Caching in Large-Scale Cellular Networks with D2D Assistance

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Abstract—This paper deals with the wireless 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, and 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 average 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 wireless 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 heterogeneous network is introduced in [3], where both macro and small BSs are equipped with storage units; it is demonstrated that for a certain requested 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 coexisting with cellular networks. They consider a guard-zone around each active D2D transmitter, such that the interference on the active link is limited. 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 the 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 operating in the same frequency band (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 also 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, and iii) the backhaul network. We model the three levels of connectivity by taking into account spatial randomness. 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) $\Phi_b$ with density $\lambda_b$. 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 $\Phi_{CN}$ with intensity $\lambda_{CN}$, where $\lambda_{CN} < \lambda_b$. 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 $\lambda_b$ [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 $\Phi_d$, with density $\lambda_d$. 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]

$$f(r, \lambda) = 2\pi \lambda r \exp \left(-\pi \lambda r^2\right),$$

where $\lambda$ 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 $r_{n,i}^{-\alpha}$ where $r_{n,i}$ is the distance from the typical receiver to the $i$-th transmitter and $\alpha$ is the propagation exponent with $\alpha > 2$. 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

$$\text{SIR}_{n,0} = \frac{P_n h_{n,0} r_{n,0}^{-\alpha}}{I_d + I_b},$$

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

C. Caching policy

Let $F = \{f_1, f_2, \ldots, f_N\}$ 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 with PDF [6]
exists in the BS’s cache and the threshold rate 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 rate, 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 as well as 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

\[
P_{ck}^d = \sum_{i=0}^{S_d-1} p_k(N - i)(1 - p_k(N - i))^{S_d - i - 1},
\]

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,

\[
P_{ck}^b = 1 - \exp \left( -\lambda_d \pi d^2 P_{ck}^d \right).
\]

Using the above expression, we can derive the cluster’s hit probability \( P_{hc}^b \), 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

\[
P_{hc}^b = \sum_{k=1}^{N} p_k(N) P_{ck}^b,
\]

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

\[
P_{ck}^s = \begin{cases} 1, & 1 \leq k \leq S_b, \\ 0, & k > S_b. \end{cases}
\]

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

\[
P_{hc}^s = \sum_{k=1}^{N} p_k(N) \left( P_{ck}^s + (1 - P_{ck}^s) P_{hc}^b \right).
\]

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 Shannon capacity is given by

\[C_n = W_c \log_2 (1 + \text{SIR}_n),\]

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 \( T = 2^{d/W} - 1 \) denote the target SIR with which the link’s threshold rate \( \delta \) is achieved; the coverage probability can be expressed as

\[
\Pi_{cov}^n = P \left( W_c \log_2 (1 + \text{SIR}_n) > \delta \right) = P \left( \text{SIR}_n > T \right). \tag{10}
\]

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

\[
\mathcal{L}_{I_n}(s, v, \lambda) = \exp \left( -2\pi \lambda s P_n \int_0^\infty \frac{x}{x^\alpha + s P_n} \, dx \right), \tag{11}
\]

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

\[
\Pi_{cov}^b(T) = 4\pi^2 \lambda_b \lambda_{I_b} \int_0^\infty \mathcal{L}_{I_b}(s, v, \lambda_{I_b}) x^{-\lambda_b \pi v^2} \delta \lambda_{I_b} \pi v^2 \, dx \, dv, \tag{12}
\]

where \( s = \frac{T e^{-\nu}}{\nu} \), \( \lambda_b = \lambda_b (1 - \Pi_{ck}^b) \) and \( \lambda_{I_b} = \lambda_b \Pi_{hc}^b \).

**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

\[
\Pi_{cov}^d(T, \lambda_d) = 8\pi^3 \lambda_d \lambda_{I_d} \int_0^d \int_0^{\infty} e^{-\lambda_d \pi x^2} \delta \lambda_d \pi x^2 \mathcal{L}_{I_d}(s, v, \lambda_{I_d}) \, dx \, dv, \tag{13}
\]

where \( s = \frac{T e^{-\nu}}{\nu} \), \( \lambda_{I_d} = \lambda_d (1 - \Pi_{ck}^d) \) and \( \lambda_{I_d} = \lambda_d \Pi_{hc}^d \).

**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 rate. Thus, the success probability is given by

\[
\Pi_s(T) = \sum_{k=1}^{N} p_k(N) \left( \Pi_{cov}^d(\lambda_{d,k}) + (1 - \Pi_{ck}^d) \Pi_{hc}^b \Pi_{cov}^b \right), \tag{14}
\]

where \( \lambda_{d,k} = \Pi_{ck}^d \lambda_d \) 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 rate. This is simply the ratio of the file size \( Q \) over the capacity of the link \( C \), i.e. \( \tau = Q/C \) with \( C > \delta \). The delivery 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
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 “No D2D”. Unless otherwise stated, our results use the following parameters: $N = 100$ files, $Q = 10^7$ bits, $z = 0.4$, $S_0 = 50$ files, $S_d = 5$ files, $\lambda_{CN} = 10^{-6}$, $\lambda_b = 10^{-4}$, $\lambda_d = 0.05$, $d = 10$ m, $P_d = 0$ dB, $P_b = 10$ dB, $a = 4$, $W_c = 100$ MHz, $W_{CN} = 1$ GHz and $\mu = 20$.

Fig. 2 plots the average success probability versus the target SIR $T$ for different values of $d$, $\lambda_d$ and $S_d$. 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. As expected, the success probability increases with a larger storage size $S_d$, with higher device’s density in the cluster $\lambda_d$, 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 leads to a better success probability. Finally, the analytical results match the simulation results which validates our theoretical expressions. In Fig. 3 the success probability is shown with respect to the BSs’ density. For small values of $\lambda_b$, the caching capabilities of devices increase the success probability and it is clearly higher than the “No D2D” case. As $\lambda_b$ 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 connectivity; this can be overcome, by a smaller cluster radius and a less dense D2D cluster. Finally, Fig. 4 presents the average delivery delay $\tau$ of a requested file versus the target SIR $T$. As the target SIR increases, the average delivery delay decreases.
delay decreases which is expected since the link’s threshold rate 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 CN serves the BSs with higher capacity 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 \( I_v \) evaluated at \( s \) can be derived as follows [10]

\[
\mathcal{L}_{I_v}(s, v, \lambda) = \mathbb{E}_{I_v} \left[ \exp \left( -s I_v \right) \right] = \mathbb{E}_{\Phi_n} \left[ \exp \left( -s \sum_{j \in \Phi_v \setminus \{v\}} P_n h_{n,j} r_{n,j}^{-a} \right) \right]
\]

\[
= \mathbb{E}_{\Phi_v} \left[ \prod_{j \in \Phi_v \setminus \{v\}} \frac{1}{1 + s P_n r_{n,j}^{-a}} \right] \exp \left( -2\pi \lambda \int_0^\infty \int_0^\infty \mathbb{I}(r_{n,j} > x) x dx \right),
\]

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

\[
\Pi_{cov} = \mathbb{P} \left( \frac{P h_{b,0} v^{-a}}{I_d + I_b} > T \right) = \mathbb{P} \left( h_{b,0} > T \frac{I_d + I_b}{P h_{b,0} v^{-a}} \right) = \int_0^b \mathbb{E}_{I_d} \left[ \exp \left( -T I_d \frac{v}{P h_{b,0} v^{-a}} \right) \right] \mathbb{E}_{I_b} \left[ \exp \left( -T I_b \frac{v}{P h_{b,0} v^{-a}} \right) \right] f(v, \lambda_b) dv,
\]

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

\[
\Pi_{cov} = 2\pi \frac{\lambda}{\lambda_b} \int_0^\infty \mathcal{L}_{I_b}(s, v, \lambda_b (1 - \Pi_{cov})) e^{-\lambda_b s v^2} dx dv,
\]

where \( L_{I_b} \) and \( L_{I_d} \) 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 \( \Phi \) [12], equals to \( \lambda_b (1 - \Pi_{cov}) \), where \( \Pi_{cov} \) 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 \( \lambda h_{b,0} \). 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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