Cache-Enabled Device to Device Networks with Aloha Based Multimedia Delivery

Xiaoshi Song, Chao Jia, Jiacheng Wang, Xile Shen, Ning Ye, and Weimin Lei
School of Computer Science and Engineering, Northeastern University
Shenyang, China
songxiaoshi@cse.neu.edu.cn

ABSTRACT

In this paper, we study the performance of large-scale cache-enabled device to device (D2D) networks. The mobile helpers(MHs) and the user equipments(UEs) are modeled as two independent homogeneous Poisson pointprocess (HPPP). The UEs can get file from MHs which are assumed to have caching capabilities within the collaboration distance of D2D transmission. An Aloha type of multimedia delivery protocol is considered, under which the available MHs make independent decisions to launch the transmissions with probability p_m. According to stochastic geometry, we derive and analyze the transmission probability of MHs . And then, the coverage probability of the randomly requested files is characterized. Next, we work out the successful content delivery probability of the cache-enabled D2D network. By applying the obtained results of successful content delivery probability, we optimize the probabilistic caching strategy of MHs. Particularly, under the proposed Aloha based multimedia delivery protocol, to maximize the successful content delivery probability of the cache-enabled D2D network, each MH should simply cache the most popular file. Simulations are included to demonstrate our analysis.

KEYWORDS

Cache-enabled D2D networks, Aloha based multimedia delivery protocol, optimal probabilistic caching strategy, stochastic geometry, successful content delivery probability.

1 INTRODUCTION

Driven by the ever-increasing demand of bandwidth-intensive multimedia services, due to the proliferation of smart mobile devices growing exponentially, data traffic boomed over recent years. The mobile data traffic is expected to reach 49 exabytes per month by 2021, an sevenfold increase over 2016, in which multimedia streaming contribute more than three-fourths percent, predicted by Cisco [4]. In response to such a rapid the multimedia contents closer to users, but also simultaneously the spatial recuse and (coded or uncoded) multicasting opportunities in data dissemination are utilized to reduce the heavy pressure of the fast growing traffic with caching ability enabled at the nearest mobile helpers.

In order to study cache-enabled device-to-device networks, it is necessary to apply tools from stochastic geometry [2, 3, 10–12, 19] for tractable characterization of key network performance metrics, such as coverage, spatial throughput, and so on. In particularly, In [11], aiming at maximizing the average density of successful receptions under different fading distributions, Malak et al. developed the optimal spatially-independent content caching strategies. In [12], Malak et al. further researched the optimal geographic content placement problem for device-to-device networks, and put forward spatially correlated caching strategies by maximizing the device-to-device cache hit probability. In [2], for different degrees of node mobility, Jarray et al. discussed the hit performance of caching in device-to-device networks. In [3], Chen et al. offered analytical and numerical results to compare caching at small cells and the performance of caching at mobile devices, based on the density of cache-served requests, average power consumption and the cache hit probability. In [19], analyzing a closed-form approximation of cache-aided throughput, Chen et al. further investigated the optimal caching probabilities with numerical optimization. In [10], Afshang et al. developed a comprehensive analytical framework with foundations in stochastic geometry to describe the performance of cluster-centric content placement in a cache-enabled device-to-device network

In this paper, different from that in [2, 3, 10–12, 19], to study the performance of large-scale cache-enabled device-to-device networks, we develop a framework of analysis which mobile helpers (MHs) and user equipments (UEs) follow homogeneous Poisson point process (HPPP)distribution. An Aloha type multimedia delivery protocol is considered, under which an available MH[1] decides to launch the transmission with probability p_m. Besides, we assume that the popularity of the multimedia files obeys a Zipf distribution. By making use of tools from stochastic geometry, we derive the transmission probability of MHs with the Aloha based multimedia delivery protocol. Then, We describe the coverage probability of the randomly requested files. Next, The successful content delivery probability is characterized. According to the obtained results of successful content delivery probability,

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[1] An available MH is defined as the MH which caches the requested files.

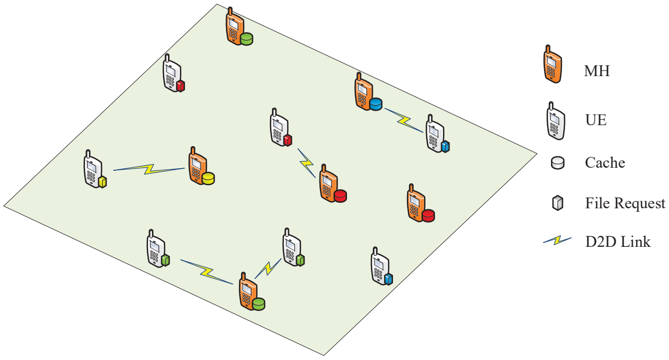

Figure 1: Cache-enabled device to device network formed by MHs, UEs, and a library of multimedia files $\mathcal{F}$.

we optimize the probabilistic caching strategy of MHs. Especially, we find each MH caching the most popular file can maximize the successful content delivery probability. Finally, we validate our analysis through simulations.

The remainder of this paper is organized as follows. In Section II, the system model is introduced. In Section III, we derive the transmission probability of MHs. The successful content delivery performance of is given in Section IV. In Section V, We discuss the optimal probabilistic caching strategy. Section VI provides simulation results to demonstrate the validity of our proposals. Finally, Section VII conclude the paper .

2 SYSTEM MODEL

We consider a large-scale cache-enabled device-to-device network formed by dedicated MHs, intended UEs, and a library of multimedia files $\mathcal{F} := \{1, 2, \cdots, F\}$ on $\mathbb{R}^2$ as illustrated in Fig. 1. We model the locations of MHs and UEs as two independent HPPPs with density λ_m and λ_u, respectively. To simplify the analysis, the files in library $\mathcal{F}$ is assumed to be of the same size, and each MH possess a cache memory of only 1 file($M = 1$). The MH caches the f-th file randomly in $\mathcal{F}$ with probability c_f, which is decentralized probabilistic caching strategy. The popularity of the f-th file in $\mathcal{F}$ is assumed to follow the Zipf distribution as

$$p_f = \frac{1/f^{\gamma}}{\Sigma_{j=1}^{F} 1/j^{\gamma}}, \tag{1}$$

where $\gamma \geq 0$ denotes the Zipf parameter.

The model of propagation channel is the combination of the large-scale path-loss and the small-scale Rayleigh fading given by

$$g(d) = hd^{-\alpha}, \tag{2}$$

where d denotes the propagation distance, h denotes the exponentially distributed power coefficient with unit mean, and α denotes the path-loss exponent. To do this simply, we ignore the thermal noise in the regime of interest and simply focus on the received signal to interference ratio (SIR). The transmit power of MHs is denoted by P_d. Let R_d denote the collaboration distance of device-to-device transmission between MH and UE. θ_d is defined as the SIR target for successful data receptions under device-to-device communication.

An Aloha type multimedia delivery protocol is considered, under which an available MH makes independent decisions to launch the transmission with probability p_m. Then, upon finding the active MHs, the UEs simply associate with the nearest ones for data transmissions. Further, it is assumed that each MH may simultaneously serve multiple UEs with the same content request in the vicinity.

3 TRANSMISSION PROBABILITY

In this section, under the Aloha based multimedia delivery protocol. Particularly, we characterize the transmission probability of MHs in large-scale cache-enabled device-to-device networks. To derive the transmission probability, we define ζ_d as the probability that a MH is under request. At first, we deduce ζ_d in the following lemma.

Lemma 3.1. *For large-scale cache-enabled device-to-device networks, the probability that a MH is under request is given by*

$$\zeta_d = \sum_{f=1}^{F} c_f \cdot \left(1 - e^{-\lambda_u p_f \pi R_d^2}\right). \tag{3}$$

Proof. Given p_f, c_f, and R_d, we can consider the void probability that The tagged MH doesn't get request of the file which it has cached within a distance of R_d, which completes the proof of Lemma 3.1. ☐

Based on Lemma 3.1, we prepare for evaluating the transmission probability of MHs under the Aloha based multimedia delivery protocol, as given by following theorem.

Theorem 3.2. *For large-scale cache-enabled device-to-device networks, the transmission probability of MHs under the Aloha based multimedia delivery protocol is given by*

$$q_d = \zeta_d \cdot p_m. \tag{4}$$

Proof. With Lemma 3.1, under the Aloha based multimedia delivery protocol, (4) is immediately obtained. This thus completes the proof of Theorem 3.2. ☐

We define Ψ_m^a as the point process formed by active MHs with the Aloha based multimedia delivery protocol and define λ_m^a as the corresponding density. According to Theorem 3.2, we have the following corollary.

Corollary 3.3. *For large-scale cache-enabled device-to-device networks with the Aloha based multimedia delivery protocol, the density of Ψ_m^a is given by*

$$\lambda_m^a = \lambda_m \cdot q_d. \tag{5}$$

We paying attention to that the requests of UEs are spatially correlated for MHs within a distance of R_d. Hence, Ψ_m^a does't follow a HPPP. Besides, since the higher order statistics of Ψ_m^a are tricky, the successful content delivery probability of the cache-enabled device-to-device networks, which bases on the probability generating functional (PGFL) [9] of Ψ_m^a, is hard to be described exactly. To work out this difficulty, similar to [9, 16, 18], we make the following approximation on Ψ_m^a, which will be proved later by simulations in Section VI.

Conjecture 3.4. *For large-scale cache-enabled device-to-device networks, Ψ_m^a follows a HPPP with density λ_m^a.*

In the following section, with Theorem 3.2 and Assumption 3.4, it will be characterized that the successful content delivery performance of large-scale cache-enabled device-to-device networks with the Aloha based multimedia delivery protocol.

4 SUCCESSFUL CONTENT DELIVERY PROBABILITY

Thanks to the stationarity of the point processes composed by the MHs and UEs, we concentrates on a typical UE at the origin denoted by $\mathbf{U}$ with its related MH at a random distance of d_f away denoted by $\mathbf{M}$, where the distribution of d_f depends on the popularity of file f, to analyze the successful content delivery performance of the large-scale cache-enabled device-to-device networks. Then, under Assumption 3.4, by Slivnyak's theorem [9], the locations of the rest of the active MHs follow a HPPP with density λ_m^a. Based on this fact, in the following theorem, the successful content delivery probability of the cache-enabled device-to-device network is characterized.

Theorem 4.1. *For large-scale cache-enabled device-to-device networks, with the Aloha based multimedia delivery protocol, according to Assumption 3.4, the successful content delivery probability is expressed as*

$$\begin{aligned}\tau_d = \sum_{f=1}^{F} p_f \int_0^{R_d} & \exp\left\{-\left(1-c_f\right)\int_0^{\infty}\eta(u)u\mathrm{d}u\right\} \\ & \times \exp\left\{-c_f\int_{d_f}^{\infty}\eta(u)u\mathrm{d}u\right\}\cdot\varpi_f(d_f)\mathrm{d}\mathrm{d}_\mathrm{f},\end{aligned} \tag{6}$$

where

$$\eta(u) = \frac{2\pi\lambda_m^a}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}, \tag{7}$$

and

$$\varpi_f(d_f) = 2\lambda_m^a c_f \pi d_f \cdot e^{-\lambda_m^a c_f \pi d_f^2}. \tag{8}$$

Proof. The proof is omitted due to the space limitation. ☐

5 PROBABILISTIC CACHING PLACEMENT

In this section, we aim at maximizing the successful content delivery probability τ_d of the cache-enabled device-to-device networks with the Aloha based multimedia delivery protocol by finding the optimal solutions of c_f. In particular, according to Theorem 4.1, the optimization problem is formulated as

$$(\text{P1}):\ \max_{c_f} \tau_d \tag{9}$$

$$\text{s.t.}\ \sum_{f=1}^{F} c_f \le 1, \tag{10}$$

$$c_f \ge 0. \tag{11}$$

We find the expression of τ_d complex and the coupling effect between λ_m^a and c_f, so it is hard to obtain an exact characterization of the optimal solutions $\tilde{c}_f^*$ of (P1). To work out this trouble, by applying that τ_d is an increasing function in regards to λ_m^a (which can be numerically proved) and thereby ζ_d, we consider an replaceable optimization problem as

$$(\text{P2}):\ \max_{c_f} \zeta_d \tag{12}$$

$$\text{s.t.}\ \sum_{f=1}^{F} c_f \le 1, \tag{13}$$

$$c_f \ge 0. \tag{14}$$

According to (3), we deduce the optimal solution c_f^* of (P2) in the following lemma.

Lemma 5.1. *The optimal solution c_f^* of* (P2) *is given by*

$$\begin{aligned} & c_1^* = 1 \\ & c_i^* = 0,\ i = 2, 3, ..., F, \end{aligned} \tag{15}$$

i.e.,to maximize ζ_d we can cache the most popular file in $\mathcal{F}$.

Proof. It can be easily proved that (P2) is a linear programming problem in regards to c_f. So by applying simplex method [17] on (P2), we can immediately obtain (15). This thus completes the proof of Lemma 5.1. ☐

6 NUMERICAL RESULTS

In this section, we present simulation results on the performance of the studied large-scale cache-enabled device-to-device network with Aloha based multimedia delivery protocol to validate our analytical results. Throughout this section, unless specified otherwise, we set $P_d/N_d = 20$, $\theta_d = 1$, $R_d = 15$, $\gamma = 1$, $\alpha = 4$, $c_f = p_f$, $p_m = 0.9$, $F = 5$, and $\lambda_m = 0.005$.

6.1 Transmission Probability

Fig. 2 compares the analytical and simulated results on the transmission probability q_d versus the density of UEs λ_u. It is shown in the picture that the transmission probability q_d of MHs is an increasing function with respect to λ_u (and thereby ζ_d), which is visually expected according to Theorem 3.2.

6.2 Successful Content Delivery Probability

Fig. 3 reveals the successful content delivery probability τ_d versus the density of UEs λ_u. Several observations are in order. Firstly, it is shown that τ_d is an increasing function of λ_u (and thereby ζ_d, q_d, and λ_m^a), which is consistent with

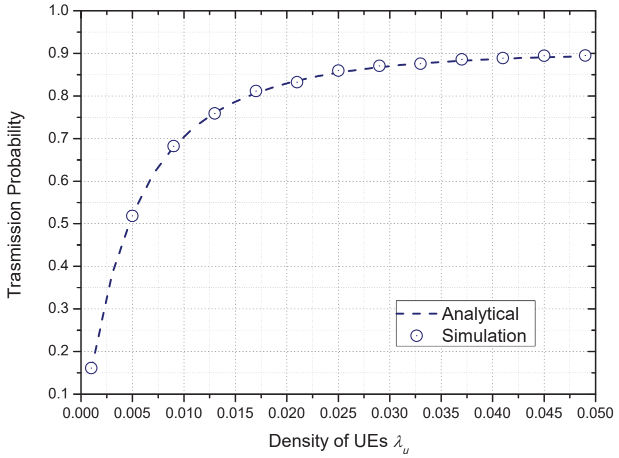

Figure 2: Transmission probability q_d versus the density of UEs λ_u.

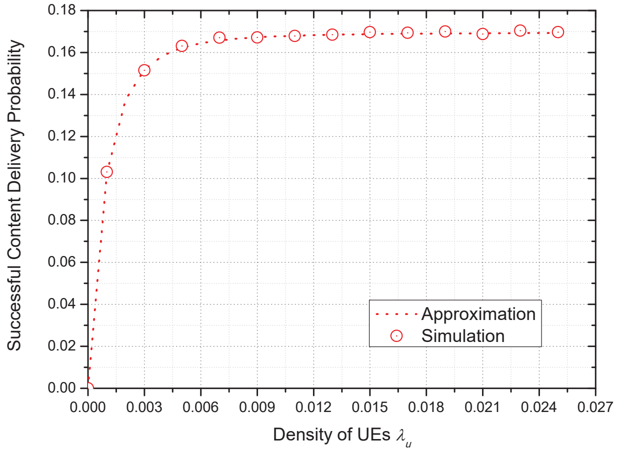

Figure 3: Successful content delivery probability τ_d versus the density of UEs λ_u.

the monotonicity of ξ_f but varied from that of $\mathcal{C}_f$. Secondly, we derive the approximated successful content delivery probability τ_d in Theorems 4.1 which is quite accurate. An direct explanation of the above observation is that, as mentioned in [18] and [8], the higher-order statistics of Ψ_m^a have a marginal effect on the computed Laplace transform of the aggregate interference from all active MH (except the typical MH) to the typical UE at the origin.

6.3 Optimal Probabilistic Caching Placement

In the end, Fig. 4 confirms the optimality of the mentioned content caching strategy for $\gamma = 1$. In particular, we compare the performance of the optimal content caching strategy with the even caching strategy (where the MHs independently cache the files in $\mathcal{F}$ with even probabilities) and that of the p_f caching strategy (where the MHs independently cache the f-th file in $\mathcal{F}$ with probability p_f) as far as successful content delivery probability. We can observe from Fig. 4 that the successful content delivery performance of the proposed content caching strategy overweighs that of the even caching strategy and the p_f caching strategy, which is expected.

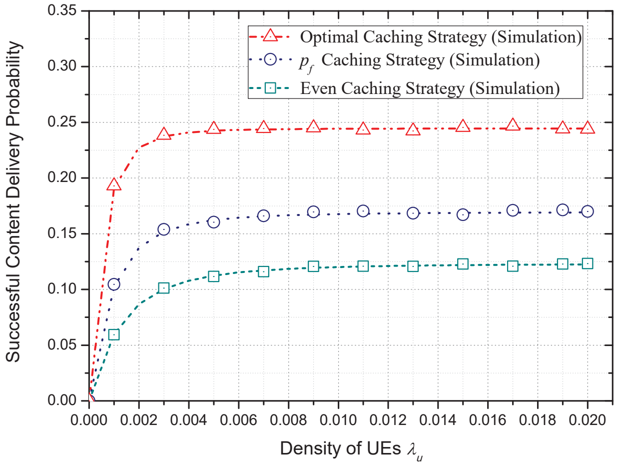

Figure 4: Comparison of the successful content delivery performance.

7 CONCLUSION

In this paper, we have studied the performance of large-scale cache-enabled device-to-device networks under Aloha based multimedia delivery protocol. By using tools from stochastic geometry,we characterize the transmission probability of MHs and the successful content delivery probability of the cache-enabled device-to-device network. According to the obtained results of successful content delivery probability, we work out the optimal probabilistic caching strategy of MHs. In particular, with the Aloha based multimedia delivery protocol, we suggest to simply cache the most popular file at the MHs for the sake of maximizing the successful content delivery probability of the cache-enabled device-to-device network. Simulations has been supplied for validating our analysis. It is hoped that the results in this paper will offer new insights the practical design of large-scale cache-enabled device-to-device networks.

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