Caching in Large-Scale Cellular Networks with D2D Assistance

Eleni Demarchou, Constantinos Psomas, and Ioannis Krikidis
KIOS Research Center for Intelligent Systems and Networks
Department of Electrical and Computer Engineering, University of Cyprus, Cyprus
e-mail: {edemar01, psomas, krikidis}@ucy.ac.cy

***Abstract*—This paper deals with edge caching and investigates a cellular network where both base-stations (BSs) and distributed devices have caching capabilities. The proposed caching policy allows each device to cache files according to the user's preferences while the most requested files are cached in the BSs. In this way, a three-level hierarchical connectivity scheme is employed, where a file request is satisfied with priority order by i) the closest paired device, ii) the closest BS, iii) the backhaul network. By using stochastic geometry, we derive the success probability of a requested file. Moreover, we model the capacity of the backhaul link and evaluate the delivery delay of a file. We show that our proposed protocol increases the success probability and reduces the delivery delay.**

***Index Terms*—Cache-enabled D2D, backhaul link, clusters, stochastic geometry.**

I. INTRODUCTION

The upcoming fifth generation (5G) systems are expected to offer higher throughput, increased spectral efficiency and reduced latency compared with the current technologies. In this context, industry and academia have focused on heterogeneous networks while significant attention has been given to device-to-device (D2D) communications. Considering the high proportion of traffic due to video streaming and the fact that file demands are predictable, researchers have suggested to employ edge caching, i.e. store the most requested files in either base stations (BSs) or devices [1]. As a result, the distance between the user and the information provider is reduced, achieving traffic offloading and reduction of multimedia playback latencies.

The design of cache-enabled systems mainly focuses on two aspects; the system's architecture and the caching policy. Several studies deal with the impact of employing storage units for caching in different tier levels. Using tools from stochastic geometry, the work in [2] studies the performance of cache-enabled small-cell networks showing the impact of the BS density and their storage size. An extension in a two-tier network, is introduced in [3] where both macro and small BSs are equipped with storage units; it is demonstrated that for a certain desired rate, there exists a threshold capacity after which additional storage does not improve the quality of service. Furthermore, another promising approach proposed in the literature, is the integration of D2D communications in cache-enabled networks. The authors in [4] study the performance of D2D communications in-band with cellular networks. They consider a guard-zone around each active D2D transmitter, in order to minimize the interference on the active link. The work in [5], studies a cache-enabled D2D network where the users are distributed in clusters and investigates the optimal locations of the transmitters to maximize the clusters' performance. In order to increase the offloading probability, several studies deal with the design of caching policies based on a given file popularity distribution. In [2], the authors follow the conventional "most popular" policy, i.e. the most popular files are cached in the storage units. On the other hand, the work in [6] develops a probabilistic caching policy showing that when a user is covered by more than one BSs, using the "most popular" caching policy everywhere, is not always optimal. The authors in [7], propose to cache the initial part of a file at user terminals, which can be used as a buffer while the remaining file is obtained from the BS. In [8], a cooperative caching between groups with different file preferences is investigated and the optimal group caching is derived. Moreover, the authors in [9] consider a D2D-assisted cellular network and provide the optimal caching placement that maximizes the offloading probability.

In contrast to the above, in this paper, we study a cellular network in-band with a D2D network where both devices and BSs have caching capabilities. In the proposed caching policy, BSs employ the conventional "most popular" approach and store the most popular files in the network. However, the devices cache random files based on the network's file popularity; in this way, less popular files are available in the network's cache. Any non-cached file can be obtained from the BSs via the backhaul network. Therefore, a communication scheme is implemented with three levels of connectivity where a file request is satisfied with priority order by i) the closest paired device, ii) the closest BS, iii) the backhaul network. By using stochastic geometry tools, the success probability and delivery delay of a requested file are derived in closed-form. Our results show the benefits of both our proposed caching policy and the assistance of D2D communications against conventional cellular architectures.

II. SYSTEM MODEL

A. Network topology

Consider a downlink cellular network where the BSs are spatially distributed according to a homogeneous Poisson point process (PPP) Φ_b with density λ_b. The BSs are connected to a backhaul network via a set of central nodes (CNs) which utilize a bandwidth W_{CN}. The locations of the CNs also follow a PPP Φ_{CN} with intensity λ_{CN}, where $\lambda_{\mathrm{CN}} < \lambda_b$. Each BS is wired connected with its closest CN, which can serve several BSs simultaneously. An orthogonal multiple access scheme is assumed and thus a single receiver is considered in each cell. The location of each receiver in its cell is uniformly distributed and so the locations of the receivers are considered to form a PPP with intensity λ_b [10]. Each receiver is the centre of a disk of radius d and is paired with a distinct set of D2D transmitters. Similar to [11], the D2D transmitters are spatially distributed in the disk, forming a PPP, denoted by Φ_d, with density λ_d. We will refer to the set of the D2D transmitters inside the disk as the D2D cluster. The distance distribution of the receiver to its closest BS or its closest device follows a probability distribution function (PDF) given by [12]

$$f(r) = 2\pi\lambda r \exp\left(-\pi\lambda r^2\right) \tag{1}$$

where λ is the intensity of the considered PPP. Finally, it is assumed that both the BSs and the D2D transmitters have caching capabilities and occupy a cache-dedicated bandwidth W_c. Fig. 1 schematically depicts the system model where the solid lines and dashed lines represent the active and interfering signals respectively.

B. Channel Model

We assume an interference-limited network where all links in the network experience Rayleigh distributed fading implying that the power of the channel fading is an exponential random variable with unit variance. We denote by $h_{n,i}$ the channel coefficient for the link between the i-th transmitter and the typical receiver where $n \in \{d, b\}$ denotes a D2D transmitter and a BS respectively. In addition, all wireless links suffer from path-loss effects following a power-law distribution $r_{n,i}^{-a}$ where $r_{n,i}$ is the distance from the typical receiver to the i-th transmitter and a is the propagation exponent with $a > 2$. The analysis is performed for a typical receiver located at the origin but results hold for all receivers (Slivnyak's theorem [12]). The interference experienced at the typical receiver occurs from both D2D transmitters and BSs, denoted by I_d and I_b, respectively. Therefore, the signal-to-interference-ratio (SIR) of the typical user can be expressed as

$$\mathrm{SIR}_{n,0} = \frac{P_n h_{n,0} r_{n,0}^{-a}}{I_d + I_b}, \tag{2}$$

where $I_n = \sum_{j \in \Phi_n \setminus \{n_0\}} P_n h_{n,j} r_{n,j}^{-a}$, P_n denotes the transmit power and n_0 is the transmitter associated with the typical receiver.

C. Caching policy

Let $\mathcal{F} = \{f_1, f_2, \ldots, f_N\}$ denote a finite library consisting of N popular files each of size Q bits, where f_k represents a file with popularity rank $k \in [1, N]$, i.e. f_k is less popular than f_{k-1}. The files' popularity, formed by the users' preferences, follows Zipf's law [6] with PDF

$$p_k(N) = \frac{k^{-z}}{\sum_{n=1}^{N} n^{-z}}, \tag{3}$$

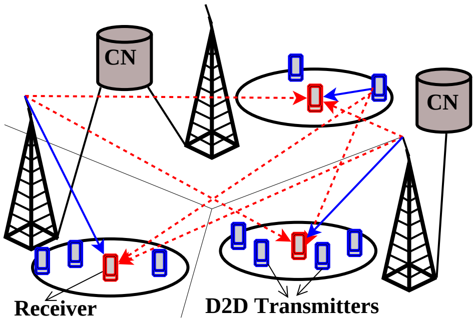

Fig. 1. Cache-enabled cellular network with D2D communications.

where z is the Zipf exponent indicating the steepness of the PDF. For a given $\mathcal{F}$, each BS follows the "most popular" caching policy [2] and stores the S_b most popular files, i.e. files $\{f_1, f_2, \ldots, f_{S_b}\}$. Each device caches S_d distinct files, independently from the other D2D transmitters, according to its user's preferences. As such, S_d random files are stored in each device based on the file's popularity PDF. Although, each D2D transmitter does not store the same file more than once, it is possible for any file to be cached more than once in the D2D cluster's cache. Due to the storage limitations of a device, it is assumed that $S_d < S_b$. This caching policy exploits the storage capability of devices in an efficient way by allowing less requested files to be cached while we ensure that a request of a very popular file will be satisfied by the BS. Using the same "most popular" caching policy for devices would not be beneficial in terms of satisfied requests; since $S_d < S_b$ all the devices would store the same files which are available at the BSs [6]. However, it is still possible for a file to be cached in both BS's and device's cache but in this case we exploit the small range of the D2D communications and the request is satisfied by the device.

III. PROTOCOL DESIGN & ANALYSIS

In this section, the network protocol is presented and the success probability and delivery delay are derived.

A. Network protocol

The proposed network protocol implements a three-level hierarchical communication scheme. Specifically, each receiver places a request for a file from the network's library $\mathcal{F}$, and is satisfied as follows

- *Check devices' cache*: The request is first assigned to the receiver's associated D2D cluster. The paired devices in the cluster will search in their caching storage for the file. If more than one D2D transmitter responds positively to the request, then the receiver connects to the one closest to it. The file is successfully downloaded, if the link's capacity attains the required threshold.
- *Check BS's cache*: If none of the paired D2D transmitters are able to satisfy the receiver's request, then it is forwarded to the receiver's associated BS. The BS searches for the file in its own caching storage; if the requested file exists in the BS's cache and the threshold capacity is achieved, the file is delivered to the receiver.

- *Download from backhaul*: If the requested file was not cached in the available storage, then it is downloaded from the backhaul to the BS through its closest CN and if the link between the BS and the user achieves the required threshold capacity, the file is delivered to the user.

B. Performance Analysis

In what follows, the cache and hit probabilities are obtained based on the considered caching policy and network protocol. Furthermore, using tools from stochastic geometry, the coverage and success probabilities together with the delivery delay of a requested file are derived.

The cache probability is the probability of a file being stored in at least one storage unit. According to the D2D caching policy, each D2D transmitter caches S_d distinct files based on the files' distribution. Therefore, the cache probability of a device storing the file of rank k is given by

$$\Pi_k^d = \sum_{i=0}^{S_d-1} p_k(N-i)\left(1-p_k(N-i)\right)^{S_d-i-1}, \qquad (4)$$

where $p_k(N-i)$ is given by (3) and the parameter $N-i$ ensures that S_d distinct files are taken into account. Hence, the cache probability of a D2D cluster, is simply the probability of at least one of the cluster's devices to cache the file of rank k, that is,

$$\Pi_k^c = 1 - \exp\left(-\lambda_d \pi d^2 \Pi_k^d\right). \qquad (5)$$

Using the above, we can now derive the cluster's hit probability Π_h^c, which is the probability of a receiver obtaining a positive response to its request from a device in its associated cluster. This is given by

$$\Pi_h^c = \sum_{k=1}^{N} p_k(N)\Pi_k^c, \qquad (6)$$

where $p_k(N)$ is the probability of requesting the k-th file given by (3). Similarly, we derive the cache probability of the BS which follows the conventional "most popular" caching policy, i.e. it stores the S_b most popular files. Hence, the probability that a file of rank k is stored in a BS's cache is

$$\Pi_k^b = \begin{cases} 1, & 1 \le k \le S_b, \\ 0, & k > S_b. \end{cases} \qquad (7)$$

Due to the hierarchical property of the proposed protocol, the receiver will request a file from its associated BS if the file does not exist in its cluster. Hence, the hit probability of a requested file is

$$\Pi_h = \sum_{k=1}^{N} p_k(N)\left(\Pi_k^c + \left(1-\Pi_k^c\right)\Pi_k^b\right). \qquad (8)$$

We now turn our attention to the coverage probability, defined as the probability that a link's capacity is above a predefined threshold. The link's capacity is given by

$$\mathcal{C}_n = W_c \log_2\left(1 + \mathrm{SIR}_n\right), \qquad (9)$$

where W_c is the bandwidth dedicated for the BSs and D2D transmitters and $n \in \{d, b\}$ where d and b refer to connection with D2D transmitter and BS respectively. Let $T = 2^{\delta/W} - 1$ denote the target SIR with which the link's threshold capacity δ, is achieved; the coverage probability can be expressed as

$$\Pi_{cov}^n = \mathbb{P}\left(W_c \log_2(1+\mathrm{SIR}_n) > \delta\right) = \mathbb{P}\left(\mathrm{SIR_n} > T\right) \qquad (10)$$

To derive the coverage probability, we need the following proposition.

Proposition 1. *The Laplace transform of the interference term I_n evaluated at s is given by*

$$\mathcal{L}_{I_n}(s, v, \lambda) = \exp\left(-2\pi\lambda s P_n \int_v^{\infty} \frac{x}{x^a + sP_n}\,dx\right), \qquad (11)$$

where $n \in \{d, b\}$ and d and b refer to the out-of-cell interference resulting from D2D transmitters and BSs respectively.

Proof: See Appendix A. ■

The coverage probabilities when connecting to each of the two available networks are obtained by applying in (10) the Laplace transform of interference given in Proposition 1 resulting in the theorems provided below.

Theorem 1. *The coverage probability of the typical receiver when connected to its associated BS is given by*

$$\Pi_{\mathrm{cov}}^b(T) = 4\pi^2\lambda_b\lambda_{I_d}\int_0^{\infty}\mathcal{L}_{I_b}\left(s, v, \lambda_{I_b}\right) v e^{-\lambda_b \pi v^2} \times \int_0^{\infty}\mathcal{L}_{I_d}\left(s, x-d, \lambda_{I_d}\right) x e^{-\lambda_{I_d}\pi x^2}\,dx\,dv, \qquad (12)$$

where $s = \frac{Tv^a}{P_b}$, $\lambda_{I_b} = \lambda_b\left(1 - \Pi_h^c\right)$ and $\lambda_{I_d} = \lambda_b \Pi_h^c$.

Proof: See Appendix B. ■

Theorem 2. *The coverage probability of the typical receiver when connected to its associated D2D transmitter within its cluster is given by*

$$\Pi_{\mathrm{cov}}^d(T, \lambda_d) = 8\pi^3\lambda_d\lambda_b\lambda_{I_d}\int_0^{d} r e^{-\lambda_d\pi r^2}\int_0^{\infty} v e^{-\lambda_b\pi v^2}\mathcal{L}_{I_b}(s, v, \lambda_{I_b}) \times \int_0^{\infty} x e^{-\lambda_{I_d}\pi x^2}\mathcal{L}_{I_d}\left(s, x-d, \lambda_{I_d}\right)\,dx\,dv\,dr, \qquad (13)$$

where $s = \frac{Tr^a}{P_d}$, $\lambda_{I_b} = \lambda_b\left(1 - \Pi_h^c\right)$ and $\lambda_{I_d} = \lambda_b \Pi_h^c$.

Proof: The proof of Theorem 2 is similar to the one of Theorem 1, thus is omitted due to space limitations. ■

Using the coverage probability and the caching policy, we can now derive the success probability. The success probability, is the probability of a user obtaining its requested file from the available network cache whilst achieving the predefined threshold capacity. Thus, the success probability is given by

$$\Pi_s(T) = \sum_{k=1}^{N} p_k(N)\left(\Pi_{\mathrm{cov}}^d(\tilde{\lambda}_{d,k}) + \left(1 - \Pi_k^c\right)\Pi_k^b\Pi_{\mathrm{cov}}^b\right), \qquad (14)$$

where $\tilde{\lambda}_{d,k} = \Pi_k^d \lambda_d$ expresses the thinned D2D density of the devices that have cached the file of rank k.

Finally, we present the delivery delay which is defined as the time period needed for a user to obtain a requested file conditioned that the link's capacity achieved the predefined threshold. this is simply the ratio of the file size Q over the capacity of the link $\mathcal{C}$, i.e. $\tau = Q/\mathcal{C}$ with $\mathcal{C} > \delta$. The delivery

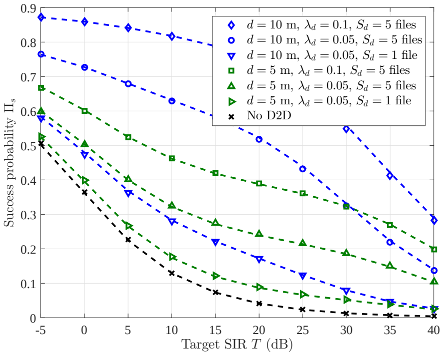

Fig. 2. Success probability Π_s versus target SIR T.

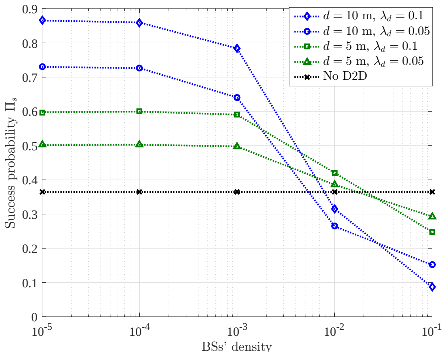

Fig. 3. Success probability Π_s versus BS density with $T = 0$ dB.

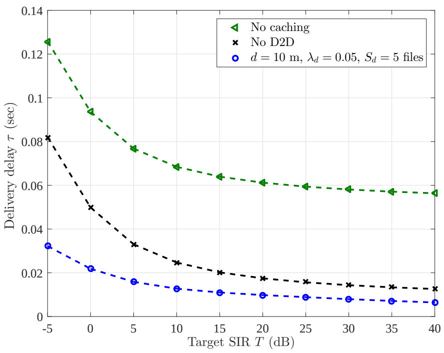

Fig. 4. Delivery delay τ (in seconds) versus target SIR T.

delay is obtained considering both cases of a user receiving positive and negative response to its request.

The delivery delay of a file transmitted from the BS is

$$\begin{aligned}\tau_b(T) &= \mathbb{E}_{\mathrm{SIR}}\left[\frac{Q}{W_c \log_2\left(1+\mathrm{SIR}\right)}\middle|\mathrm{SIR} > \mathrm{T}\right] \\ &= \frac{Q}{W_c \Pi^b_{cov}(T)} \int_T^{\infty} \frac{1}{\log_2\left(1+x\right)} g_b\left(x\right) dx, \end{aligned} \tag{15}$$

where $g_b(\mathrm{SIR}) = d(1 - \Pi^b_{\mathrm{cov}})/d\mathrm{SIR}$ is the PDF of SIR evaluated by taking the derivative of its cumulative distribution function, which follows by the complementary of the coverage probability given above. In case a file is cached in the BS' cache then the delivery delay is $\tau_b(T)$. Note that $\tau_b(T)$ expresses the delay of the link between the BS and the user, thus we will also use this in the case of a negative response to the request.

On the other hand the file of rank k is downloaded from a device only if the file is cached in the D2D cluster. Thus, considering the cache probability of a device and following the same method as above, the delivery delay when downloading the file of rank k from a D2D transmitter is

$$\tau_{d,k}(T) = \frac{Q}{W_c \Pi^d_{cov}(T, \tilde{\lambda}_{d,k})} \int_T^{\infty} \frac{g_d\left(x, \tilde{\lambda}_{d,k}\right)}{\log_2\left(1+x\right)} dx, \tag{16}$$

where $g_d(\mathrm{SIR}, \tilde{\lambda}_{d,k}) = d(1 - \Pi^d_{\mathrm{cov}}(\mathrm{SIR}, \tilde{\lambda}_{d,k}))/d\mathrm{SIR}$.

In case both D2D cluster's and BS's response to user's request is negative, then the BS first downloads the file from the backhaul via its closest CN and then transmits it to the user. Hence, the link connecting the user with the backhaul consists of two independent links. Each CN serves several BSs simultaneously with a capacity

$$\mathcal{C}_{\mathrm{CN}} = W_{\mathrm{CN}} \frac{\lambda_{\mathrm{CN}}}{\lambda_b} \frac{\mu}{(1 - \Pi_h)}, \tag{17}$$

where Π_h is given by (8) and μ is a non-negative constant such that $\mathcal{C}_{\mathrm{CN}} > \delta$. Since each CN serves multiple BSs, the more BSs assigned to a CN, the more requests it has to satisfy, resulting to lower capacity. In addition, when the available cache contains the requested file, the backhaul traffic is directly offloaded and the CN has less requests to serve, offering higher capacity. So, the download delay from a CN to a BS is simply $\tau_\mu = Q/\mathcal{C}_{\mathrm{CN}}$. However, to attain successful transmission of the file, the link between the BS and the receiver should still achieve the threshold capacity δ and the delay of this link is given in (15). Based on the protocol, the delivery delay experienced by a user is given by

$$\begin{aligned}\tau(T) = \sum_{k=1}^{N} p_k(N) &\left(\tau_{d,k}(T) + \left(1 - \Pi^c_k\right) \Pi^b_k \tau_b(T)\right) \\ &+ \left(1 - \Pi_h\right)\left(\tau_b(T) + \tau_\mu\right). \end{aligned} \tag{18}$$

IV. NUMERICAL RESULTS

In this section, the proposed analytical model is validated and evaluated with computer simulations. The scheme where only BSs are cache-enabled following the "most popular" caching policy is used as a benchmark and is referred to throughout this section as "No D2D". Unless otherwise stated, our results use the following parameters: $N = 100$ files, $Q = 10^7$ bits, $z = 0.4$, $S_b = 50$ files, $S_d = 5$ files, $\lambda_{\mathrm{CN}} = 10^{-6}$, $\lambda_b = 10^{-4}$, $\lambda_d = 0.05$, $d = 10$ m, $P_d = 0$ dB, $P_b = 10$ dB, $a = 4$, $W_c = 10^8$ Hz, $W_{\mathrm{CN}} = 10^9$ Hz and $\mu = 20$.

Fig. 2 plots the average success probability versus the target SIR for different values of d, λ_d and S_d. Markers represent simulation's results which are evaluated with the analytical results represented with the dashed lines. As can be seen, the employment of a cache-enabled D2D network to a conventional cache-enabled cellular network provides significant gains to the success probability. At expected, the success probability increases with a larger storage size S_d, with higher device's density in the cluster λ_d, and also with a larger cluster radius d. This is because the growth of devices within a cluster, each with more storage available corresponds to a higher number of cached files implying increment of the hit probability. This, as a result, leads to a better success probability. In Fig. 3 the success probability is shown with respect to the BSs' density. For small values of λ_b, the caching capabilities of devices increase the success probability and it is clearly higher than the "No D2D" case. As λ_b increases, the success probability decreases and, in the case of dense BS deployment, the employment of cache-enabled devices results in lower performance compared to "No D2D" case.

This is because the D2D clusters overlap with each other and the interference received at the active receivers degrades D2D communications; this can be overcome, as shown in the figure, by a smaller cluster radius and a less dense D2D cluster. Finally, Fig. 4 presents the average delivery delay τ of a requested file versus the target SIR T. As the target SIR increases, the average delay decreases which is expected since the link's threshold capacity increases. Furthermore, when cache-enabled networks are employed, the average delivery delay decreases significantly compared to a conventional cellular network which is due to the traffic offloading achieved by caching. In this case, the CN's link is less frequently used for downloading files and when used, the link's capacity is higher resulting in a lower delivery delay. When both devices and BSs are cache-enabled, the achieved delivery delay is the lowest of the three cases due to the improvement of both hit and success probabilities.

V. CONCLUSIONS

In this paper, we studied the benefits associated with the integration of cache-enabled D2D networks to conventional cache-enabled cellular networks. The proposed caching policy stores random files to the devices based on the network's file popularity, while cellular BSs cache the most popular content. The proposed scheme enables a hierarchical connectivity, where priority is given to the closest information source to the users. In addition, the capacity of the backhaul link has been modeled and the performance gains of the D2D communications have been analyzed in terms of success probability and delivery delay.

APPENDIX

A. Proof of Proposition 1

The Laplace transform of the interference I_n evaluated at s can be derived as follows [10]

$$\begin{aligned}
\mathcal{L}_{I_n}(s,v,\lambda) &= \mathbb{E}_{I_n}\left[\exp(-sI_n)\right] \\
&= \mathbb{E}_{\Phi_n}\left[\mathbb{E}_{h_{n,j}}\left[\exp\left(-s\sum_{j\in\Phi_n\setminus\{n_0\}} P_n h_{n,j} r_{n,j}^{-a}\right)\right]\right] \\
&\overset{(a)}{=} \mathbb{E}_{\Phi_n}\left[\prod_{j\in\Phi_n\setminus\{n_0\}} \frac{1}{1+sP_n r_{n,j}^{-a}}\right] \\
&\overset{(b)}{=} \exp\left(-2\pi\lambda\int_v^\infty\left(1-\frac{1}{1+sP_n x^{-a}}\right)xdx\right), \qquad (19)
\end{aligned}$$

where (a) follows from the moment generating function of an exponential random variable and the fact that the variables $h_{n,j}$ are independent and identically distributed; (b) is obtained using the probability generating functional of a PPP [12] and the lower limit v denotes the distance to the nearest interferer. After some algebraic manipulations, the result follows.

B. Proof of Theorem 1

From (10), the coverage probability of the typical receiver connected to its associated BS is evaluated as

$$\begin{aligned}
\Pi_{\text{cov}}^b &= \mathbb{P}\left(\frac{P_b h_{b,0} r_{b,0}^{-a}}{I_d+I_b} > T\right) = \mathbb{P}\left(h_{b,0} > \frac{T(I_d+I_b)}{P_b r_{b,0}^{-a}}\right) \\
&= \int_0^\infty \mathbb{E}_{I_d}\left[\exp\left(-\frac{TI_d}{P_b v^{-a}}\right)\right]\mathbb{E}_{I_b}\left[\exp\left(-\frac{TI_b}{P_b v^{-a}}\right)\right] f(v)\,dv,
\end{aligned}$$

which follows from the fact that $h_{b,0}$ is exponentially distributed with unit variance and $f(v)$ is given by (1) where v is the distance of the typical receiver to its associated BS. By setting $s=\frac{Tv^a}{P_b}$ and using Proposition 1, we have

$$\begin{aligned}
\Pi_{\text{cov}}^b &= 2\pi\lambda_b\int_0^\infty \mathcal{L}_{I_b}\left(s,v,\lambda_b\left(1-\Pi_h^c\right)\right) v e^{-\lambda_b\pi v^2} \\
&\quad\times 2\pi\lambda_b\Pi_h^c\int_0^\infty \mathcal{L}_{I_d}\left(s,x-d,\lambda_b\Pi_h^c\right) x e^{-\lambda_b\Pi_h^c\pi x^2}\,dx\,dv
\end{aligned}$$

where $\mathcal{L}_{I_b}$ and $\mathcal{L}_{I_d}$ are the Laplace transforms of the out-of-cell interference from BSs and devices, respectively, and are obtained as follows. The density of the interfering BSs is a thinning PPP of Φ_b [12], equals to $\lambda_b(1-\Pi_h^c)$, where Π_h^c is given by (6). The distance to the nearest interfering BS is greater than the distance to the typical receiver's associated BS and so the lower limit is v. Similarly, the density of the interfering devices is $\lambda_b\Pi_h^c$. The distance to the nearest interfering device is evaluated approximately assuming that the D2D clusters do not overlap with each other. Specifically, denote by x the distance between the typical receiver and the nearest active receiver employing D2D communications. By subtracting the cluster radius d from x we obtain a lower tight bound for the distance between the typical receiver and the nearest interfering device.

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