Performance Analysis of Fog-Aided D2D Networks with Multicast-Based Opportunistic Content Delivery

Xiaoshi Song, Mengying Yuan, Huan Zhou, and Haijun Zhang

Abstract

In this paper, we develop a comprehensive and tractable analytical framework based on stochastic geometry to evaluate the performance of large-scale fog-aided device-to-device (F-D2D) networks with opportunistic content multicasting. As a part of the analysis, to resolve the contentions of file requests from the cache-incapable conventional user equipments (C-UEs), two simple yet typical candidate file selection schemes for cache-enabled fog user equipments (F-UEs), namely the random file selection (RFS) scheme and the most requested file selection (MRFS) scheme, are considered. Further, to suppress the harmful interference among the concurrent transmissions of F-UEs, a multicast-based opportunistic content delivery strategy is proposed by exploring the idea of opportunistic spectrum access (OSA). Assuming decentralized probabilistic caching, we first derive the activation probability of the F-UEs. Then, by adopting an appropriate approximation, the cache-hit probability, the coverage probability, and thereby the successful content delivery probability (SCDP) of the F-D2D network are evaluated. We also develop an iterative algorithm based on the gradient projection method to obtain a suboptimal caching policy for the maximization of SCDP. Extensive simulation and numerical results are presented to verify our analysis and demonstrate the superior performance of the proposed multicast-based opportunistic content delivery strategy.

Index Terms

Fog-aided device to device networks, multicast-based opportunistic content delivery strategy, stochastic geometry, activation probability, successful content delivery probability.

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Xiaoshi Song, and Mengying Yuan are with the School of Computer Science and Engineering, Northeastern University, Shenyang, China, 110819. Email: songxiaoshi@cse.neu.edu.cn.

Huan Zhou is with the College of Computer and Information Technology, China Three Gorges University, Yichang 443002, China.

Haijun Zhang is with the Beijing Advanced Innovation Center for Materials Genome Engineering, Beijing Engineering and Technology Research Center for Convergence Networks and Ubiquitous Services, Institute of Artificial Intelligence, University of Science and Technology Beijing, Beijing, China, 100083.
I. INTRODUCTION

With the tremendous growth of smartphone devices and the accompanied bandwidth-killer applications, the past few decades have witnessed the explosive increase of mobile data traffic on video streaming, online gaming, and augmented reality [1]. To satisfy the unprecedented demands of the mobile users, the architecture of wireless networks is undergoing a fundamental shift from the conventional connection-oriented communication to the novel content-oriented data dissemination [2][3]. As such, substantial research efforts have been invested into the advancement of innovative technologies to facilitate the content-centric design of the next generation wireless networks [4]–[7].

The emerging fog-aided device to device (F-D2D) communication paradigm is considered to be an effective and promising approach to cope with the upcoming wireless data challenge and enable the content-centric networking [8]–[12]. Particularly, envisioned as an evolved architecture of cloud radio access network (C-RAN), the F-D2D network integrates the computing, caching, and communication functionalities at the dedicated edge mobile devices, and thereby is capable of providing high spectrum efficiency and ultra-low latency data transmission services for the end users. Further, compared with the C-RAN, the F-D2D network can efficiently relieve the heavy burden on the congested fronthaul and backhaul links, and thus significantly improve the network performance.

Due to its distinctive characteristics, there has been growing interest recently in the studies of caching placement and content delivery under the F-D2D communication paradigm [13]–[17]. Particularly, in [13], Golrezaei et al. investigated the performance of wireless video content dissemination in cellular networks with cache-enabled mobile devices and derived the optimal collaboration distance of D2D transmissions. In [14], under the Gupta and Kumar protocol model, Ji et al. characterized the throughput-outage region of the D2D one-hop caching networks and showed that in the regime of small library, the per-node throughput is independent of the number of users $n$ and increases linearly with the ratio $M/m$, where $M$ denotes the cache size and $m$ denotes the library size. Further, in [15], Ji et al. proved that it is infeasible to achieve a better throughput scaling law performance of cache-enabled D2D networks by jointly exploiting the spatial reuse gain and the coded multicasting gain, since these two different types of gains are countervailing. In [16], with distributed MIMO and hierarchical cooperation schemes, Guo et al. extended the results derived in [14] and showed that the aggregated throughput of the cache-enabled D2D network increases almost linearly with the number of users $n$, which is independent of both $m$
and $M$. In [17], Giatsoglou et al. studied the content sharing in cache-enabled D2D network with the novel technique of high-rate millimeter wave.

It is worth noting that though the wireless caching communication paradigm was originally proposed and investigated in the unicast scenario due to the asynchronous nature of the on-demand video streaming, substantial efforts have been devoted to the multicasting design to further enhance the content dissemination efficiency [18]–[20]. Particularly, in [18], Chen et al. investigated the optimal proactive multicast content pushing strategy by using the structured deep learning. In [19], Zhong et al. addressed the multicast-aware caching scheduling problem via reinforcement learning. In [20], Cui et al. analyzed the performance of the large-scale cache-enabled and multicast-based wireless networks, and asymptotically captured the optimal caching and multicasting design.

Interference management is essential and critical for F-D2D networks to enhance the successful content delivery performance and boost the network throughput. It is worth noting that for the above mentioned works, in [13]–[16], the time-frequency-space resource reuse based interference management strategies were considered, under which the inter-cluster interference and intra-cluster interference were effectively avoided. In [17], the co-channel interference of D2D transmission was mitigated by the directional property of millimeter wave. In [20], the inter-cell interference was simply treated as noise, while the intra-cell interference was avoided via FDMA. It is worth noting that, though the aforementioned methods can address the interference issue in some extent, more sophisticated techniques are needed to further improve the performance.

Opportunistic spectrum access (OSA) [21]–[23] is considered as an effective approach of interference avoidance in cognitive radio (CR) networks [24]–[26] for the enhancement of spectral efficiency. Particularly, by allowing the secondary users opportunistically utilize the spectrum holes in the CR networks, the harmful interference from secondary transmissions to the primary receivers is subtly prevented and thereby the spectrum sharing performance is improved. Over recent years, thanks to the rapid development of mobile sensing and machine learning based technologies, the concept of OSA has been considerably evolved and widely applied in the typical communication scenarios (e.g., D2D, V2X, UAV, and IoT) of future wireless networks [27]–[30].

In this paper, motivated by the idea of OSA, different from [13]–[17] and [18]–[20], we investigate the multicast-based opportunistic content delivery in F-D2D networks and develop a tractable modeling paradigm for performance evaluation. To the best of our knowledge, this

1In [18] and [19], the interference management issue was not technically addressed.
paper is the first study which presents a comprehensive analytical framework by applying tools from stochastic geometry to characterize the performance of F-D2D networks with opportunistic content multicasting. The main contributions of this paper are summarized as follows:

- To resolve the contentions of file requests from the C-UEs, two simple yet typical candidate file selection schemes are considered, namely the random file selection (RFS) scheme and the most requested file selection (MRFS) scheme. Upon receiving the requests from the C-UEs within a distance of $R_d$, each F-UE is designed to select a requested file as the candidate file for multicast-based opportunistic content delivery based on the two schemes.

- To suppress the harmful “inter-file” interference received at the C-UEs, a multicast-based opportunistic content delivery strategy is proposed. Under this strategy, the F-UEs are designed to monitor the content requests broadcasted by the C-UEs at the beginning of each time slot and use the received signal as the proxy to estimate their reverse interference. Let $\Phi_n$ denote the point process (PP) formed by C-UEs which request the $n$-th file. Further, let $\Phi_n = \sum_{i \in \mathcal{N}, i \neq n} \Phi_i$ denote the PP formed by C-UEs which request other files except the $n$-th file. Then, a F-UE is allowed to multicast its cached $n$-th file only if the $n$-th file is selected as the candidate file based on the RFS or MRFS scheme, and the maximum received signal power of the content requests sent from C-UEs in $\Phi_n$ is less than or equal to a predefined interference threshold $I_{th}$. As such, the proposed multicast-based opportunistic content delivery strategy can effectively constrain the interference from the transmissions of the $n$-th file received at the C-UEs in $\Phi_n$ and thereby enhance the overall network performance.

- We first derive the probability that a F-UE caches the $i$-th combination of the files and selects the $n$-th file as the candidate file for the potential multicast-based content delivery. Then, based on the derived results, the activation probability of F-UEs under the proposed multicast-based opportunistic content delivery strategy is characterized. Further, we derive the conditional distribution of the active F-UEs given a typical C-UE at the origin. It is worth noting that the access of F-UEs in proximity under the proposed multicast-based opportunistic content delivery strategy are dependent. As such, the conditional spatial distribution of the active F-UEs does not follow a HPPP, which thereby results in the intractability of the network performance. To enable the analysis, we assume that the conditional spatial distribution of the active F-UEs on each concentric circle centered at the typical C-UE is HPPP. Under this assumption, approximate but accurate expressions for
cache-hit probability, coverage probability, and thereby SCDP are obtained.

- The optimization of probabilistic caching placement policy for F-UEs is investigated to maximize the SCDP of the F-D2D network. Particularly, due to the complex expression of the objective function, an exact characterization of the optimal caching placement is infeasible. To tackle this difficulty, an iterative algorithm based on the gradient projection method is developed to obtain a suboptimal solution of the caching placement policy at F-UEs.

- Our numerical results show that the MRFS scheme is more beneficial for the requests of the most popular file, while the RFS scheme is more favorable for the requests of the less popular files. Further, it is shown that the proposed multicast-based opportunistic content delivery strategy outperforms the baseline (non-OSA of F-UEs) strategy on the coverage probability and SCDP. We also demonstrate the superiority of the proposed gradient projection based caching placement policy over the existing methods especially in the intermediate region of the Zipf parameter $\gamma$.

It is worth noting that the paper by Emara et al. [31] considered the opportunistic content delivery in cellular network with cache-enabled small cell base stations (SBSs), which is similar in scope to our work. However, our work differs from [31] in the following two main aspects. First, the network model investigated in this paper is different from that in [31]. Specifically, in [31], the authors considered a cache-enabled cellular network, where the coverage regions of the SBSs form a Voronoi tessellation on the plane. In our paper, different from that in [31], we consider a F-D2D network, where the coverage region of a F-UE is the intersection of the respective Voronoi cell and the disc of radius $R_d$ centered at the tagged F-UE. As such, the distribution of the distances between the C-UEs and their associated F-UEs in our paper is considerably different from that between the UEs and their associated SBSs in [31]. Second, the multicast-based opportunistic content delivery strategy studied in our paper is essentially different from that in [31]. Specifically, in [31], the proposed opportunistic content delivery strategy is idle-channel based, under which a user associated with its $m$-th closest SBS is able to successfully establish the OSA link only if the assigned channel is not used by the $(m-1)$ closer SBSs. Further, the opportunistic content delivery strategy proposed in [31] is file independent, i.e., the access of the SBSs is irrespective of the requested file. In contrast, in this paper, our proposed opportunistic content delivery strategy is threshold based and file dependent, under which a F-UE is allowed to multicast the $n$-th file only if the maximum received signal power of the content
TABLE I
SYMBOL NOTATION

| Symbol   | Meaning                                           |
|----------|--------------------------------------------------|
| $\lambda_g, \lambda_a$ | Densities of F-UEs and C-UEs                      |
| $P_g, P_a$ | Transmit powers of F-UEs and C-UEs                |
| $\theta_u$ | SIR target at C-UEs                              |
| $I_{th}$ | Interference threshold                          |
| $N$ | File library                                    |
| $N$ | Size of the file library $N$                     |
| $p_n$ | The probability that C-UEs request for the $n$-th file |
| $c_i$ | The probability that F-UEs cache the $i$-th combination |
| $\zeta_n$ | The probability that a F-UE selects the $n$-th file as the candidate file |
| $\theta_n$ | OSA probability for the $n$-th file               |
| $\xi_n$ | Activation probability for the $n$-th file       |
| $\xi$ | Activation probability of F-UEs                  |
| $\varsigma_n$ | Conditional cache-hit probability for the $n$-th file |
| $C_n$ | Conditional coverage probability for the $n$-th file |
| $C$ | Coverage probability                             |
| $\tau_n$ | Conditional successful content delivery probability for the $n$-th file |
| $\tau$ | Successful content delivery probability          |
| $C, F$ | Typical C-UE and its associated F-UE             |
| $l_n$ | Distance between $C$ and $F$                     |
| $\Psi^n_m(C_n)$ | Point process formed by the active F-UEs which select the $n$-th file as the candidate file around $C$, conditioned on that $C$ is requesting the $n$-th file |
| $\lambda^n_m(C_n, r)$ | Density of $\Psi^n_m(C_n)$ at a distance of $r$ away from $C$ |
| $\Phi_n, \Phi_m$ | Point processes formed by C-UEs which request the $n$-th file, and which request other files except the $n$-th file |
| $\Psi^n_g, \Psi^n_g$ | Point processes formed by the active F-UEs which select the $n$-th file as the candidate file, and which select other files as the candidate file except the $n$-th file |
| $\lambda^n_g, \lambda^n_g$ | Densities of $\Psi^n_g$ and $\Psi^n_g$ |

requests sent from C-UEs in $\Phi_n$ is less than or equal to a predefined interference threshold $I_{th}$, where $\Phi_n$ denotes the PP of C-UEs requesting other files except the $n$-th file. As such, the spatial distribution of the active F-UEs derived in our paper is also considerably different from that of the SBSs in [31].

The remainder of this paper is organized as follows. In Section II, we describe the system model and present the proposed multicast-based opportunistic content delivery strategy. In Section III, we analyze the activation probability of F-UEs. In Section IV, we evaluate the SCDP of the F-D2D network. In Section V, we study the optimization of the probabilistic caching placement policy at F-UEs to maximize the SCDP. Section VI validates the derived analytical results through numerical simulations. Finally, the conclusions are drawn in Section VII.

Notations of selected symbols used in this paper are summarized in Table I.
II. Network Model

We consider a F-D2D network, where the cache-enabled fog user equipments (F-UEs) and the cache-incapable conventional user equipments (C-UEs) are coexisted and spatially distributed as homogeneous Poisson point processes (HPPPs) with densities $\lambda_g$ and $\lambda_u$, respectively, on $\mathbb{R}^2$. The transmit powers of F-UEs and C-UEs are given by $P_g$ and $P_u$, respectively. Further, as that given in [32]–[35], the power gain $l(d)$ of the wireless channel over a distance of $d$ is given by $l(d) = hd^{-\alpha}$, where $h$ denotes the Rayleigh fading power coefficient with unit mean, and $\alpha \geq 2$ denotes the path-loss exponent. For successful content reception at C-UEs, the SIR target is given by $\theta_u$.

Let $\mathcal{N} := \{1, 2, \ldots, N\}$ denote the library of $N$ equal-sized multimedia files in the network. It is worth noting that the cache memory of F-UEs is assumed to be $K \leq N$ files. As such, by defining that every $K$ different files form a combination, there are in total $J \triangleq \binom{N}{K}$ different combinations available for content caching at F-UEs. Let $J \triangleq \{N_1, N_2, \ldots, N_J\}$ denote the set of $J$ combinations. Then, with decentralized probabilistic caching placement policy [36], each F-UE is assumed to independently select the $j$-th combination $N_j$ in $J$ for content caching with probability $c_j$. At the beginning of each time slot, the C-UEs are assumed to broadcast their requests of the $n$-th file in $\mathcal{N}$ to surrounding F-UEs with probability $p_n$, where $p_n$ follows the Zipf distribution [37] and is given by

$$p_n = \frac{1/n^\gamma}{\sum_{j=1}^{N} 1/j^\gamma} \quad (1)$$

with $\gamma \geq 0$ denoted as the Zipf parameter. It is worth noting that different from the cellular network setting [31], a predefined collaboration distance $R_d$ is considered under the F-D2D network scenario. As such, only the F-UEs within a distance of $R_d$ can serve the requests from the respective C-UEs for content delivery.

It is worth noting that with the received requests from C-UEs within a distance of $R_d$, each F-UE is designed to first select a candidate file from its cached $K$ files for the potential data transmission. Two simple yet typical candidate file selection schemes, namely the random file selection (RFS) scheme and the most requested file selection (MRFS) scheme, are considered. Particularly, under the RFS scheme, the F-UE is designed to select the candidate file at random from the requested files (which are cached in the storage) in the tagged time slot with equal probability. Under the MRFS scheme, on the other hand, the F-UE is designed to select the

\footnote{For simplicity and analytical tractability, we ignore the background thermal noise in this paper.}
candidate file which is mostly requested in the tagged time slot by the C-UEs within a distance of $R_d$ from its cached $K$ files. As such, the RFS scheme is mainly designed to address the fairness issue of the file requests, while the MRFS scheme is designed for the maximization of the cache-hit probability of the F-D2D network.

With the candidate files determined, the F-UEs then makes decisions to launch the transmissions under the proposed multicast-based opportunistic content delivery strategy, which is described in detail as follows.

**Multicast-based Opportunistic Content Delivery Strategy:** It is assumed that the F-UEs are capable of estimating the reverse interference at the C-UEs by utilizing the signal power of the received file requests as the proxy. Let $\Phi_n$ denote the PP formed by C-UEs which request the $n$-th file. Further, let $\bar{\Phi}_n = \sum_{i \in \mathcal{N}, i \neq n} \Phi_i$ denote the PP formed by C-UEs which request other files except the $n$-th file. Then, a F-UE with the $n$-th file selected as the candidate file is allowed to multicast the cached content only if the maximal received signal power of the file requests sent from C-UEs in $\bar{\Phi}_n$ is less than or equal to a predefined interference threshold $I_{th}$. It is worth noting that, under the proposed multicast-based opportunistic content delivery strategy, for a tagged C-UE, there may be multiple F-UEs within $R_d$ which are eligible to serve its request. In that case, the tagged C-UE is assumed to simply associate with the nearest eligible F-UE for content reception. Intuitively, under the proposed multicast-based opportunistic content delivery strategy, the F-UEs with the $n$-th file selected as the candidate file elaborately exploit the spatial spectrum holes of $\bar{\Phi}_n$ to suppress the harmful “inter-file” interference received at the unintended C-UEs, which thereby along with the technique of content multicasting can substantially enhance the performance of the F-D2D network.

It is worth noting that the primary goal of this paper is to enable an accurate analysis of the F-D2D networks with multicast-based opportunistic content delivery. As such, to confine our focus to the SCDP and the optimization of caching placement, the spectrum sensing overheads, the multicast overheads, and the respective implementation issues are beyond the scope of the paper. Further, as that given in [22], [32], [38] and [40], it is assumed that the fading channel coefficient of each transmission link keeps unchanged during one time slot. We also assume that the file transfer under the proposed multicast-based opportunistic content delivery strategy can be completed within one time slot as long as the received SIR is larger than the target $\theta_u$.

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3 It is worth noting that under the MRFS scheme, if there are $q$ ($1 < q \leq K$) most requested files, the F-UE is designed to randomly select the $j$-th file as the candidate file among the tagged $q$ files with probability $\frac{1}{q}$.

4 In this paper, to simplify the analysis, perfect sensing is considered.
In the next section, under the proposed multicast-based opportunistic content delivery strategy, we first derive the activation probability of F-UEs.

III. Activation Probability of F-UEs

The activation probability of F-UEs under the proposed multicast-based opportunistic content delivery strategy is analyzed in this section. Particularly, let $\xi_i^n$ denote the activation probability of F-UEs which cache the $i$-th combination and successfully transmit the $n$-th file to the surrounding C-UEs as

$$
\xi_i^n = \zeta_i^n \cdot \vartheta_n,
$$

where $\zeta_i^n$ is the probability that a F-UE caches the $i$-th combination and selects the $n$-th file as the candidate file for the potential data transmission with $n \in \mathcal{N}_i$, and $\vartheta_n$ denotes the OSA probability for the $n$-th file. In the following two subsections, we characterize $\zeta_i^n$ and $\vartheta_n$, respectively.

A. Characterization of $\zeta_i^n$

It is worth noting that the characterization of $\zeta_i^n$ is determined by the candidate file selection scheme applied. Particularly, we characterize $\zeta_i^n$ under the RFS and MRFS schemes, respectively, in the following two lemmas.

Lemma 3.1: For F-D2D networks, the probability $\zeta_i^n$ with the RFS scheme applied is given by

$$
\zeta_i^n = c_i \cdot \sum_{q=0}^{K-1} \sum_{s=1}^{c_{K-1}^q} \frac{1}{q+1} \cdot \left(1 - e^{-\lambda u p_m \pi R_d^2}\right) \cdot \prod_{m \in \mathcal{D}_i^q(s)} \left(1 - e^{-\lambda u p_m \pi R_d^2}\right) \cdot \prod_{j \in \mathcal{\tilde{D}}_i^q(s)} e^{-\lambda u p_j \pi R_d^2},
$$

where $\mathcal{D}_i^q(s) \subseteq \mathcal{N}_i$ with $|\mathcal{D}_i^q(s)| = q$ denotes the set of files in $\mathcal{N}_i$ requested by C-UEs within the communication range $R_d$ except the $n$-th file, and $\mathcal{\tilde{D}}_i^q(s) \subseteq \mathcal{N}_i$ denotes the complementary set of $\mathcal{D}_i^q(s)$ with respect to $\mathcal{N}_i \setminus \{n\}$.

Proof: See Appendix A.

Remark 3.1: From Lemma 3.1, it can be observed that $\zeta_i^n$ is an increasing function of $p_n$ with the RFS scheme applied. Intuitively, as $p_n$ increases, it is more likely for C-UEs to request the $n$-th file instead of other files, which therefore results in a shrink of $\mathcal{D}_i^q(s)$ from a probabilistic perspective. As such, the $n$-th file can find more opportunities to be selected as the candidate file as $p_n$ increases.
Lemma 3.2: For F-D2D networks, the probability $\zeta^n_i$ with the MRFS scheme applied is given by

$$\zeta^n_i = c_i \sum_{q=0}^{K-1} \sum_{s=1}^{C_q^K} \sum_{k=1}^{\infty} \left( \frac{1}{q + 1} \right) \frac{\left( \lambda_u p_n \pi R_d^2 \right)^k}{k!} \cdot e^{-\lambda_u p_n \pi R_d^2} \times \prod_{m \in G^q_i(s)} \frac{\left( \lambda_u p_m \pi R_d^2 \right)^k}{k!} \cdot e^{-\lambda_u p_m \pi R_d^2} \prod_{j \in \tilde{G}^q_i(s)} \sum_{t=0}^{k-1} \frac{\left( \lambda_u p_j \pi R_d^2 \right)^t}{t!} \cdot e^{-\lambda_u p_j \pi R_d^2} \right),$$

(4)

where $G^q_i(s) \subseteq \mathcal{N}_i$ with $|G^q_i(s)| = q$ denotes the set of the most requested files in $\mathcal{N}_i$ by C-UEs within the communication range $R_d$ except the $n$-th file, and $\tilde{G}^q_i(s) \subseteq \mathcal{N}_i$ denotes the complementary set of $G^q_i(s)$ with respect to $\mathcal{N}_i \setminus \{n\}$.

Proof: See Appendix B

Remark 3.2: From Lemma 3.2, it can be verified that $\zeta^n_i$ is also an increasing function of $p_n$ with the MRFS scheme applied. Intuitively, this is due to the fact that as $p_n$ increases, it is more likely for the $n$-th file to be the most requested file from C-UEs within a distance of $R_d$. 

B. Characterization of $\psi_n$

It is worth noting that under the proposed multicast-based opportunistic content delivery strategy, $\psi_n$ is the same for both the RFS and MRFS schemes. Based on this fact, we derive $\psi_n$ in the following lemma.

Lemma 3.3: Under the proposed multicast-based opportunistic content delivery strategy, for F-UEs with the $n$-th file selected as the candidate file, the OSA probability $\psi_n$ is given by

$$\psi_n = \exp \left\{ -2\pi \lambda_u (1 - p_n) \cdot \frac{\Gamma\left(\frac{2}{\alpha}\right)(\frac{P_r}{I_{th}})^{\frac{2}{\alpha}}}{\alpha} \right\},$$

(5)

with RFS or MRFS scheme applied.

Proof: See Appendix C

Remark 3.3: From Lemma 3.3, it can be observed that $\psi_n$ is an increasing function of $I_{th}$. Intuitively, as $I_{th}$ increases, the interference constraint at the C-UEs is relaxed, and thereby the F-UEs can find more opportunities over the spatial domain to access the network for content delivery. It is also observed from Lemma 3.3 that $\psi_n$ is a decreasing function of $\lambda_u$, which is due to the fact that the available “good” spatial spectrum resources for F-UEs vanish as $\lambda_u$ increases.
C. Characterization of $\xi^n_i$

In this subsection, with Lemmas 3.1, 3.2, and 3.3, we eventually characterize $\xi^n_i$ in following theorem.

**Theorem 3.1:** For F-D2D networks, under the proposed multicast-based opportunistic content delivery strategy, the activation probability $\xi^n_i$ is given by

$$\xi^n_i = c_i \cdot \sum_{q=0}^{K-1} \sum_{s=1}^{C_q} K^{-1} \sum_{q=0}^{K-1} s \left( \frac{1}{q+1} \cdot \left( 1 - e^{-\lambda_{up} \pi R_d^2} \right) \cdot \prod_{m \in D_i^q(s)} \left( 1 - e^{-\lambda_{up} \pi R_d^2} \right) \cdot \prod_{j \in \tilde{D}_i^q(s)} e^{-\lambda_{up} \pi R_d^2} \right) \times \exp \left\{ -2\pi \lambda_u (1 - p_n) \cdot \frac{\Gamma \left( \frac{2}{\alpha} \right) \left( \frac{P_u}{2th} \right)^{\frac{2}{\alpha}}}{\alpha} \right\},$$

with the RFS and MRFS schemes applied, respectively.

**Proof:** By noting that $\xi^n_i = \zeta^n_i \cdot \vartheta_n$, based on Lemmas 3.1, 3.2, and 3.3, (6) and (7) are readily obtained.

**Remark 3.4:** Let $\xi^n_i$ denotes the activation probability of F-UEs which transmit the $n$-th file to surrounding C-UEs. Then, it can be easily verified that

$$\xi^n = \sum_{i \in J_n} \xi^n_i,$$

where $J_n$ denotes the set of combinations in $J$ which contains the $n$-th file with the respective cardinality given by $|J_n| = \binom{N-1}{K-1}$, and $\xi^n_i$ is given by (6) and (7) with RFS and MRFS schemes applied, respectively.

**Remark 3.5:** Let $\xi$ denotes the average activation probability of F-UEs. Then, it can be easily verified that

$$\xi = \sum_{n=1}^{N} \xi^n = \sum_{n=1}^{N} \sum_{i \in J_n} \xi^n_i.$$
density of $\Psi^g_n$. Then, based on Theorem 3.1, we characterize $\Psi^g_n$ in the following corollary.

**Corollary 3.1:** For F-D2D networks with the proposed multicast-based opportunistic content delivery strategy, the density $\lambda^g_n$ of $\Psi^g_n$ is given by

$$\lambda^g_n = \lambda_g \sum_{i \in \mathcal{J}_n} \xi^n_i,$$

(10)

where $\xi^n_i$ is given by (6) or (7) with the RFS or MRFS scheme applied, respectively.

**Proof:** By noting that $\lambda^g_n = \lambda_g \cdot \xi^n$, based on (8) and Theorem 3.1, (10) is obtained. \qed

**Remark 3.6:** It is worth noting that, due to the complicated process involved in the proposed multicast-based opportunistic content delivery, $\Psi^g_n$ is not a HPPP.

Let $\Psi^a_g$ be the PP of the active F-UEs under the proposed multicast-based opportunistic content delivery strategy. Further, let $\lambda^a_g$ be the density of $\Psi^a_g$. Then, based on Theorem 3.1, we characterize $\Psi^a_g$ in the following corollary.

**Corollary 3.2:** For F-D2D networks with the proposed multicast-based opportunistic content delivery strategy, the density $\lambda^a_g$ of $\Psi^a_g$ is given by

$$\lambda^a_g = \lambda_g \sum_{n=1}^{N} \sum_{i \in \mathcal{J}_n} \xi^n_i,$$

(11)

where $\xi^n_i$ is given by (6) or (7) with the RFS or MRFS scheme applied, respectively.

**Proof:** By noting that $\lambda^a_g = \lambda_g \cdot \xi$, based on (9), (11) is thus obtained. \qed

**Remark 3.7:** It can be easily verified that $\Psi^a_g$ is not a HPPP as that of $\Psi^g_n$.

In the next section, based on the characterization of $\Psi^g_n$, we derive the SCDP of F-D2D networks under the proposed multicast-based opportunistic content delivery strategy.

## IV. SUCCESSFUL CONTENT DELIVERY PROBABILITY

The SCDP of F-D2D network, denoted by $\tau$, is defined as

$$\tau = \sum_{n=1}^{N} p_n \cdot \varsigma_n \cdot C_n,$$

(12)

where $\varsigma_n$ and $C_n$ denote the conditional cache-hit probability and conditional coverage probability, respectively, with respect to the $n$-th file. To derive $\tau$, by the spatial stationarity of the F-D2D network, a typical C-UE denoted by $C$ is considered to be located at the origin. Particularly, assuming that $C$ is requesting the $n$-th file, let $\Psi^m_g(C_n)$ denote the PP of active F-UEs which transmit the $m$-th file around $C$, where $m \in \mathcal{N}$. Then, we characterize the spatial distribution of $\Psi^m_g(C_n)$ in the following lemma.
Lemma 4.1: Under the proposed multicast-based opportunistic content delivery strategy, conditioned on that $C$ is requesting the $n$-th file, the spatial density $\lambda^m_y(C_n, r)$ of $\Psi^m_g(C_n)$ at a distance of $r$ away from $C$ is given by

$$
\lambda^m_y(C_n, r) = \begin{cases} 
\lambda^n_y, & \text{for } m = n, \\
\lambda^m_y \left(1 - e^{-\frac{I_{th}^{m,n}}{P_u}}\right), & \text{for } m \neq n.
\end{cases}
$$

(13)

Proof: Under the proposed multicast-based opportunistic content delivery strategy, conditioned on that $C$ is requesting the $n$-th file, it can be easily verified that the spatial distribution of $\Psi^m_g(C_n)$ is same as that of $\Psi^n_g$ for $m = n$. As such, we have $\lambda^m_g(C_n, r) = \lambda^n_g$ for $m = n$. On the other hand, for $m \neq n$, the F-UEs in $\Psi^m_f(C_n)$ are required to satisfy the interference constraint at $C$ and all other C-UEs which are not requesting the $m$-th file for content delivery. As such, we have

$$
\lambda^m_y(C_n, r) = \lambda^m_y \left(1 - e^{-\frac{I_{th}^{m,n}}{P_u}}\right),
$$

for $m \neq n$, which thus completes the proof of Lemma 4.1.

Remark 4.1: It can be verified that

$$
\lim_{r \to \infty} \lambda^m_y(C_n, r) = \lim_{I_{th} \to \infty} \lambda^m_y(C_n, r) = \lambda^m_y,
$$

for $m \neq n$.

Remark 4.2: It can be also verified that the access of F-UEs in proximity under the proposed multicast-based opportunistic content delivery strategy are dependent. As such, $\Psi^m_g(C_n)$ is not a HPPP, which results in that the successful content delivery probability of the F-D2D network is infeasible to be derived. To overcome this obstacle, by applying a similar method as that given by [22] and [39]–[42], we make the following assumption on $\Psi^m_g(C_n)$.

Assumption 1: $\Psi^m_g(C_n)$ is a HPPP with density given by $\lambda^m_y(C_n, r)$.

In the following two subsections, under Assumption 1 we derive $\varsigma_n$ and $C_n$, respectively.

A. Characterization of $\varsigma_n$

The conditional cache-hit probability $\varsigma_n$ of the $n$-th file is defined as the probability that the request of the $n$-th file can be served by the active F-UEs within a distance of $R_d$. Then, with Assumption 1 we derive $\varsigma_n$ in the following lemma.
Lemma 4.2: For F-D2D networks with the proposed multicast-based opportunistic content delivery strategy, under Assumption 1, the conditional cache-hit probability \( \varsigma_n \) is given by

\[
\varsigma_n = 1 - e^{-\lambda_g \pi R_d^2}.
\] (14)

Proof: Based on Lemma 4.1, we have \( \lambda^m_g(C_n, r) = \lambda^n_g \) for \( m = n \). Then, under Assumption 1, by considering that there is no active F-UE in \( \Psi^n_g(C_n) \) available within a distance of \( R_d \), (14) is immediately obtained.

Remark 4.3: Let \( \varsigma \) denote the average cache-hit probability of the F-D2D networks. Then, it can be easily verified that

\[
\varsigma = \sum_{n=1}^{N} p_n \cdot \left( 1 - e^{-\lambda^n_g \pi R_d^2} \right). \tag{15}
\]

B. Characterization of \( C_n \)

Let \( F \) denote the associated F-UE of \( C \). Further, conditioned on that \( C \) is requesting the \( n \)-th file, let \( l_n \) denote the distance between \( C \) and \( F \). Then, based on Assumption 1, we derive the distribution \( f_{l_n}(l) \) of \( l_n \) in the following lemma.

Lemma 4.3: Under the proposed multicast-based opportunistic content delivery strategy, conditioned on that \( C \) is requesting the \( n \)-th file, based on Assumption 1, the distribution \( f_{l_n}(l) \) of \( l_n \) is given by

\[
f_{l_n}(l) = \frac{2\lambda^n_g \pi l \cdot e^{-\lambda^n_g \pi l^2}}{1 - e^{-\lambda^n_g \pi R_d^2}}.
\] (16)

Proof: Under the proposed multicast-based opportunistic content delivery strategy, conditioned on that \( C \) is requesting the \( n \)-th file, \( F \) is the nearest F-UE in \( \Psi^n_g(C_n) \) within a distance of \( R_d \). As such, it can be easily verified that the cumulative distribution function \( F_{l_n}(l) \) of \( l_n \) is given by

\[
F_{l_n}(l) = \Pr (l_n \leq l | l_n \leq R_d)
\]
\[
= \frac{1 - \Pr (l_n > l)}{\Pr (l_n \leq R_d)}
\]
\[
= \frac{1 - e^{-\lambda^n_g \pi l^2}}{1 - e^{-\lambda^n_g \pi R_d^2}}.
\] (17)

Then, by taking the derivative of (17) with respect to \( l \), (16) is obtained. This thus completes the proof of Lemma 4.3.
With Lemmas [4.1] and [4.3] conditioned on that C is requesting the n-th file, the conditional coverage probability \( C_n \) of the F-D2D network under the proposed multicast-based opportunistic content delivery strategy is evaluated in the following lemma.

**Lemma 4.4:** Under the proposed multicast-based opportunistic content delivery strategy, conditioned on that C is requesting the n-th file, based on Assumption 1, the conditional coverage probability \( C_n \) is given by

\[
C_n = \int_0^{R_d} \frac{2\lambda^n_g \pi l \cdot e^{-\lambda^n_g \pi l^2}}{1 - e^{-\lambda^n_g \pi R_d^2}} \cdot \exp \left\{ -\frac{2\pi^2}{\alpha \sin \left( \frac{2\pi}{\alpha} \right)} \theta_u^2 l^2 \lambda_g^n \right\} \cdot \exp \left\{ -2\pi \lambda_g^n \int_l^{\infty} \frac{1}{1 + \frac{\lambda^n_g}{\theta_u l^2}} u du \right\} \cdot \exp \left\{ \frac{2\pi \lambda^n_g \int_l^{\infty} \frac{P_u}{\Gamma \left( \frac{2}{\alpha} \right)} \cdot \exp \left\{ -2\pi \lambda_g^n \int_l^{\infty} \frac{1}{1 + \frac{\lambda^n_g}{\theta_u l^2}} \cdot \exp \left\{ -2\pi \lambda_g^n \int_l^{\infty} \frac{1}{1 + \frac{\lambda^n_g}{\theta_u l^2}} \cdot \exp \left\{ -2\pi \lambda_g^n \int_l^{\infty} \frac{1}{1 + \frac{\lambda^n_g}{\theta_u l^2}} \right\} \right\} \right\} \right\} dl, \tag{18}
\]

where \( \lambda_g^n = \lambda^n_g - \lambda^n_g \).

**Proof:** See Appendix [D] \( \Box \)

**Remark 4.4:** Let \( C \) denote the average coverage probability of F-D2D networks under the proposed multicast-based opportunistic content delivery strategy. Then, based on (18), we can obtain the coverage probability \( C \) as \( C = \sum_{n=1}^{N} p_n C_n \).

**C. Characterization of \( \tau \)**

Based on the obtained \( \varsigma_n \) derived in Lemma [4.2] and \( C_n \) derived in Lemma [4.4] we eventually characterize \( \tau \) in the following theorem.

**Theorem 4.1:** For F-D2D networks, under the proposed multicast-based opportunistic content delivery strategy, \( \tau \) is given by

\[
\tau = \sum_{n=1}^{N} p_n \cdot \int_0^{R_d} 2\lambda^n_g \pi l \cdot e^{-\lambda^n_g \pi l^2} \cdot \exp \left\{ -\frac{2\pi^2}{\alpha \sin \left( \frac{2\pi}{\alpha} \right)} \theta_u^2 l^2 \lambda_g^n \right\} \cdot \exp \left\{ -2\pi \lambda_g^n \int_l^{\infty} \frac{1}{1 + \frac{\lambda^n_g}{\theta_u l^2}} u du \right\} \cdot \exp \left\{ \frac{2\pi \lambda^n_g \int_l^{\infty} \frac{P_u}{\Gamma \left( \frac{2}{\alpha} \right)} \cdot \exp \left\{ -2\pi \lambda_g^n \int_l^{\infty} \frac{1}{1 + \frac{\lambda^n_g}{\theta_u l^2}} \right\} \right\} \right\} dl. \tag{19}
\]

**Proof:** Based on (12), by applying Lemmas [4.2] and [4.4] (19) is obtained. \( \Box \)

**Remark 4.5:** Let \( T \) denote the spatial throughput of F-D2D networks under the proposed multicast-based opportunistic content delivery strategy. Then, with Theorem [4.1] we can obtain \( T \) as \( T = \lambda_u \tau \).
Algorithm 1 Gradient Projection Based Algorithm for SCDP Maximization

1: Let $c(t) = [c_1(t), c_2(t), ..., c_J(t)]^T$. Initialize $t = 1$, and $c_i(1) = \frac{1}{J}$ for $1 \leq i \leq J$.
2: Set $P\nabla \tau(c(t))$ as the feasible direction, where $P$ denotes the projection matrix as

$$P = I - \frac{1}{J}A_J$$

with $A_J$ representing the all-ones square matrix of order $J$, and $\nabla \tau(c(t))$ denotes the gradient of $\tau$ with respect to $c(t)$ as

$$\nabla \tau(c(t)) = \left[ \frac{\partial \tau(c(t))}{\partial c_1(t)}, \frac{\partial \tau(c(t))}{\partial c_2(t)}, ..., \frac{\partial \tau(c(t))}{\partial c_J(t)} \right]^T,$$

with $\frac{\partial \tau(c(t))}{\partial c_i(t)}$ for $1 \leq i \leq J$ given by [23].
3: Set the stepsize $s(t)$ as

$$s(t) = \arg \max_{s \in [0, \bar{s}]} \tau\left(c(t) + s \cdot P\nabla \tau(c(t))\right),$$

with $\bar{s} = \min(\hat{s}, \check{s})$, where $\hat{s}$ and $\check{s}$ are given by

$$\hat{s} = \min_{1 \leq i \leq J} \left\{ \frac{1 - c_i(t)}{[P\nabla \tau(c(t))]_i} \right\}, \text{ for } [P\nabla \tau(c(t))]_i > 0,$$

and

$$\check{s} = \min_{1 \leq i \leq J} \left\{ -\frac{c_i(t)}{[P\nabla \tau(c(t))]_i} \right\}, \text{ for } [P\nabla \tau(c(t))]_i < 0,$$

respectively, and $[P\nabla \tau(c(t))]_i$ denotes the $i$-th element of the $J \times 1$ vector $P\nabla \tau(c(t))$.
4: Set $c(t+1) = c(t) + s(t) \cdot P\nabla \tau(c(t))$.
5: If $|\tau(c(t+1)) - \tau(c(t))| < \sigma$, then stop the algorithm and return the solution $c^* = c(t+1)$. Otherwise, set $t = t + 1$ and go to Step 2.

In the next section, with the obtained SCDP $\tau$, we study the optimization of caching placement policy of F-UEs based on the gradient projection method.

V. CACHING PLACEMENT OPTIMIZATION

In this section, under the proposed multicast-based opportunistic content delivery strategy, we formulate the caching placement optimization problem to maximize the SCDP $\tau$ of the F-D2D network given by [19]. Particularly, the problem is formulated as follows

$$(P1) : \max_{c_i} \tau$$

s.t. $\sum_{i=1}^{J} c_i = 1,$

$0 \leq c_i \leq 1.$
\[
\frac{\partial \tau(c(t))}{\partial c_i(t)} = \int_0^{R_d} \sum_{n \in \mathcal{N}_i} 2\pi \lambda_g \xi_i^n \cdot \exp \left\{ - \left( \pi l^2 + 2\pi \int_0^\infty \frac{1}{1 + \frac{u}{\theta_u \alpha}} u du \right) \sum_{j \in \mathcal{J}_n} \lambda_g \xi_j^n \right\} \\
\times \exp \left\{ - \frac{2\pi^2}{\alpha} \lambda_g \left( \xi - \sum_{j \in \mathcal{J}_n} \xi_j^n \right) \right\} \\
\times \exp \left\{ -2\pi \lambda_g \left( \xi - \sum_{j \in \mathcal{J}_n} \xi_j^n \right) \int_0^\infty \frac{u^\alpha}{1 + \frac{u^\alpha}{\theta_u \alpha}} \times e^{- \frac{u \xi_{th} \alpha}{\theta_u \alpha}} u du \right\} \\
\times \exp \left\{ \frac{2\pi}{\alpha} \left( \frac{P_u}{\mathcal{I}_th} \right)^\frac{2}{\alpha} \Gamma \left( \frac{2}{\alpha} \right) \lambda_g \left( \xi - \sum_{j \in \mathcal{J}_n} \xi_j^n \right) \right\} \\
+ \sum_{n \notin \mathcal{N}_i} 2\pi \lambda_g \xi_i^n \times \exp \left\{ - \sum_{m \in \mathcal{N}_i} \lambda_g \xi_m^n \right\} \, dl. \quad (23)
\]

It is worth noting that \( \tau \) is differentiable, and the constraints given by (21) and (22) are linear. However, due to the complex expression presented in (19), the convexity of \( \tau \) is difficult to be identified in general. As such, Problem (P1) is a differentiable yet non-convex maximization problem over a convex set \([43]\). To solve this problem, a gradient projection based algorithm is developed for the optimization of the caching placement policy at F-UEs, which is given by Algorithm 1. Particularly, in Step 2 of Algorithm 1, \( \mathbf{P} \) is obtained based on the equality constraint given by (21). In Step 3, \( s(t) \) can be obtained by applying the one-dimensional search methods, and \( \underline{s} \) and \( \overline{s} \) are derived based on the constraint given by (22). In Step 5, \( \sigma > 0 \) is a predefined algorithm parameter which is determined by the precision requirement of the solution. It is worth noting that, based on \([44]\), the proposed gradient projection based algorithm is guaranteed to converge to at least a local optimal solution\(^5\) of Problem (P1). The performance of the proposed gradient projection based algorithm will be verified by simulations in the following section.

**VI. NUMERICAL RESULTS**

In this section, we present simulation results on the performance of the studied F-D2D network under the proposed multicast-based opportunistic content delivery strategy to validate our analytical results. Throughout this section, unless specified otherwise, we set \( P_u/\mathcal{I}_th = 20, \theta_u = 1, R_d = 10 \, \text{m}, \gamma = 1, \alpha = 4, N = 5, K = 3, \lambda_g = 0.01, \) and \( c_i = \frac{1}{J} \) for \( 1 \leq i \leq J \).

\(^5\)It is worth noting that the global convergence of the proposed gradient projection based algorithm is out of the scope of this paper. The interested reader may refer to \([45]-[47]\) for further information.
It is worth noting that, to simulate the F-D2D network, we start with the deployment of F-UEs and C-UEs based on HPPPs with densities $\lambda_g$ and $\lambda_u$, respectively, in a circular region of radius $R_s = 500$ m. Further, the caching placement is randomly generated at F-UEs with probability $c_i$ based on [36]. Then, under the proposed multicast-based opportunistic content delivery strategy, by placing a typical UE at the origin, the activation probability, cache-hit probability, coverage probability, and SCDP are numerically evaluated by averaging over the locations and caching placements of F-UEs.
Fig. 3. Conditional cache-hit probability $\varsigma_n$ versus the density of UEs $\lambda_u$ under the MRFS scheme.

A. Activation Probability

Fig. 1 shows the conditional activation probability $\xi^n$ under the RFS and MRFS schemes, respectively, for $1 \leq n \leq 5$. It is observed that the analytical value of conditional activation probability $\xi^n$ is consistent with the simulated value. Further, it is observed that the conditional activation probability $\xi^n$ is an increasing function of $\lambda_u$ when $\lambda_u$ is small, while a decreasing function of $\lambda_u$ when $\lambda_u$ becomes large, under both the RFS and MRFS schemes. Intuitively, when the density of C-UEs $\lambda_u$ is small, $\xi^n$ is dominated by the content request probability of C-UEs within the communication range $R_d$. As such, $\xi^n$ increases rapidly with $\lambda_u$ in the region of small $\lambda_u$. On the other hand, when $\lambda_u$ is large, $\xi^n$ is dominated by the OSA probability $\vartheta_n$, which is instead a decreasing function of $\lambda_u$. As such, $\xi^n$ decreases with $\lambda_u$ in the region of relatively large $\lambda_u$. It is also observed that $\xi^n$ of the most popular file, i.e., file 1, under the MRFS scheme is much larger than that under the RFS scheme, while $\xi^n$ of the less popular files, i.e., file 3, file 4, and file 5, under the MRFS scheme is smaller than that under the RFS scheme. This is because that the MRFS scheme is designed to simply select the most requested file as the candidate file for data transmission, while the RFS scheme is designed to select the candidate file among all the requested files with equal probability. An implication of the above observation is that it is more recommended to apply the RFS scheme instead of the MRFS scheme in the candidate file selection phase to address the fairness issue of the F-D2D network, especially when there is a hard constraint on the minimum request-response probability of the less popular files.
Fig. 4. Conditional coverage probability $C_n$ versus the density of UEs $\lambda_u$ under the RFS scheme.

### B. Conditional Cache-Hit Probability

In Figs. 2 and 3, we plot the conditional cache-hit probability $\varsigma_n$ versus the density of C-UEs $\lambda_u$ under the RFS and MRFS schemes, for $1 \leq n \leq 5$, when $\lambda_g = 0.005$, and 0.01, respectively. Several observations are in order. First, it is shown that the conditional cache-hit probability $\varsigma_n$ is a function with respect to $\lambda_u$ which increases at the beginning and declines afterwards. Intuitively, this is due to the fact that, based on (10) and (14), $\varsigma_n$ is a function of $\lambda^\gamma$ and thereby a function of the conditional activation probability $\xi^n$. As such, the monotonicity of $\varsigma_n$ is similar to that of the conditional activation probability $\xi^n$ with respect to $\lambda_u$. Secondly, the conditional cache-hit probability $\varsigma_n$ is an increasing function with respect to $\lambda_g$ while a decreasing function with respect to $n$ (i.e., an increasing function of $p_n$), which are intuitively expected according to Lemma 4.2 and Corollary 3.1. Thirdly, it is shown that $\varsigma_n$ of the most popular file, i.e., file 1, under the MRFS scheme is much larger than that under the RFS scheme, while $\varsigma_n$ of the less popular files, i.e., file 3, file 4, and file 5, under the MRFS scheme is smaller than that under the RFS scheme, which is again due to the fact that $\varsigma_n$ is a function of $\xi^n$. As such, the MRFS scheme is more beneficial for the requests of the most popular file, while the RFS scheme is more favorable for the requests of the less popular files. Finally, it is observed that the analytical value is consistent with the simulated value, which thereby validates Assumption 1. As discussed in [22] and [39]–[42], the essential reason of the validity of Assumption 1 is that, the higher order statistics of $\Psi^m_g(C_n)$ is negligible in the probability generating functional [48] based calculations.
C. Conditional Coverage Probability

Figs. 4 and 5 shows the conditional coverage probability $C_n$ versus the density of C-UEs $\lambda_u$, for $1 \leq n \leq 5$, when $\lambda_g = 0.005$, and 0.01, respectively. It is observed that the analytical value of $C_n$ is consistent with the simulated value, and thereby again validates Assumption 1. It is also observed that the coverage probability $C_n$ is a function of $\lambda_u$ which decreases sharply at the beginning and grows gradually afterwards. Intuitively, this is due to the fact that $C_n$ is a decreasing function of $\lambda_g$ and thereby $\xi^n$. As such, the monotonicity of $C_n$ is just opposite to that of $\xi^n$ as illustrated in Fig. 1. Further, it can be observed that $C_n$ of the most popular file, i.e., file 1, under the MRFS scheme is larger than that under the RFS scheme, while $C_n$ of other files, i.e., file 2, file 3, file 4, and file 5, under the MRFS scheme is smaller than that under the RFS scheme. Intuitively, this is because that the distance between the typical C-UE and its associated F-UE for the most popular file/other files under the MRFS scheme is smaller/larger than that under the RFS scheme in a probabilistic sense.

Fig. 6 compares the coverage performance of the proposed multicast-based opportunistic content delivery strategy and the baseline strategy (non-OSA of F-UEs) with respect to the Zipf parameter $\gamma$ for $\lambda_u = 0.02$ and $\lambda_u = 0.05$, respectively. Particularly, it is observed that the proposed multicast-based opportunistic content delivery strategy outperforms the baseline strategy on the average coverage probability $C$ under both the RFS and MRFS schemes as expected. It is also observed that the respective performance gain vanishes as $\gamma \to \infty$. Intuitively, this is due to the fact that the proposed multicast-based opportunistic content delivery strategy is designed
Fig. 6. Performance comparison of coverage probability $C$ with respect to the Zipf parameter $\gamma$ for $\lambda_u = 0.02$ and $\lambda_u = 0.05$, respectively.

Fig. 7. SCDP $\tau$ versus the density of C-UEs $\lambda_u$.

to mainly address the “inter-file” interference instead of the “intra-file” interference among the concurrent transmissions. As such, it is more beneficial to apply the proposed multicast-based opportunistic content delivery strategy when $\gamma \to 0$ (i.e., the request distribution of different files becomes uniform, and therefore the “inter-file” interference turns to be dominant), and vise versa.

D. Successful Content Delivery Probability

Fig. 7 shows the SCDP $\tau$ versus the density of C-UEs $\lambda_u$, when $\lambda_g = 0.005$, and 0.01, respectively. It is observed that the SCDP $\tau$ is a function with respect to $\lambda_u$ which increases at first and decreases later on under both the RFS and MRFS schemes. An intuitive explain is
that in the region of interest, the conditional cache-hit probability $\varsigma_n$ is the dominant factor of SCDP $\tau$, and thereby determines the respective monotonicity. It is also observed that the SCDP $\tau$ under the MRFS scheme is larger than that under the RFS scheme, which is due to the fact that the SCDP of the most popular file, i.e. file 1, dominates the SCDP $\tau$.

Fig. 8 compares the SCDP of the proposed multicast-based opportunistic content delivery strategy and the baseline strategy (non-OSA of F-UEs) with respect to the Zipf parameter $\gamma$ for $\lambda_u = 0.02$ and $\lambda_u = 0.05$, respectively. Particularly, it is observed that the proposed multicast-based opportunistic content delivery strategy outperforms the baseline strategy on $\tau$ under both the RFS and MRFS schemes as expected. It is worth noting that due to the effect of cache-hit probability, the performance gain on SCDP is smaller than that on coverage probability.

E. Caching Placement Optimization

In Fig. 9 we compare the SCDP performance of our proposed gradient projection based caching placement policy with the conventional “most popular combination (MPC)” and uniform caching placement policies, under the RFS and MRFS schemes, respectively, for $\lambda_u = 0.01$ and $\lambda_g = 0.01$. It is observed that our proposed gradient projection based caching placement policy outperforms both the MPC and uniform caching placement policies as expected. It is also observed that the performance gap between the proposed gradient projection caching placement policy and the other two policies narrows down as $\gamma \to 0$ and $\gamma \to \infty$. As such, the proposed gradient projection based caching placement policy is more beneficial in the intermediate region of $\gamma$. Further, it is observed that the SCDP performance of the MPC caching placement policy
is very close to that of the proposed gradient projection based caching placement policy under the MRFS scheme. Therefore, the MPC caching placement policy is a good approximation of the proposed gradient projection based caching placement policy under the MRFS scheme to maximize the SCDP.

VII. CONCLUSION

In this paper, we proposed a multicast-based opportunistic content delivery strategy in F-D2D networks and presented a comprehensive analysis of the network performance. Particularly, under the proposed multicast-based opportunistic content delivery strategy, the F-UEs are designed to monitor the content requests broadcasted by the C-UEs and use the received signal as proxy to estimate the reverse interference. Let $\Phi_n$ denote the PP formed by C-UEs which request the $n$-th file. Further, let $\overline{\Phi}_n = \sum_{i \in N, i \neq n} \Phi_i$ denote the PP formed by C-UEs which request other files except the $n$-th file. Then, a F-UE is allowed to multicast its cached $n$-th file only if the $n$-th file is selected as the candidate file based on the RFS scheme or the MRFS scheme, and the maximum received signal power of the content requests sent from C-UEs in $\overline{\Phi}_n$ is less than or equal to a predefined interference threshold $I_{th}$. Assuming decentralized probabilistic caching, the activation probabilities of F-UEs under the proposed multicast-based opportunistic content delivery strategy was derived. Further, the cache-hit probability, the coverage probability and thereby the SCDP of the F-D2D network were characterized. We also proposed a gradient projection based algorithm for the optimization of the caching placement policy to maximize the SCDP. Finally, the effectiveness of the studied caching placement and content delivery strategy
for F-D2D networks was validated through extensive simulations. It was shown through both numerical and simulation results that the proposed multicast-based opportunistic content delivery strategy can enhance the network performance. It is worth noting that the proposed multicast-based opportunistic content delivery strategy can effectively constrain the “inter-file” interference received at the UEs but fails to suppress the “intra-file” interference. As such, an important extension of this work is to investigate more advanced techniques to further address the issue of “intra-file” interference.

APPENDIX A

PROOF OF LEMMA 3.1

Proof: For the $i$-th combination $N_i$, given a set $D_i^q(s) \cup \{n\}$ of $q+1$ files are requested by C-UEs within a distance of $R_d$, it can be easily verified that the probability of selecting the $n$-th file as the candidate file is given by

$$
\tilde{\zeta}_n^q(s) = \frac{1}{q+1} \cdot (1 - e^{-\lambda_u p_n \pi R_d^2}) \cdot \prod_{m \in D_i^q(s)} (1 - e^{-\lambda_u p_m \pi R_d^2}) \cdot \prod_{j \in \tilde{D}_i^q(s)} e^{-\lambda_u p_j \pi R_d^2}. \tag{24}
$$

Then, by noting that $0 \leq q \leq K - 1$ and there are in total $C_{K-1}^q$ different cases of $D_i^q(s)$, we have

$$
\zeta_i^n = c_i \cdot \sum_{q=0}^{K-1} \sum_{s=1}^{C_{K-1}^q} \tilde{\zeta}_n^q(s). \tag{25}
$$

This thus completes the proof of Lemma 3.1.

APPENDIX B

PROOF OF LEMMA 3.2

Proof: For a tagged F-UE with $N_i$ cached in the storage, let $N(f)$ denote the number of C-UEs which request the $f$-th file within $R_d$. Then, given a set $G_i^q(s) \cup \{n\}$ of $q+1$ files with the same amount of requests within a distance of $R_d$, with the MRFS scheme, the probability
that the tagged F-UE selects the \( n \)-th file as the candidate file is given by

\[
\zeta_n^q(s) = \frac{1}{q+1} \cdot \Pr \left\{ \bigcap_{m \in G_i^q(s)} N(n) = N(m) \bigcap_{j \in G_i^q(s)} N(n) > N(j) \right\}
\]

\[
\overset{(a)}{=} \frac{1}{q+1} \cdot \sum_{k=1}^{\infty} \Pr \{N(n) = k\} \cdot \prod_{m \in G_i^q(s)} \Pr \{N(m) = k\} \cdot \prod_{j \in G_i^q(s)} \Pr \{k > N(j)\}
\]

\[
= \frac{1}{q+1} \cdot \sum_{k=1}^{\infty} \left( \frac{\lambda_u p_n \pi R^2_d}{k!} e^{-\lambda_u p_n \pi R^2_d} \right) \prod_{m \in G_i^q(s)} \left( \frac{\lambda_u p_m \pi R^2_d}{k!} e^{-\lambda_u p_m \pi R^2_d} \right)
\]

\[
\times \prod_{j \in G_i^q(s)} \sum_{t=0}^{k-1} \left( \frac{\lambda_u p_j \pi R^2_d}{t!} e^{-\lambda_u p_j \pi R^2_d} \right), \tag{26}
\]

where \((a)\) follows from the fact that the events \{\(N(n) = N(m)\}\} and \{\(N(n) > N(j)\)\} for \(n, m, j \in N_i\) are conditionally independent given \(N(n) = k\). Then, by noting that \(0 \leq q \leq K-1\) and there are in total \(C_{K-1}^q\) different cases of \(G_i^q(s)\), we have

\[
\zeta_i^n = c_i \cdot \sum_{q=0}^{K-1} \sum_{s=1}^{C_{K-1}^q} \zeta_n^q(s), \tag{27}
\]

which completes the proof of Lemma \ref{lem:lemma3.2}. \hfill \Box

### APPENDIX C

**PROOF OF LEMMA 3.3**

**Proof:** Without loss of generality, we consider a F-UE at location \(x\) which selects the \(n\)-th file as candidate file for content delivery. Let \(\Phi_n\) denote the PP formed by C-UEs which request the \(n\)-th file. Further, let \(\Phi_n = \sum_{i \in N, i \neq n} \Phi_i\) denote the PP formed by C-UEs which request other files except the \(n\)-th file. Then, under the proposed multicast-based opportunistic content delivery strategy, the tagged F-UE is capable of multicasting the \(n\)-th file only if it is in the spatial spectrum hole \cite{22} of \(\Phi_n\). Particularly, let \(S_j^n(x)\) denote the signal strength of the file request received at \(x\) sent from the \(j\)-th C-UE in \(\Phi_n\) at \(X_j\) as

\[
S_j^n(x) = \frac{P_u h_j}{|X_j - x|^\alpha}, \tag{28}
\]

where \(h_j\) denotes the power coefficient of the fading channel between \(X_j\) and \(x\). Further, let \(M_n(x)\) be the maximum value of \(\{S_j^n(x)\}\) over index \(j\) as

\[
M_n(x) = \max_{X_j \in \Phi_n} S_j^n(x). \tag{29}
\]
Then, under the proposed multicast-based opportunistic content delivery strategy, we have

\[ \vartheta_n = \Pr \{ M_n(x) \leq I_{th} \} \]

\[ = \mathbb{E} \left[ \prod_{X_j \in \Phi_n} 1 \{ S_j^n(x) \leq I_{th} \} \right] \]

\[ = \exp \left\{ -2\pi \varphi_n \int_{0}^{\infty} e^{-\frac{I_{th}r^\alpha}{P_u}} r dr \right\} \]

\[ = \exp \left\{ -2\pi \varphi_n \frac{\Gamma \left( \frac{2}{\alpha} \right) (\frac{P_u}{I_{th}})^{\frac{2}{\alpha}}}{\alpha} \right\}, \quad (30) \]

where

\[ \varphi_n = \lambda_u (1 - p_n), \quad (31) \]

which thus completes the proof of Lemma 3.3.

\[ \square \]

**APPENDIX D**

**PROOF OF LEMMA 4.4**

*Proof:* Under the proposed multicast-based opportunistic content delivery strategy, conditioned on that C is requesting the n-th file and \( l_n = l \), the received SIR is given by

\[ \text{SIR}_i^n = \frac{P_g h_0 l^{-\alpha}}{\sum_{X_i \in \Psi_g(C_n)} P_g h_i |X_i|^{-\alpha} + \sum_{Y_j \in \Psi_g(C_n)} P_g g_j |Y_j|^{-\alpha}}, \quad (32) \]

where \( \Psi_g(C_n) = \sum_{m \neq n} \Psi_g(C_n) \), \( h_0 \) is the fading channel power coefficient between C and F, \( h_i \) is the power coefficient of the fading channel between \( X_i \) and C, \( g_j \) is the power coefficient...
of the fading channel between \(Y_j\) and \(C\). As such, by applying Lemma 4.1 we obtain \(C^n_l\) as

\[
C^n_l = \Pr \left( \text{SIR}^n_l \geq \theta_u \right)
\]

\[
= \Pr \left\{ \frac{P_g h_0 l^{-\alpha}}{\sum_{X_i \in \Psi_g(C_n)} X_i^{-\alpha} + \sum_{Y_j \in \Psi_g(C_n)} Y_j^{-\alpha}} \geq \theta_u \right\}
\]

\[
= \mathbb{E}_X \left[ \prod_{X_i \in \Psi_g(C_n)} \mathbb{E}_h \left[ e^{-\theta_u |X_i|^{-\alpha}} \right] \right] \cdot \mathbb{E}_Y \left[ \prod_{Y_j \in \Psi_g(C_n)} \mathbb{E}_g \left[ e^{-\theta_u |Y_j|^{-\alpha}} \right] \right]
\]

\[
= \exp \left\{ -2\pi \lambda^n_g \int_{l_1}^{l} \left( 1 - \int_{0}^{\infty} e^{-\left(\theta_u u^{-\alpha} + 1\right)h} dh \right) du \right\}
\]

\[
\times \exp \left\{ -2\pi \int_{0}^{\infty} \left( 1 - \int_{0}^{\infty} e^{-\left(\frac{\theta_u u^{-\alpha}}{\theta_u^{-\alpha}}\right)g} \right) \tilde{\lambda}^m_g(u) du \right\}
\]

\[
= \exp \left\{ -2\pi \lambda^n_g \int_{l_1}^{l} \frac{1}{1 + \frac{u}{\theta_u^{-\alpha}}} \ du \right\} \cdot \exp \left\{ -\frac{2\pi^2}{\alpha \sin \left(\frac{2\pi}{\alpha}\right)} \theta_u^{\alpha} \tilde{\lambda}^m_g \right\}
\]

\[
\times \exp \left\{ \frac{2\pi}{\alpha} \lambda^n_g \left( \frac{P_u}{I_{th}} \right) \frac{1}{2} \Gamma \left( \frac{2}{\alpha} \right) \right\} \cdot \exp \left\{ -2\pi \lambda^n_g \int_{l_1}^{l} \frac{\frac{u}{\theta_u^{-\alpha}}}{1 + \frac{u}{\theta_u^{-\alpha}}} \times e^{-\frac{\theta_u x u^{-\alpha}}{\theta_u^{-\alpha}}} du \right\}, \quad (33)
\]

where

\[
\tilde{\lambda}^m_g(u) = \sum_{m \neq n} \lambda^m_g(C_n, u)
\]

\[
= \tilde{\lambda}^n_g \left( 1 - e^{-\frac{\theta_u x u^{-\alpha}}{\theta_u^{-\alpha}}} \right).
\]

Then, with (33), by taking expectation over \(l\), we have

\[
C_n = \int_{0}^{R_d} C^n_l \times f_{l_n}(l) dl,
\]

which completes the proof of Lemma 4.4.

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