_\mathrm{d}^2\right)\mathrm{d}r,
\end{aligned}$$

where (a) is based on the definition of coverage probability, (b) just replaces equation (7) and (8), (d) is based on $h \sim \exp\left(1\right)$, and (g) is based on the definition of Laplace transform.

G. Proof of Lemma 3

According to Theorem 4, and by substituting (14), (20) and $s = \frac{\gamma_0 r^\alpha}{P_0}$ into (21), the approximate coverage probability of the typical D2D receiver in the clustered D2D networks is obtained as follows:

$$\begin{aligned}
p_\mathrm{c} &= \int_0^\infty \exp\left[-\lambda_\mathrm{c}\pi\bar{c}(k\gamma_0 r^\alpha)^{\frac{2}{\alpha}} B\left(1-\frac{2}{\alpha}, \bar{c}+\frac{2}{\alpha}\right) - \left(\frac{1}{4\sigma_\mathrm{d}^2}+\pi\lambda_\mathrm{d}\right)\bar{m}\left(\gamma_0 r^\alpha\right)^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)} - \frac{r^2}{4\sigma_\mathrm{d}^2}\right]\frac{r}{2\sigma_\mathrm{d}^2}\mathrm{d}r \\
&= \frac{1}{2\sigma_\mathrm{d}^2}\int_0^\infty \exp\left[-\left(\lambda_\mathrm{c}\pi\bar{c}k^{\frac{2}{\alpha}}\gamma_0^{\frac{2}{\alpha}} r^2 B\left(1-\frac{2}{\alpha}, \bar{c}+\frac{2}{\alpha}\right) + \left(\frac{1}{4\sigma_\mathrm{d}^2}+\pi\lambda_\mathrm{d}\right)\bar{m}\gamma_0^{\frac{2}{\alpha}} r^2 \frac{2\pi/\alpha}{\sin(2\pi/\alpha)} + \frac{r^2}{4^2}\right)\right] r\mathrm{d}r
\end{aligned}$$

$$= \frac{1}{2\sigma_{\mathrm{d}}^2}\int_0^\infty \exp\left[-\left(\lambda_{\mathrm{c}}\pi\bar{c}k^{\frac{2}{\alpha}}\gamma_0^{\frac{2}{\alpha}}B\left(1-\frac{2}{\alpha},\bar{c}+\frac{2}{\alpha}\right)+\left(\frac{1}{4\sigma_{\mathrm{d}}^2}+\pi\lambda_{\mathrm{d}}\right)\bar{m}\gamma_0^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}+\frac{1}{4\sigma_{\mathrm{d}}^2}\right)r^2\right]r\mathrm{d}r$$

$$= \frac{1}{4\pi\lambda_{\mathrm{c}}\sigma_{\mathrm{d}}^2\bar{c}k^{\frac{2}{\alpha}}\gamma_0^{\frac{2}{\alpha}}B(1-\frac{2}{\alpha},\bar{c}+\frac{2}{\alpha})+(4\pi\lambda_{\mathrm{d}}\sigma_{\mathrm{d}}^2+1)\bar{m}\gamma_0^{\frac{2}{\alpha}}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}+1}$$

$$= \frac{1}{\left[4\pi\lambda_{\mathrm{c}}\sigma_{\mathrm{d}}^2\bar{c}k^{\frac{2}{\alpha}}B(1-\frac{2}{\alpha},\bar{c}+\frac{2}{\alpha})+(4\pi\lambda_{\mathrm{d}}\sigma_{\mathrm{d}}^2+1)\bar{m}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right]\gamma_0^{\frac{2}{\alpha}}+1}.$$

H. Proof of Theorem 5

We assume the average transmission rate of the typical D2D receiver in clustered D2D networks is greater than a specific threshold R_0, the average achievable rate of the typical D2D receiver in the clustered D2D caching networks can be derived as:

$$\begin{aligned}
R_{\mathrm{d}} &\overset{(a)}{=} \mathbb{E}[\log_2(1+\gamma(x_{\mathrm{d0}}))] \\
&\overset{(b)}{=} \mathbb{E}[\mathbb{P}\left(\log_2(1+\gamma(x_{\mathrm{d0}}))>R_0\right)] \\
&\overset{(c)}{=} \mathbb{E}\left[\mathbb{P}\left(h>\frac{r^\alpha}{P_0}(2^{R_0}-1)(I_{\mathrm{cd}}+I_{\mathrm{dd}})\right)\right] \\
&\overset{(d)}{=} \mathbb{E}\left[1-\int_0^{\frac{r^\alpha}{P_0}(2^{R_0}-1)(I_{\mathrm{cd}}+I_{\mathrm{dd}})}\exp(-x)\mathrm{d}x\right] \\
&\overset{(e)}{=} \mathbb{E}\left[\exp\left(-\frac{r^\alpha(2^{R_0}-1)}{P_0}\right)(I_{\mathrm{cd}}+I_{\mathrm{dd}})\right]
\end{aligned}$$

$$\overset{(f)}{=} \int_0^\infty \mathcal{L}_{I_{\mathrm{cd}}}\left(\frac{r^\alpha(2^{R_0}-1)}{P_0}\right)\cdot\mathcal{L}_{I_{\mathrm{dd}}}\left(\frac{r^\alpha(2^{R_0}-1)}{P_0}\right)Ra\left(r|2\sigma_{\mathrm{d}}^2\right)\mathrm{d}r$$

where (a) is based on the definition of average achievable rate, (d) is based on $h\sim\exp(1)$, and (f) is based on the definition of Laplace transformation.

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