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Fog-aided wireless networks for content delivery: A file-level carrier sensing based approach

Xiaoshi Song*, Mengying Yuan, Chao Jia, Ning Ye, Weimin Lei

School of Computer Science and Engineering, Northeastern University, Shenyang, 110819, China

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A B S T R A C T

We investigate a novel file-level carrier sensing based content delivery (FL-CSBCD) protocol to accommodate the transmission of multimedia files in fog-aided wireless networks. Particularly, the proposed FL-CSBCD protocol contains two phases, i.e., the file contention phase and the communication contention phase. The file contention phase aims to resolve the contentions among the requested multimedia files at each fog user equipments (F-UEs), such that the cache-hit performance is maximized. The communication contention phase is designed to resolve the collisions among concurrent content deliveries of the same file, such that the mutual interference can be suppressed. By modeling the fog-aided wireless networks with Poisson point process, we capture the density of active F-UEs, and evaluate the successful content delivery probability (SCDP) with the FL-CSBCD protocol. We show by simulations that the FL-CSBCD protocol can enhance the cache-hit performance while guarantee the coverage probability of content delivery.

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1. Introduction

Recent advancements in smartphone industry and wireless internet technology have triggered a dramatic increase in the demand of bandwidth-hungry multimedia services [12]. Particularly, according to recent industry predictions [3], the annual traffic generated by multimedia content delivery in 2021 will be 4 times of that in 2016 with an increasing rate of 26% per year. To satisfy such unprecedented growth of user demands on multimedia services, it is necessary to investigate novel network architectures and develop advanced transmission techniques for the next generation wireless networks [2,7,10,11,19,23,29].

Fog-aided wireless network is considered to be a promising content-centric network architecture to alleviate the congestion of current cellular networks induced by the massive and redundant downloadings of multimedia contents [15–17,28]. Particularly, by deploying a generic caching, computing, and communication platform across the wireless edges, fog-aided wireless network can effectively offload the data traffic from the remote cloud sever and execute the delay-sensitive tasks in the proximity of the end users, which thereby substantially improves the network performance.

To further enhance the spectral efficiency of the fog-aided wireless networks, the innovative technique of cache-enabled D2D communication [4,9,14,26] is utilized for multimedia content delivery. Particularly, by leveraging the cache-enabled D2D communications, a conventional cellular user equipment (C-UE) can directly obtain the multimedia content from a fog user equipment (F-UE) with caching capability in its proximity without the use of infrastructure based edge nodes. As such, the

* Corresponding author.
E-mail address: songxiaoshi@cse.neu.edu.cn (X. Song).

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D2D communication based fog-aided wireless network enables a more flexible paradigm to facilitate the content sharing among the cache-enabled F-UEs.

The research of wireless caching strategies in D2D communication based fog-aided wireless networks have attracted growing interests. Particularly, in [18], Sengupta et al. investigated the fundamental limits of the normalized delivery time in fog-aided wireless networks and captured the interplay between the centralized cooperative cloud processing and decentralized edge caching. In [6], with the user demands known a priori, Gregori et al. studied the joint caching and transmission design in fog-aided wireless networks by formulating a continuous time optimization problem. In [22], Su et al. proposed a novel caching scheme in fog-aided wireless networks based on the Steiner tree to minimize the total cost and thereby maximize the network performance. In [27], Zhang et al. provided a novel analytical framework to cope with the mutual interference in fog-aided wireless networks through link scheduling and power allocation. In [25], Wang et al. analyzed the performance of fog-aided wireless networks with social-tie based data sharing. In [13], Liu et al. investigated both the decentralized and centralized content caching strategies in fog-aided wireless networks to minimize the transmission delay with the storage capacity constraints. In [24], Wang et al. exploited the user mobility in the design of content caching schemes to maximize the ratio of data offloading via D2D links. In [5], Giatsoglou et al. proposed a high-rate multimedia content sharing scheme in fog-aided wireless networks by using millimeter-wave based D2D communication. In [1], Bai et al. investigated the social ties and common interests based fog-aided wireless networks under the paradigm of hypergraph. In [20], the authors studied the contention based multimedia delivery (CBMD) protocol in fog-aided wireless networks. It is worth noting that in [20], though the mutual interference of the concurrent transmissions is effectively constrained by the mechanism of contentions among the mobile helpers, the diversity of the available files for C-UEs within the distance of the D2D communication range R_d and thereby the respective cache-hit performance may also be reduced.

In this paper, different from the above mentioned works [5,6,13,18,22,24,25,27], we investigate the D2D communication based fog-aided wireless networks over the spatial domain. Further, different from Song et al. [20], we consider a file-level carrier sensing based content delivery (FL-CSBCD) protocol to enhance the cache-hit performance while guarantee the coverage probability of content delivery. The main contributions from this work can be summarized as follows.

- We provide a tractable analytical approach for the design of fog-aided wireless networks to accommodate the access of cached files via D2D communication. Particularly, to reduce the redundant delivery of the cached contents and alleviate the potential "intra-file" collisions of F-UEs, a novel file-level carrier sensing based content delivery (FL-CSBCD) protocol is proposed. Different from the CBMD protocol presented in [20], the proposed FL-CSBCD protocol simply resolves the collisions of the transmissions of the same file. As such, under the FL-CSBCD protocol, the diversity of the available files within the coverage of each C-UE and thereby the respective conditional cache-hit performance can be guaranteed.
- We characterize the spatial distribution of the active F-UEs under the FL-CSBCD protocol. It should be noted that the transmission probabilities for F-UEs in proximity are dependent since the received requests from the C-UEs are correlated. Therefore, the active F-UEs is a non-HPPP. This then results in the infeasibility of the evaluation of the network performance. To tackle this issue, we approximate the active F-UEs as HPPP and characterize the performance of the proposed FL-CSBCD protocol.
- Under the proposed FL-CSBCD protocol, with the HPPP assumption on the active F-UEs, the conditional cache-hit probability, the conditional coverage probability, and the successful content delivery probability (SCDP) of F-UEs are derived. It is shown by simulations that the proposed FL-CSBCD protocol can significantly enhance the network performance.

The rest of this paper is organized as follows. We first present the mathematical model of the fog-aided wireless networks and demonstrate the proposed FL-CSBCD protocol in Section 2. Then, we quantify the transmission probability of F-UEs under the FL-CSBCD protocol in Section 3. In Section 4, the cache-hit probability, the coverage probability, and the SCDP of the fog-aided wireless networks with the FL-CSBCD protocol are deirved. Further, Section 5 illustrates the numerical results. Finally, Section 6 concludes the paper. Notations of selected symbnols used in this paper are summarized in Table 1.

2. Network model

The fog-aided wireless network is assumed to be formed by a set of C-UEs and a set of dedicated F-UEs with caching capabilities as given by Fig. 1. The C-UEs and F-UEs are randomly deployed as HPPPs with densities given by μ_0 and λ_0, respectively. We further consider a file library $\mathcal{F}$ of size F for the fog-aided wireless network and denote

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

as the corresponding popularity with $\gamma \geq 0$. The cache memory of F-UEs is assumed to be M files. As such, there are in total $J \triangleq \binom{F}{M}$ combinations available for caching at each F-UE. Let $\mathcal{J}$ denote the set of J combinations, and let $\mathcal{N}_j$ denote the set of files in the jth combination of $\mathcal{J}$. Then, assuming decentralized random caching for F-UEs, we denote c_j as the caching probability of $\mathcal{N}_j$, which satisfies

$$0 \leq c_j \leq 1, \quad j \in \mathcal{J}, \tag{2}$$

and

$$\sum_{j \in \mathcal{J}} c_j = 1, \tag{3}$$

Table 1
Symbol notation.

Symbol	Meaning
λ_0, μ_0	Density of F-UEs/C-UEs
γ	Zipf parameter
α	Path-loss exponent
P_d	Transmit power
R_d	Collaboration distance for D2D transmission
θ_d	SIR target
N_d	Contention threshold
c_f	Probability that F-UEs cache file f
p_f	Request probability of file f
ξ_f	Conditional cache-hit probability of file f
ξ_d	Cache-hit probability
q_d	Transmission probability of F-UEs
$\mathcal{C}_f$	Coverage probability of D2D transmissions with respect to file f
τ_d	Successful content delivery probability
C, F	Typical active C-UE/F-UE

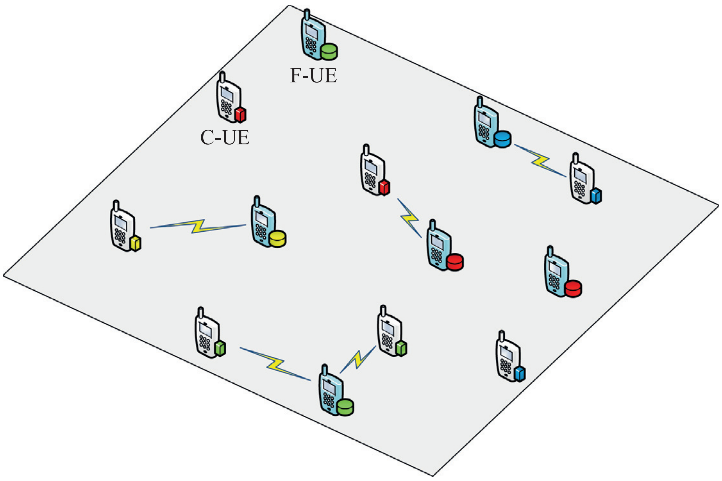


Fig. 1. Fog-aided wireless network with F-UEs and C-UEs.

respectively. The transmit power of F-UEs is P_d. The small-scale fading h is assumed to be Rayleigh distributed with unit mean, and the large-scale path loss with parameter α is given by $d^{-\alpha}$ for distance d. We further denote R_d as the communication range of F-UE transmission, i.e., a F-UE can only communicate with a C-UE within a distance of R_d.

At the beginning of each transmission interval, the C-UEs are designed to issue a vector of file requests according to p_f. Upon receiving the requests, the F-UEs then employ the FL-CSBCD protocol for data transmission. Particularly, the FL-CSBCD protocol contains two phases, namely the file contention phase and the communication contention phase. We elaborate the two phases as follows.

- **File Contention Phase:** The file contention phase picks the candidate file for data transmission at each F-UE. Particularly, under the FL-CSBCD protocol, in the file contention phase, upon receiving the file requests, the tagged F-UE is assumed to select the most requested file among its cached files as the candidate file. Therefore, the file contention phase can satisfy the service requests of the majority of C-UEs and thereby enhance the cache-hit performance of the network.
- **Communication Contention Phase:** The communication contention phase resolves the contentions among concurrent transmissions of F-UEs while guarantee the cache-hit performance. Particularly, under the FL-CSBCD protocol, in the communication contention phase, only the F-UEs with the same file selected as the candidate file compete with each other for data transmission. As such, the potential collisions of F-UEs can be effectively relieved without severely degrading the cache-hit performance. Let Ψ_f be the set of F-UEs which select the fth file as the candidate file. Then, at the beginning of the communication contention phase, the F-UE in Ψ_f randomly generates a back-off timer over the range [0, 1], and monitors the spectrum. We define that a F-UE in Ψ_f at location $\mathbf{x}$ conflicts with another F-UE in Ψ_f at location $\mathbf{y}$ iff $P_d h|\mathbf{y}-\mathbf{x}|^{-\alpha} \geq N_d$, where N_d denotes the predefined collision threshold. Then, if there is no other conflicting F-UE in Ψ_f being detected prior to the back-off timer counts down to 0, the tagged F-UE confirms its attempt and initiates the content delivery. Otherwise, the tagged F-UE cancels the transmission in the current time slot.

With the mathematical model of fog-aided wireless network, we study the performance metrics of transmission probability, cache-hit probability, coverage probability, and successful content delivery probability (SCDP) under the proposed FL-CSBCD protocol. Particularly, the definitions of the performance metrics are given as follows.

Definition 1 (Transmission Probability)**.** For F-UEs, the transmission probability ϱ_f of the fth file is defined as

$$\varrho_f = \sum_{j \in \mathcal{J}_f} c_j \cdot q_j \cdot \zeta_j^f \cdot \vartheta_f, \tag{4}$$

where q_j is the request probability of the jth combination from the C-UEs within a distance of R_d, ζ_j^f denotes the probability that the fth file is confirmed as the candidate file for data transmission with $f \in \mathcal{N}_j$, and ϑ_f denotes the respective successful competition probability.

Definition 2 (Cache-Hit Probability)**.** The cache-hit probability for a random request from an arbitrary C-UE, denoted by ξ_d, can be defined as

$$\xi_d = \sum_{f=1}^{F} p_f \cdot \xi_f, \tag{5}$$

where ξ_f denotes the conditional cache-hit probability that there exists at least one active F-UE which transmits the fth file within a distance of R_d.

Definition 3 (Coverage Probability)**.** The coverage probability of the fth file, denoted by $\mathcal{C}_f$, is defined as

$$\mathcal{C}_f = \Pr(\mathrm{SIR}_f \geq \theta_d), \tag{6}$$

where θ_d denotes the SIR threshold.

Definition 4 (Successful Content Delivery Probability)**.** The SCDP of the fog-aided wireless network, denoted by τ_d, is defined as

$$\tau_d = \sum_{f=1}^{F} p_f \cdot \xi_f \cdot \mathcal{C}_f. \tag{7}$$

3. Transmission probability

To analyze the network performance under the FL-CSBCD protocol, we first analyze ϱ_f of F-UEs which is defined in (4). Particularly, let $\mathbf{x}_j$ be the location of an arbitrary F-UE which caches the jth combination $\mathcal{N}_j$ of $\mathcal{J}$. Further, let q_j be the probability that at least one C-UE requests the file in $\mathcal{N}_j$ within a distance of R_d from $\mathbf{x}_j$. Then, the following lemma derives q_j.

Lemma 3.1. *For fog-aided wireless networks, under the FL-CSBCD protocol, the probability q_j is given by*

$$q_j = 1 - e^{-\mu_0 \pi R_d^2 \sum_{f \in \mathcal{N}_j} p_f}. \tag{8}$$

Proof. Let $\bar{q}_j$ denote the probability that there is no requests of files in $\mathcal{N}_j$ within a distance of R_d from $\mathbf{x}_j$. Then, by applying the void probability of the Poisson point process, it can be obtained that

$$\bar{q}_j = e^{-\mu_0 \pi R_d^2 \sum_{f \in \mathcal{N}_j} p_f}.$$

By noting that $q_j = 1 - \bar{q}_j$, (8) is thus obtained. □

Conditioned on that $\mathbf{x}_j$ is under request, we denote ζ_j^f as the probability that $\mathbf{x}_j$ selects the fth file in $\mathcal{F}$ as the candidate file for data transmission, where $f \in \mathcal{N}_j$. Then, the following lemma derives the probability ζ_j^f.

Lemma 3.2. *For fog-aided wireless networks, under the FL-CSBCD protocol, the probability ζ_j^f is given by*

$$\zeta_j^f = \sum_{k_f=1}^{\infty} \frac{U_f^{k_f}}{k_f!} e^{-U_f} \cdot \prod_{i \in \mathcal{N}_j} \sum_{k_i=0}^{k_f} \frac{U_i^{k_i}}{k_i!} e^{-U_i}, \tag{9}$$

where $U_n = p_n \mu_0 \pi R_d^2$, $k_n \in \mathbb{N}$.

Proof. See Appendix A. □

We denote $\Psi_f = \{\mathbf{x}_f\}$ as the point process of F-UEs which choose the fth file in $\mathcal{F}$ as the candidate file for data transmission. Further, let λ_f denote the density of Ψ_f. Then, based on Lemmas 3.1 and 3.2, we arrive at the following corollary.

Corollary 3.1. *For fog-aided wireless networks, under the FL-CSBCD protocol, the density* λ_f *of* Ψ_f *is given by*

$$\lambda_f = \sum_{j\in\mathcal{J}_f} c_j \cdot (1 - e^{-\mu_0 \pi R_d^2 \sum_{f\in\mathcal{N}_j} p_f}) \cdot \sum_{k_f=1}^{\infty} \frac{U_f^{k_f}}{k_f!} e^{-U_f} \cdot \prod_{i\in\mathcal{N}_j} \sum_{k_i=0}^{k_f} \frac{U_i^{k_i}}{k_i!} e^{-U_i} \cdot \lambda_0, \tag{10}$$

where $\mathcal{J}_f$ *denotes the set of combinations which contain the fth file in* $\mathcal{F}$.

Proof. By noting that

$$\lambda_f = \sum_{j\in\mathcal{J}_f} c_j \cdot q_j \cdot \zeta_j^f \cdot \lambda_0, \tag{11}$$

(10) is directly obtained based on Lemmas 3.1 and 3.2. □

Under the FL-CSBCD protocol, after the file contention phase, the F-UEs of the same candidate file are designed to further compete with each other in the communication contention phase for data transmission. Let ϑ_f denote the successful competition probability of F-UEs in Ψ_f. Then, to derive ϱ_f of F-UEs, in addition to q_j and ζ_j^f, we also need to characterize ϑ_f of the F-UEs with the fth file in $\mathcal{F}$ selected as the candidate file. Unfortunately, since Ψ_f is a non-HPPP, ϑ_f cannot be exactly characterized. To tackle this issue, for the tractability of ϱ_f, the following HPPP approximation on Ψ_f is considered as that in [2,8,21].

Assumption 1. For fog-aided wireless network with the FL-CSBCD protocol, Ψ_f is a HPPP with density λ_f.

Remark 3.1. We will examine the validity of Assumption 1 in Section VI through simulations.

Under Assumption 1, we derive ϑ_f as follows.

Lemma 3.3. *For fog-aided wireless networks, under the FL-CSBCD protocol, the successful competition probability* ϑ_f *of F-UEs in* Ψ_f *is given by*

$$\vartheta_f = \frac{1 - e^{-\pi\lambda_f \Gamma(1+\frac{2}{\alpha})\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}}{\pi\lambda_f \Gamma\left(1+\frac{2}{\alpha}\right)\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}. \tag{12}$$

Proof. See Appendix B. □

With Lemmas 3.1, 3.2, and 3.3, the main result of this section is presented as follows.

Theorem 3.1. *For fog-aided wireless networks, under the FL-CSBCD protocol, the transmission probability* ϱ_f *of F-UEs which eventually broadcast the fth file in* $\mathcal{F}$ *to their associated C-UEs is given by*

$$\varrho_f = \sum_{j\in\mathcal{J}_f} c_j \cdot (1 - e^{-\mu_0 \pi R_d^2 \sum_{f\in\mathcal{N}_j} p_f}) \cdot \frac{1 - e^{-\pi\lambda_f \Gamma(1+\frac{2}{\alpha})\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}}{\pi\lambda_f \Gamma\left(1+\frac{2}{\alpha}\right)\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}} \times \sum_{k_f=1}^{\infty} \frac{U_f^{k_f}}{k_f!} e^{-U_f} \cdot \prod_{i\in\mathcal{N}_j} \sum_{k_i=0}^{k_f} \frac{U_i^{k_i}}{k_i!} e^{-U_i}. \tag{13}$$

Proof. With Lemmas 3.1, 3.2, and 3.3, (13) is immediately obtained based on (4). □

Remark 3.2. Under the FL-CSBCD protocol, we denote Ψ_a^f as the set of active F-UEs delivering the fth file and denote λ_a^f as the respective density. Then, it can be immediately obtained from Theorem 3.1 that

$$\lambda_a^f = \lambda_0 \varrho_f. \tag{14}$$

Let ϱ denote the expected value of ϱ_f. Then, with Theorem 3.1, ϱ is derived as follows.

Corollary 3.2. *For fog-aided wireless networks, under the FL-CSBCD protocol,* ϱ *is given by*

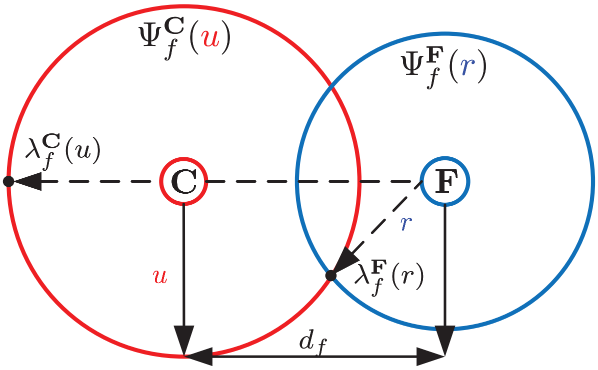


Fig. 2. Conditional distribution of active F-UEs around **F** and **C** under the FL-CSBCD protocol.

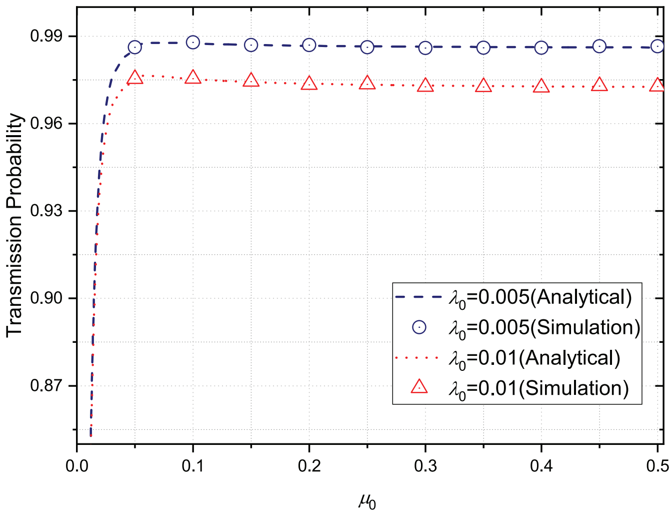


Fig. 3. ϱ versus μ_0.

$$\varrho = \sum_{f\in\mathcal{F}} \sum_{j\in\mathcal{J}_f} c_j \cdot \left(1 - e^{-\mu_0 \pi R_d^2 \sum\limits_{f\in\mathcal{N}_j} p_f}\right) \cdot \frac{1 - e^{-\pi\lambda_f \Gamma\left(1+\frac{2}{\alpha}\right)\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}}{\pi\lambda_f \Gamma\left(1+\frac{2}{\alpha}\right)\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}$$
$$\times \sum_{k_f=1}^{\infty} \frac{U_f^{k_f}}{k_f!} e^{-U_f} \cdot \prod_{i\in\mathcal{N}_j} \sum_{k_i=0}^{k_f} \frac{U_i^{k_i}}{k_i!} e^{-U_i}. \tag{15}$$

Proof. With Theorem 3.1, by noting that

$$\varrho = \sum_{f\in\mathcal{F}} \varrho_f, \tag{16}$$

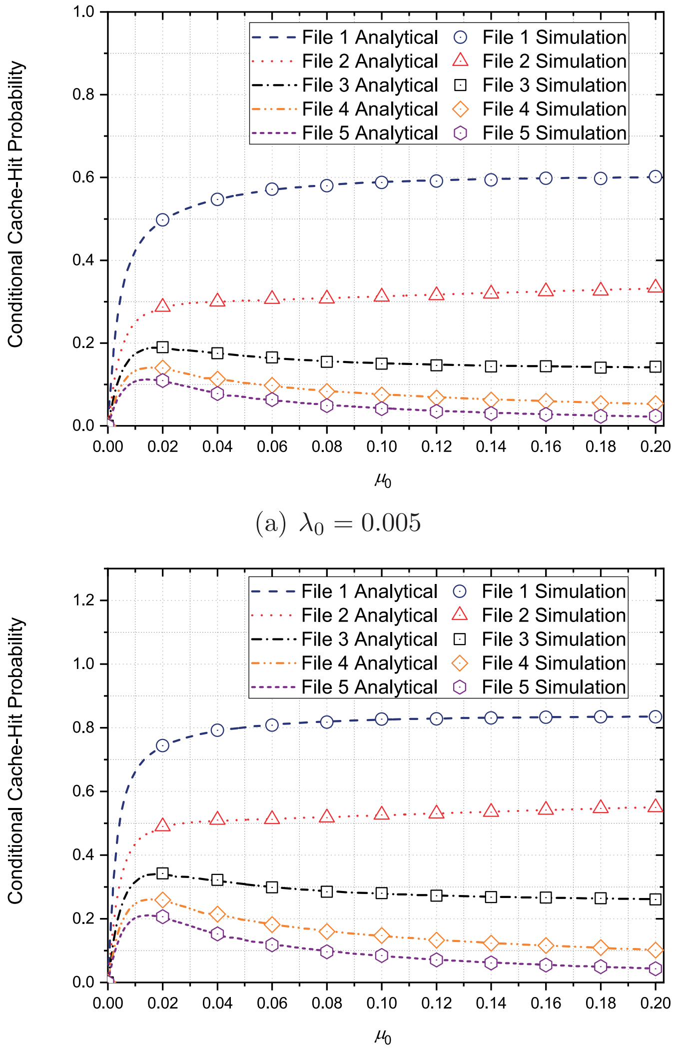
(15) is readily obtained. □

Remark 3.3. Under the FL-CSBCD protocol, the set of active F-UEs is denoted by Ψ_a. Further, we denote λ_a as the density of Ψ_a. Then, with Corollary 3.2, it can be obtained that

$$\lambda_a = \lambda_0 \varrho. \tag{17}$$

Remark 3.4. Because of the complex interactions involved in the communication contention phase, even under Assumption 1, Ψ_a^f and Ψ_a are non-HPPPs. As such, the derivation of SCDP under the FL-CSBCD protocol is infeasible. Then, for the evaluation of the SCDP under the FL-CSBCD protocol, we consider an additional assumption as follows.

Assumption 2. For fog-aided wireless network with the FL-CSBCD protocol, Ψ_a^f and Ψ_a follow HPPPs with density λ_a^f and λ_a, respectively.



(a) $\lambda_0 = 0.005$

(b) $\lambda_0 = 0.01$

Fig. 4. ξ_f versus μ_0 for file *f*.

Remark 3.5. We will examine the validity of Assumption 2 in Section VI through simulations.

In the following section, we characterize the SCDP of the fog-aided wireless networks with the FL-CSBCD protocol based on Assumptions 1 and 2.

4. Successful content delivery probability

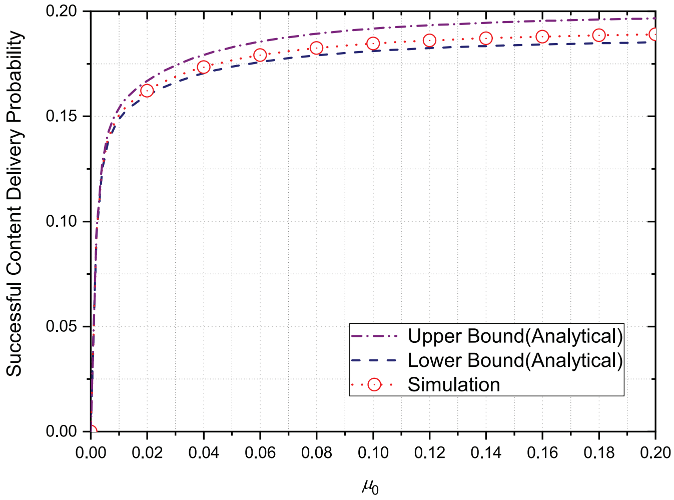
As a standard procedure for the performance evaluation of Poisson point process distributed networks, we conduct the analysis on a C-UE placed at the origin, which is labeled as **C**. Then, assuming that **C** is requesting the *f*th file, we first derive ξ_f of **C** under Assumption 2 as follows.

Lemma 4.1. *With the FL-CSBCD protocol, under Assumption 2, ξ_f of* **C** *is given by*

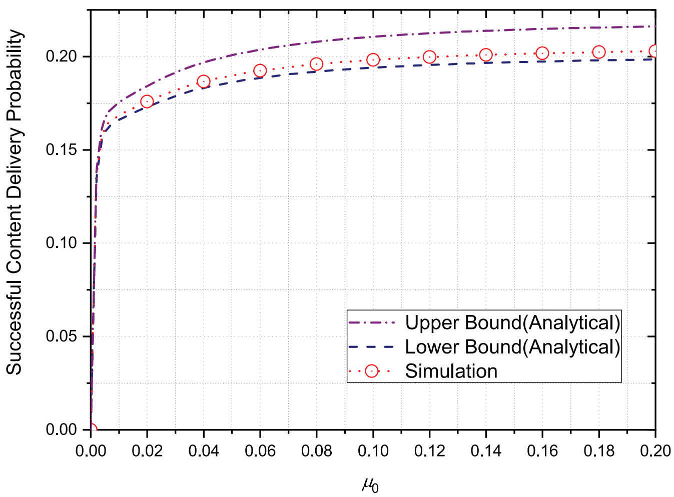
$$\xi_f = 1 - e^{-\lambda_a^f \pi R_d^2}. \tag{18}$$

Proof. Under Assumption 2, (18) is directly obtained by evaluating the probability that there exists at least one active F-UE which transmits the *f*th file within a distance of R_d from **C**. □

Remark 4.1. It should be noted that, without Assumption 2, ξ_f cannot be derived since the void probability is not available for non-HPPP distributed Ψ_a^f.



(a) $\lambda_0 = 0.005$



(b) $\lambda_0 = 0.01$

Fig. 5. τ_d versus μ_0 for file f.

By noting that the request of the fth file from **C** can be served by F-UEs within a distance of R_d, we denote **F** as the associated F-UE of **C**, and denote d_f as the distance between **C** and **F**, where $d_f \le R_d$. It should be noted that based on (7), to capture the SCDP under the FL-CSBCD protocol, we need to further derive the coverage probability of **C**. As such, the distribution of the active F-UEs around **C** and thereby the statistics of the respective introduced interference need to be carefully analyzed. Let $\mathcal{O}^{\mathbf{F}}(r)$ be the circle of center **F** and radius r. Further, let $\Psi_f^{\mathbf{F}}(r)$ denote the active F-UEs on $\mathcal{O}^{\mathbf{F}}(r)$, and let $\lambda_f^{\mathbf{F}}(r)$ be the average intensity of $\Psi_f^{\mathbf{F}}(r)$. We thus characterize $\Psi_f^{\mathbf{F}}(r)$ in Lemma 4.2.

Lemma 4.2. *With the FL-CSBCD protocol, under Assumption 2, $\Psi_f^F(r)$ is a HPPP with density $\lambda_f^{\mathbf{F}}(r)$ given by*

$$\lambda_f^{\mathbf{F}}(r) = \lambda_a^f (1 - e^{-\frac{N_d r^\alpha}{P_d}}). \tag{19}$$

Proof. Given that **C** is receiving the fth file from **F**, under the FL-CSBCD protocol, the probability that a F-UE on $\mathcal{O}^{\mathbf{F}}(r)$ is able to transmit the fth file is $\varrho_f \cdot \Pr(h \le \frac{N_d r^\alpha}{P_d})$. As such, under Assumption 2, $\Psi_f^{\mathbf{F}}(r)$ is a HPPP and $\lambda_f^{\mathbf{F}}(r)$ is given by (19). □

Let $\mathcal{O}^{\mathbf{C}}(u)$ denote the circle centered at **C** with radius u. Further, let $\Psi_f^{\mathbf{C}}(u)$ denote the active F-UEs on $\mathcal{O}^{\mathbf{C}}(u)$, and let $\lambda_f^{\mathbf{C}}(u)$ denote the average intensity of $\Psi_f^{\mathbf{C}}(u)$. Based on Lemma 4.2, we characterize $\lambda_f^{\mathbf{C}}(u)$ in Lemmas 4.3, and 4.4 as follows.

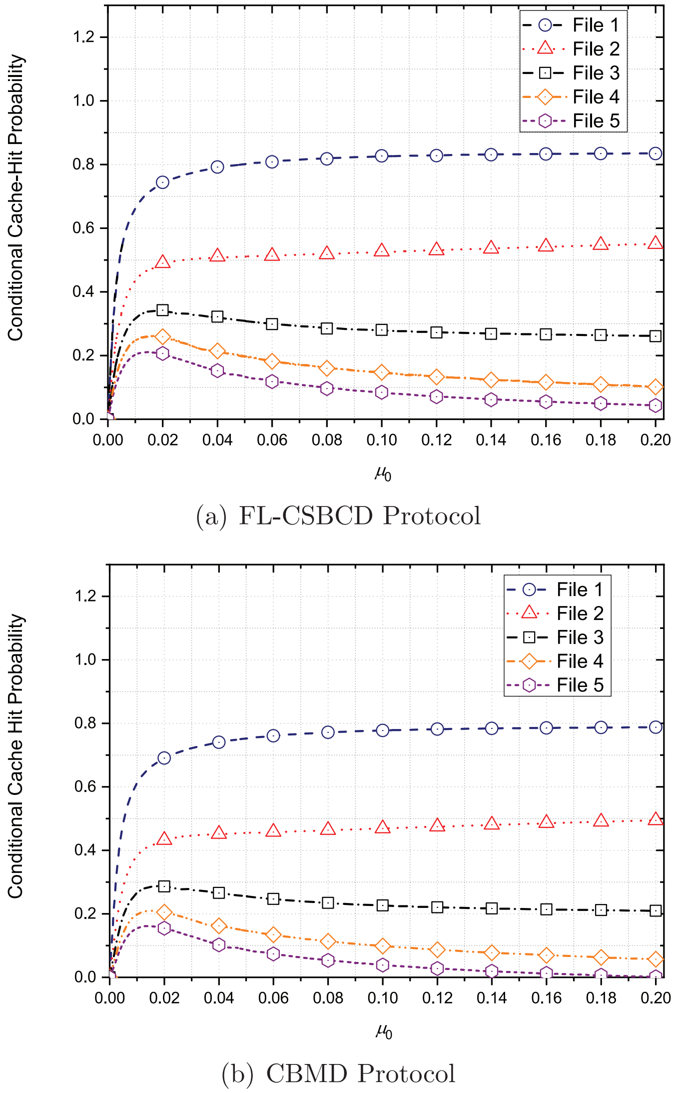


Fig. 6. Simulated ξ_f versus μ_0 for file *f*.

Lemma 4.3. *With the FL-CSBCD protocol, under Assumption 2, we have*

$$\lambda_f^{\mathbf{C}}(u) \le \lambda_a^f \cdot (1 - e^{-\frac{N_d (u+d_f)^\alpha}{P_d}}), \tag{20}$$

and

$$\lambda_f^{\mathbf{C}}(u) \ge \lambda_a^f \cdot (1 - e^{-\frac{N_d (u-d_f)^\alpha}{P_d}}), \tag{21}$$

respectively.

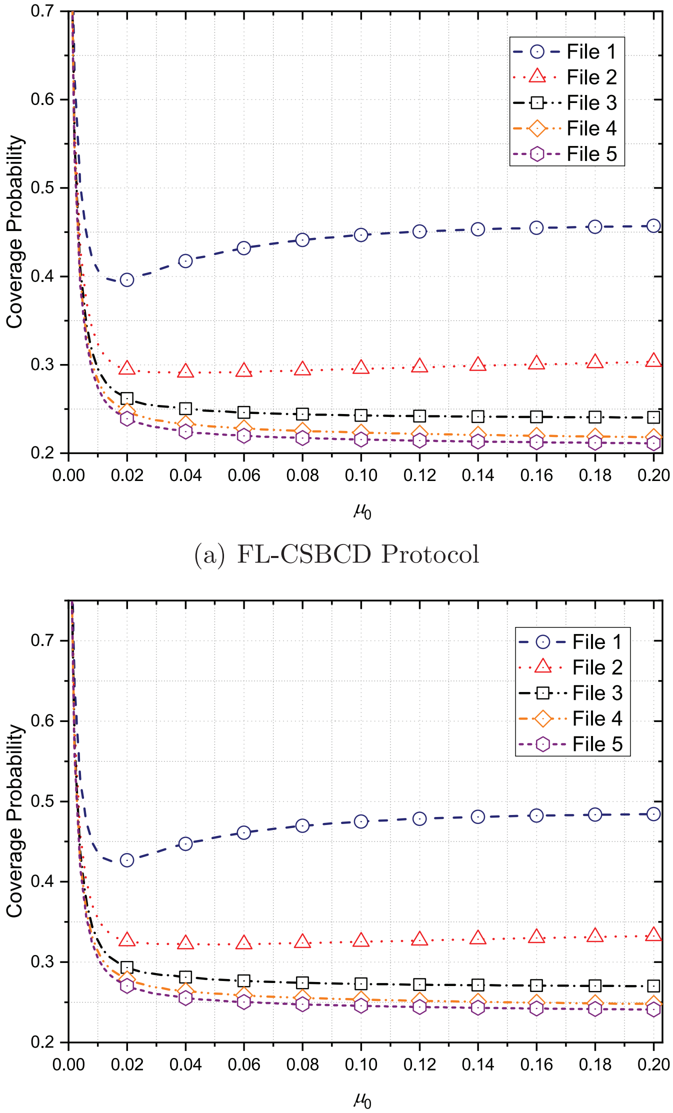
Proof. The upper and lower bound on $\lambda_f^{\mathbf{C}}(u)$ given by (20) and (21) can be directly obtained by Lemma 4.2 and Fig. 2. □

Lemma 4.4. *With the FL-CSBCD protocol, under Assumption 2, we have*

$$\int_0^\infty \frac{\lambda_f^{\mathbf{C}}(u)}{1 + \frac{u^\alpha}{\theta_d d_f^\alpha}} u du \ge \int_0^\infty \frac{\lambda_f^{\mathbf{F}}(u)}{1 + \frac{u^\alpha}{\theta_d d_f^\alpha}} u du. \tag{22}$$

Proof. See Appendix C □

Let $\overline{\Psi}_f^{\mathbf{C}}$ be the active F-UEs around **C** which transmit other files except the *f*th, and let $\overline{\lambda}_f^{\mathbf{C}}$ be the corresponding average density. We characterize $\overline{\Psi}_f^{\mathbf{C}}$ in Lemma 4.5.



(a) FL-CSBCD Protocol

(b) CBMD Protocol

Fig. 7. Simulated $\mathcal{C}_f$ versus μ_0 for file f.

Lemma 4.5. *With the FL-CSBCD protocol, under Assumption 2, $\overline{\Psi}_f^{\mathbf{C}}$ follows a HPPP with density $\overline{\lambda}_f^{\mathbf{C}}(u)$ given by*

$$\overline{\lambda}_f^{\mathbf{C}} = \lambda_0(\varrho - \varrho_f). \tag{23}$$

Proof. By noting that receiving the fth file at **C** has no effect on the distribution of the active F-UEs which transmit other files except the fth file, (23) is thus obtained. □

With the above derived lemmas, we evaluate the SCDP τ_d of the fog-aided wireless network with the FL-CSBCD protocol as follows.

Theorem 4.1. *With the FL-CSBCD protocol, under Assumption 2, τ_d is bounded by*

$$\tau_d \le \sum_{f=1}^{F} p_f \int_0^{R_d} \exp\left\{-\int_0^{\infty} \frac{2\pi \overline{\lambda}_a^f}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}} u\mathrm{d}u\right\}$$
$$\times \exp\left\{-\int_{d_f}^{\infty} \eta(u-d_f) u\mathrm{d}u\right\} \cdot \varpi_f(d_f)\mathrm{d}d_f, \tag{24}$$

and

$$\tau_d \geq \sum_{f=1}^{F} p_f \int_0^{R_d} \exp\left\{-\int_0^{\infty} \frac{2\pi \overline{\lambda}_a^f}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}} u\mathrm{d}u\right\} \times \exp\left\{-\int_{d_f}^{\infty} \eta(u+d_f)u\mathrm{d}u\right\} \cdot \varpi_f(d_f)\mathrm{d}d_f, \tag{25}$$

where

$$\eta(x) = 2\pi\lambda_a^f \frac{(1-e^{-\frac{N_d x^\alpha}{P_d}})}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}, \tag{26}$$

and

$$\varpi_f(d_f) = 2\lambda_a^f \pi d_f \cdot e^{-\lambda_a^f \pi d_f^2}. \tag{27}$$

Proof. See Appendix D. □

5. Numerical results

This section provides the simulation results and validate the effectiveness of the derived analytical results. Particularly, throughout this section, we set the SIR target θ_d as 0 dB, the collaboration distance of D2D communication R_d as 10 m, the Zipf parameter γ as 1, the cache memory of F-UEs M as 5, and α as 4.

We first plot the average transmission probability ϱ versus μ_0 in Fig. 3. It is shown by the simulation results that the derived analytical result of ϱ with the proposed FL-CSBCD protocol is effective.

Then, we plot the cache-hit probability ξ_f versus μ_0 in Fig. 4, when $\lambda_0 = 0.005$ and $\lambda_0 = 0.01$, respectively. It is shown by the simulated values of ξ_f that the analytical result obtained in Lemma 4.1 is accurate. It is also observed from Fig. 4 that ξ_1 and ξ_2 increase with μ_0, while ξ_3, ξ_4, and ξ_5 decrease with μ_0. Intuitively, this is due to the fact that the FL-CSBCD protocol simply selects the most requested file among the cached files as the candidate file for content delivery.

Fig. 5 plots the average SCDP τ_d under the proposed FL-CSBCD protocol. It can be observed that the simulated value of τ_d is between the analytical upper and lower bounds of τ_d derived in Theorem 4.1. It is also observed that τ_d increases with μ_0, which is due to the fact that the cache-hit probability dominates the SCDP.

It should be noted that the plots in Figs. 3–5 corroborate the validity of the HPPP approximations presented in Assumptions 1 and 2. The underlying reason is that, the mean effect of a large and complex point process on any given individual can be approximated by a simple HPPP based evaluation.

In Figs. 6–8, we compare the proposed FL-CSBCD protocol with the CMBD protocol given by Song et al. [20] for $\lambda_0 = 0.01$. Particularly, it can be observed in Fig. 6 that the FL-CSBCD protocol outperforms the CMBD protocol on ξ_f. Intuitively, this is because that under the FL-CSBCD protocol, in the communication contention phase, only the F-UEs with the same file selected as the candidate file compete with each other for data transmission. As such, the diversity of the available files within the coverage of each C-UEs and thereby the respective conditional cache-hit performance can be guaranteed. Further,

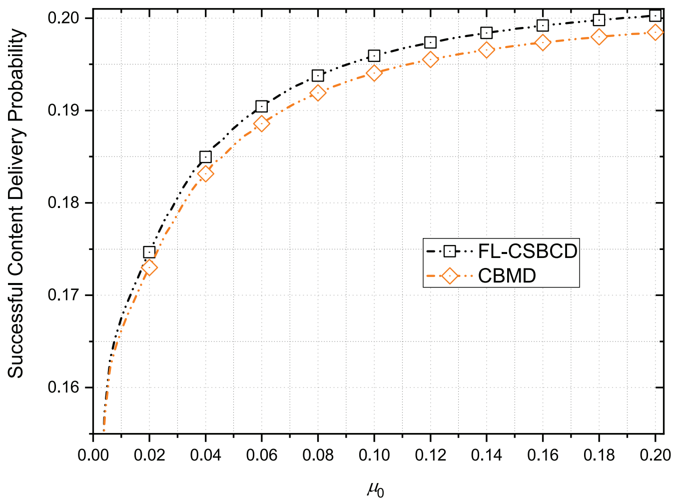


Fig. 8. Simulated τ_d versus μ_0.

it is shown in Fig. 7 that the coverage probability of the FL-CSBCD protocol is worse than that of the CBMD protocol, which is due to the fact that the constraint on the contentions of concurrent transmissions in the CMBD protocol is more stringent than that in the FL-CSBCD protocol. Finally, Fig. 8 shows that the SCDP of the FL-CSBCD is better than the CMBD protocol, which is because that ξ_f dominates the overall network performance in the region of interest.

6. Conclusion

This paper investigated a novel FL-CSBCD protocol to accommodate the transmission of multimedia files in fog-aided wireless networks via D2D communication. Particularly, the proposed FL-CSBCD protocol contains the file contention phase and the communication contention phase for data transmission. The file contention phase resolves the contentions among the requested multimedia files at each cache-enabled F-UEs, such that the cache-hit performance is maximized. The communication contention phase suppresses the collisions of the concurrent content deliveries of the same file, such that the mutual interference can be significantly reduced. By modeling the fog-aided wireless networks with Poisson point process, we captured the average transmission probability of F-UEs, and evaluate the SCDP of the fog-aided wireless networks with the proposed FL-CSBCD protocol. We showed by simulations that, compared with the CBMD protocol proposed in [20], the novel FL-CSBCD protocol can further enhance the network performance.

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Appendix A. Proof of Lemma 3.2

Proof. Let N_i be the number of C-UEs which request the ith file within a distance of R_d from a F-UE at $\mathbf{x}$. Then, under the FL-CSBCD protocol, the probability that the tagged F-UE at location $\mathbf{x}$ selects the fth file as the candidate file for data transmission is given by

$$\begin{aligned}\Pr\{N_f > N_1, \ldots, N_f > N_M\} &= \sum_{k_f=1}^{\infty} \Pr\{N_f = k_f\} \cdot \Pr\{k_f > N_1, \ldots, k_f > N_M\} \\ &= \sum_{k_f=1}^{\infty} \Pr\{N_f = k_f\} \cdot \prod_{i \neq f} \Pr\{k_f > N_i\} \\ &= \sum_{k_f=1}^{\infty} \frac{U_f^{k_f}}{k_f!} e^{-U_f} \cdot \prod_{i \neq f} \sum_{k_i=0}^{k_f} \frac{U_i^{k_i}}{k_i!} e^{-U_i}, \end{aligned} \tag{A.1}$$

where the $U_i = p_n \mu_0 \pi R_d^2$. □

Appendix B. Proof of Lemma 3.3

For an arbitrary F-UE in Ψ_f at $\mathbf{x}$, under Assumption 1, the successful competition probability ϑ_f under the FL-CSBCD protocol is given by

$$\begin{aligned}\vartheta_f &= \mathbb{E}\left[\prod_{i \in \Pi_f^{\mathbf{x}}} \Pr\left(b_i > t\right)\right] \\ &= \mathbb{E}_t\left[\exp\left\{-2\pi \int_0^{\infty} \Big(1 - \Pr(b_i > t)\Big) \lambda_f^{\mathbf{x}}(u) u du\right\}\right] \\ &= \mathbb{E}_t\left[e^{-2\pi t \int_0^{\infty} \lambda_f \cdot e^{-\frac{N_d u^{\alpha}}{P_d}} u du}\right] \\ &= \frac{1 - e^{-\pi \lambda_f \Gamma\left(1+\frac{2}{\alpha}\right)\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}}{\pi \lambda_f \Gamma\left(1 + \frac{2}{\alpha}\right)\left(\frac{N_d}{P_d}\right)^{-\frac{2}{\alpha}}}, \end{aligned} \tag{B.1}$$

where $\Pi_f^{\mathbf{x}}$ denotes the set of potential colliding F-UEs of $\mathbf{x}$, t and b_i are randomly generated back-off timers of $\mathbf{x}$ and the ith F-UE in $\Pi_f^{\mathbf{x}}$, $\lambda_f^{\mathbf{x}}(u)$ is the intensity of the potential colliding F-UEs of $\mathbf{x}$ at a distance of u,

$$\lambda_f^{\mathbf{x}}(u) = \lambda_f \cdot \Pr\left(\frac{P_d h}{u^\alpha} \geq N_d\right) = \lambda_f \cdot e^{-\frac{N_d u^\alpha}{P_d}}. \tag{B.2}$$

Appendix C. Proof of Lemma 4.4

Proof. The plane $\mathbb{R}^2$ is partitioned as illustrated in Fig. C.9a, where s_i^1 and s_i^2 are equal-sized squares with area denoted by $\triangle s$ and have the same distance to the perpendicular bisector $\mathcal{M}$ of the line between $\mathbf{C}$ and $\mathbf{F}$. Let r_i^1 denote the distance between s_i^1 and $\mathbf{F}$. Further, let r_i^2 denote the distance between s_i^2 and $\mathbf{F}$. Then, by symmetry, it can be easily verified from Fig. C.9b that the distance between s_i^2 and $\mathbf{C}$ is r_i^1, and the distance between s_i^2 and $\mathbf{C}$ is r_i^2

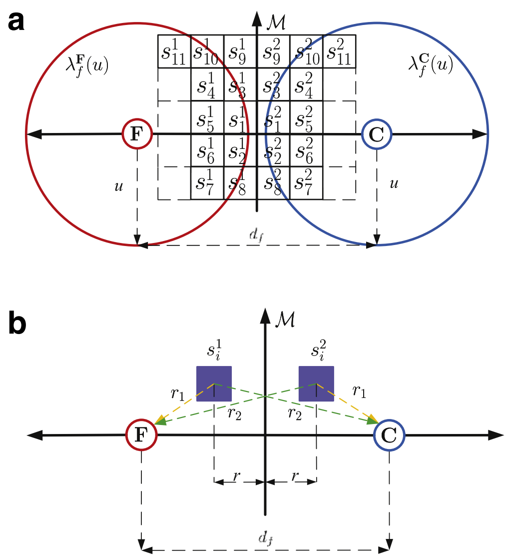

Fig. C.9. (a) Plane Partition; and (b) the aggregate pseudo interference.

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Let $P_{I(s_i^1,s_i^2)}(\mathbf{C})$ denote the aggregate pseudo interference[1] at $\mathbf{C}$ introduced by the active F-UEs of the fth file in the union of s_i^1 and s_i^2. Then, we have

$$\lim_{\Delta s \to 0} \mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{C})\right] = \lim_{\Delta s \to 0} \left(\frac{\lambda_f^{\mathbf{F}}(r_1)}{1 + \frac{r_2^\alpha}{\theta_d d_f^\alpha}} + \frac{\lambda_f^{\mathbf{F}}(r_2)}{1 + \frac{r_1^\alpha}{\theta_d d_f^\alpha}} \right) \times \Delta s, \tag{C.1}$$

where $\lambda_f^{\mathbf{F}}(r_2)$ and $\lambda_f^{\mathbf{F}}(r_1)$ denote the asymptotical density of the active F-UEs transmitting the fth file in s_i^1 and s_i^2, respectively.

Similarly, by denoting $P_{I(s_i^1,s_i^2)}(\mathbf{F})$ as the aggregate pseudo interference received at $\mathbf{F}$ from the active F-UEs transmitting the fth file in the union of s_i^1 and s_i^2, we have

$$\lim_{\Delta s \to 0} \mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{F})\right] = \lim_{\Delta s \to 0} \left(\frac{\lambda_f^{\mathbf{F}}(r_2)}{1 + \frac{r_2^\alpha}{\theta_d d_f^\alpha}} + \frac{\lambda_f^{\mathbf{F}}(r_1)}{1 + \frac{r_1^\alpha}{\theta_d d_f^\alpha}} \right) \times \Delta s. \tag{C.2}$$

[1] Please see [21] for the detailed definition of pseudo interference.

With (C.1) and (C.2), we obtain that

$$\lim_{\Delta s\to 0}\left(\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{C})\right]-\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{F})\right]\right)=\lim_{\Delta s\to 0}\left(\lambda_f^{\mathbf{F}}(r_2)-\lambda_f^{\mathbf{F}}(r_1)\right)\times\left(\frac{1}{1+\frac{r_1^\alpha}{\theta_d d_f^\alpha}}-\frac{1}{1+\frac{r_2^\alpha}{\theta_d d_f^\alpha}}\right)\times\Delta s\overset{(a)}{\geq}0, \tag{C.3}$$

where (a) follows from the fact that $r_1\leq r_2$.

It is worth noting that

$$\lim_{\Delta s\to 0}\sum_{i=1}^{\infty}\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{C})\right]=2\pi\int_0^\infty\frac{\lambda_f^{\mathbf{C}}(u)}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}u\mathrm{d}u, \tag{C. 4}$$

and

$$\lim_{\Delta s\to 0}\sum_{i=1}^{\infty}\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{F})\right]=2\pi\int_0^\infty\frac{\lambda_f^{\mathbf{F}}(u)}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}u\mathrm{d}u. \tag{C. 5}$$

Then, by noting that

$$\lim_{\Delta s\to 0}\sum_{i=1}^{\infty}\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{C})\right]-\lim_{\Delta s\to 0}\sum_{i=1}^{\infty}\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{F})\right]=\lim_{\Delta s\to 0}\sum_{i=1}^{\infty}\left(\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{C})\right]-\mathbb{E}\left[P_{I(s_i^1,s_i^2)}(\mathbf{F})\right]\right)\overset{(a)}{\geq}0, \tag{C.6}$$

where (a) follows from (C.3), we have

$$\int_0^\infty\frac{\lambda_f^{\mathbf{C}}(u)}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}u\mathrm{d}u\geq\int_0^\infty\frac{\lambda_f^{\mathbf{F}}(u)}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}u\mathrm{d}u.$$

The proof is then finished. □

Appendix D. Proof of Theorem 4.1

Proof. Based on the FL-CSBCD protocol, the respective SIR for the fth file at $\mathbf{C}$ is given by

$$\begin{aligned}\mathrm{SIR}_f&=\frac{P_d d_f^{-\alpha}h_0}{\sum_{i\in\Pi_a^f}P_d|\mathbf{X}_i|^{-\alpha}h_i+\sum_{j\in\bar{\Pi}_a^f}P_d|\mathbf{X}_j|^{-\alpha}h_j}\\&=\frac{d_f^{-\alpha}h_0}{\sum_{i\in\Pi_a^f}|\mathbf{X}_i|^{-\alpha}h_i+\sum_{j\in\bar{\Pi}_a^f}|\mathbf{X}_j|^{-\alpha}h_j}.\end{aligned} \tag{D.1}$$

Then, with Assumption 2, $\mathcal{C}_f$ is given by

$$\begin{aligned}\mathcal{C}_f&=\Pr(\mathrm{SIR}_f\geq\theta_d)\\&=\Pr\left(\frac{d_f^{-\alpha}h_0}{\sum_{i\in\bar{\Pi}_m^a(f)}|\mathbf{X}_i|^{-\alpha}h_i+\sum_{j\in\Pi_m^a(f)}|\mathbf{X}_j|^{-\alpha}h_j}\geq\theta_d\right)\\&=\mathbb{E}\left[\prod_{i\in\bar{\Pi}_m^a(f)}\exp\left\{-\frac{\theta_d|\mathbf{X}_i|^{-\alpha}h_i}{|d_f|^{-\alpha}}\right\}\cdot\prod_{j\in\Pi_m^a(f)}\exp\left\{-\frac{\theta_d|\mathbf{X}_j|^{-\alpha}h_j}{|d_f|^{-\alpha}}\right\}\right]\\&=\int_0^{R_d}\exp\left\{-2\pi\int_0^\infty\frac{\bar{\lambda}_f^{\mathbf{C}}(u)}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}u\mathrm{d}u\right\}\\&\quad\times\exp\left\{-2\pi\int_{d_f}^\infty\frac{\lambda_f^{\mathbf{C}}(u)}{1+\frac{u^\alpha}{\theta_d d_f^\alpha}}u\mathrm{d}u\right\}f_f(d_f)\mathrm{d}d_f,\end{aligned} \tag{D.2}$$

where the intensity of active F-UEs in Π_a^f and $\bar{\Pi}_a^f$ are given by $\lambda_f^{\mathbf{C}}(u)$ and $\bar{\lambda}_f^{\mathbf{C}}(u)$, respectively, and $f_f(d_f)$ denotes the PDF of the distance d_f as

$$f_f(d_f)=\frac{2\lambda_a^f c_f\pi d_f\cdot e^{-\lambda_a^f c_f\pi d_f^2}}{1-e^{-\lambda_a^f c_f\pi R_d^2}}. \tag{D.3}$$

It should be noted that

$$\tau_d=\sum_{f=1}^{F}p_f\cdot\xi_f\cdot\mathcal{C}_f, \tag{D.4}$$

where

$$\xi_f = 1 - e^{-\lambda_a^f c_f \pi R_d^2}. \tag{D.5}$$

Then, (24) and (25) can be immediately obtained by applying Lemmas 4.3–4.5 to (D.2), which thereby completes the proof. □

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ins.2019.05.036 .

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