Cooperative Full Duplex Content Sensing and Delivery Improves the Offloading Probability of D2D Caching

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***Abstract*—A novel policy is conceived for device-to-device (D2D) caching that facilitates content sensing and delivery using full duplex (FD) communications. As a benefit, the user devices become capable of performing content sensing and delivery over an extended geographic range, where more aggregate cache units are available, hence circumventing both the limited communication range and the limited storage of individual devices. Based on a stochastic geometry aided modeling of the network, we analytically derive the hit ratio, defined as the probability that a content requester (CR) can obtain desired file via a D2D link or an FD D2D link with data rate larger than a given threshold. The accuracy of our analysis is validated by our Monte Carlo simulations. Our numerical results show that the proposed policy achieves higher offloading probability than that of the existing approaches, even in the face of limited self-interference cancellation capability.**

***Index Terms*—Full duplex, stochastic geometry, D2D caching.**

I. Introduction

By combining files cached by user devices with short-range device-to-device (D2D) communications, wireless D2D caching has been shown to attain significant offloading gains in D2D networks [1]–[3]. However, a challenging issue in D2D caching is the limited communication range of the devices, affecting the two basic procedures involved in offloading, namely *content sensing* and *content delivery*. On the one hand, when a user device acts as a content requester (CR), discovery of the specific devices having the requested file cached is referred to as content sensing, constituting the prelude to the direct delivery of local files. Technically, due to the limited sensitivity of proximity discovery, only the content found within a certain geometric range can be sensed, even though a large virtual cache storage is provided by the D2D caching network. On the other hand, when a user device acts as a content provider (CP), content delivery is triggered whenever its files are requested and this request has been sensed. Generally, content delivery in D2D caching networks is restricted to single-hop links [4]–[6]. Nevertheless, direct transmissions of content are prone to hostile large scale fading when the CP is located at a distance, especially when the range of content sensing is extended. Essentially, the limited communication range of individual D2D devices limits the offloading performance achieved by D2D caching networks.

However, exploiting the full duplex (FD) functionality of sophisticated D2D nodes would alleviate the aforementioned issues. Driven by the recent progress in self-interference cancellation (SIC) techniques [7], FD transceivers are potentially capable of doubling the spectral efficiency by sending and receiving signals at the same time within the same frequency resources. In addition, the self interference (SI) at D2D nodes relying on FD transceivers may be deemed moderate due to the low transmit power required by their short communication distances [8]. However, with the aid of cooperative FD communications, a wider wireless network coverage is achievable [9]. By exploiting the listen-and-talk feature of FD communications, D2D discovery was shown to be accelerated [10]. Inspired by this, the FD functionality can be beneficially exploited by D2D caching systems for improving the proximity discovery of devices having the on-demand files cached. This considerable benefit has not been widely recognized. Besides, recent works have indicated the feasibility of employing FD techniques to improve the offloading throughput by cooperatively receiving data from several CPs [11] [12] or from the macro base station (MBS) [13], while simultaneously transmitting data to the requester. In [12], FD transmission is included when simultaneous requests occur inside a D2D pair. However, in these works, the FD functionality is solely applied during the content delivery procedure. The above-mentioned two benefits of incorporating the FD capability into a D2D caching system are promising, and there is a paucity of literature on their joint exploitation.

A. Related work

An excellent survey on data offloading can be found in [1], where the D2D caching is termed as data offloading

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through opportunistic mobile networks. In [2], D2D caching was shown to achieve a near-optimal throughput scaling law. A hierarchical bipartite method was proposed in [3] to guarantee having sufficient D2D links to support content downloading and repair. In [4], the authors studied probabilistic caching placement in a wireless D2D caching network with the objective of maximizing the cache hit probability or the cache-aided throughput. Chen *et al.* [5] investigated the joint optimization of caching and scheduling for maximizing the successful offloading probability. In [6], a hypergraph-based matching problem among CPs, CRs and cellular user resources was conceived to handle the overall transmission cost minimization problem in a D2D caching system. The authors also investigated the performance of a socially enabled multi-hop cooperative D2D caching system in [14]. Giatsoglou *et al.* [12] proposed a D2D caching policy for millimeter-wave networks and investigated its offloading gain. In [13], caching aided heterogeneous network supporting D2D communications was studied, where both the power allocation and caching placement were optimized jointly for maximizing the systems throughput. In this contribution, when a user fails to find the desired contents at other users/relays within the coverage range, the user can connect to the base station via an FD relay. In [15], the authors proposed a collaborative mechanism for motivating video streaming among multiple cache servers.

B. Our work

Against this background, we aim for designing a novel content access policy for D2D caching networks to facilitate both content sensing and delivery. Explicitly, when a CR fails to find the requested file in its vicinity, all UEs located within its proximity discovery range are permitted to perform cooperative sensing, hence these content items can be perceived within a larger area, thereby improving the success sensing probability (SSP). For the sensed CP having the on-demand file cached but located remotely, FD relaying aided transmission would be used for enhancing the performance of content delivery, thereby improving the success delivery probability (SDP). Hence, the improved SSP and SDP jointly increase the hit ratio of the caching system, which is the probability that a CR succeeds in sensing its desired file and in retrieving it with the data rate higher than a threshold. The main contributions of this paper are three-fold:

- Firstly, we propose a novel FD-aided content access policy for D2D caching networks, which intrinsically promotes offloading by improving the proximity discovery of on-demand files and enhancing the performance of content delivery.
- Secondly, we derive the hit ratio in closed form based on a stochastic geometry aided modeling of the network, and validate the accuracy of our derivations using Monte Carlo simulations.
- Thirdly, we demonstrate the improved offloading performance achieved by the proposed policy, demonstrating that exploiting the FD functionality benefits D2D caching systems, even in the face of limited SIC capability.

The rest of this paper is organized as follows. The system model is presented in Section II, and our proposed FD-aided content access policy is disclosed in Section III. The performance analysis is presented in Section IV. Numerical results and discussions are provided in Section V, followed by conclusions given in Section VI.

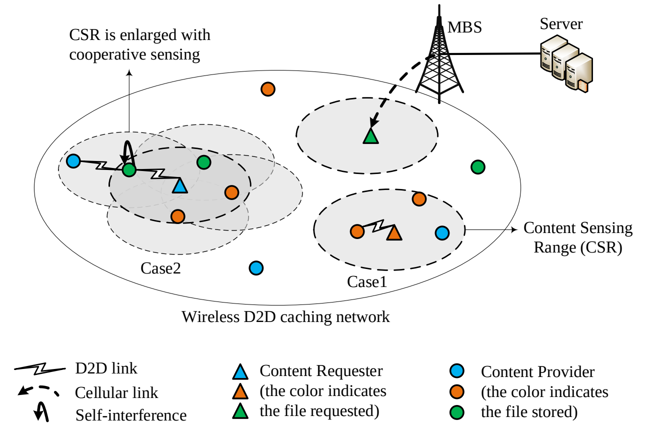

Fig. 1. An illustration of the considered scenario and the proposed content access policy.

II. System Model

As shown in Fig. 1, the scenario we considered contains an MBS over-sailing a wireless D2D caching network, including multiple user equipment (UE). Each UE is permitted to communicate with other devices in its proximity via D2D links, or with the MBS via cellular links. More particularly, the MBS is equipped with no cache, but it is connected to the core network via high-capacity backhaul links. By contrast, the UEs are deployed densely and their locations are modeled by a homogeneous Poisson Point Process (PPP) Φ_0 with intensity λ_0. Let us assume that a portion of $\delta \in (0,1)$ among the UEs is equipped with cache memories and serve as potential CPs, while the reminder of the UE-set acts as CRs. Hence, the distribution of CPs and CRs follow homogeneous PPPs with an intensity of $\delta\lambda_0 \triangleq \lambda_p$ and $(1-\delta)\,\lambda_0 \triangleq \lambda_r$, respectively.

The transmission power of each UE is P_t. All UEs are equipped with a single antenna. If necessary, the UEs are permitted to operate in their FD mode. For the large scale fading, we assume that the signal transmitted from the UE at a distance of r is attenuated by a factor of $r^{-\alpha}$, where α is the path loss exponent and $\alpha > 2$ is satisfied. For the small scale fading, a Rayleigh fading channel is assumed for an arbitrary pair of transmitter and receiver. Furthermore, each receiver experiences additive noise that obeys a zero-mean complex Gaussian distribution with variance σ_0^2.

Let $\mathcal{F} \triangleq \{1, 2, \cdots, F\}$ denote the set of F files in the content library, with the most popular one being the 1-st file and the least popular one as the F-th file. More explicitly, the popularity of content files can be modeled as a Zipf distribution and the f-th file is requested by UEs with a probability of $p_f = \frac{f^{-\varepsilon}}{\sum_{i=1}^{F} i^{-\varepsilon}}$, where ε is a shape parameter of the Zipf distribution. For simplicity, we assume that all files have an identical size, which is also identical to the size of each cache unit. Given the limited storage of the wireless terminals, we assume that the number of cache units in each CP is N and $N \ll F$. We consider a geographic caching strategy, which has been widely considered both in the context of D2D caching [4] [5] [13] and in small cell caching [16]. Specifically, each CP independently selects some files to cache according to a specific probability vector $\mathbf{q} = \{q_1, \cdots, q_f, \cdots, q_F\}$, where q_f is the probability that a CP caches the f-th file, and $\sum_{f=1}^{F} q_f \leq N$ is predefined due to the storage limit. According to the thinning property of [17], the location of CPs having the f-th file cached obeys a homogeneous PPP with density $q_f \lambda_p$.

III. Full Duplex Aided Content Access Policy

This section articulates the proposed content access policy. In the D2D caching network, each CR randomly and independently requests a file $f \in \mathcal{F}$ by sending a file-request message. Due to the finite sensitivity of the receiver, each CR can only sense the availability of the desired content within a certain content sensing range (CSR), which is depicted in Fig. 1. When a CR requests a file from the content library $\mathcal{F}$, as shown in Fig. 1, the FD-aided content access policy we conceived includes a pair of cases:

- **Case 1**: By sending a file-request message, a CR may spot the requested content at a nearby CP within its CSR. If there is more than one CP having the requested file cached, the CR will fetch the content from the nearest one via a D2D link.
- **Case 2**: When the requested file is unavailable within the CSR of a CR, a request message will be broadcast by the CR in order to ask the UEs located within its CSR for cooperative sensing. Upon receiving the request message, all UEs within the CSR will broadcast the file-request message, in the hope of finding the requested content within the respective CSRs. Once the file is found, one of the UEs located within the CR's CSR will be selected to serve as an FD relay for fetching the content via an FD D2D link [9].

When both cases fail, as shown in Fig. 1, the requested content is downloaded from the core network to the MBS via the backhaul and then transmitted to the CR. By exploiting the above policy, the range of content sensing is extended with the aid of FD cooperative sensing. Meanwhile, FD relaying is activated for enhancing the delivery performance of remote CPs. In a nutshell, the FD functionality jointly enhances both procedures in offloading.

Here we assume that the transmissions in both of the two cases are operated under the coverage of cellular networks, which are illuminated by oversailing MBSs. We consider a non-overlapping bandwidth allocation for the pair of cases. Specifying the total available bandwidth assigned for the D2D caching network as W_0, the portion of $w_1 = \theta \mathrm{W}_0$ and $w_2 = (1-\theta)\,\mathrm{W}_0$ are exclusively assigned to Case 1 and Case 2, respectively, where $0 < \theta < 1$ is the bandwidth sharing factor.

IV. Performance Analysis

In this section, we investigate the overall performance of the D2D caching network. To this end, we choose the hit ratio as our main metric, which is defined as the probability that a CR succeeds in finding its requested file within the local caching system and in retrieving it at a data rate higher than the threshold R_0. Specifically, the overall hit ratio of the considered caching network can be written as

$$\rho = \sum_{f=1}^{F} p_f \left(S_{1,f} D_{1,f} + S_{2,f} D_{2,f}\right), \tag{1}$$

where $S_{k,f}$ ($k = 1$ or 2) denotes the probability that a CR finds its requested file f via Case k, which is the SSP of Case k when requesting file f exactly. Furthermore, $D_{k,f} \triangleq \Pr\left(R_{k,f} \geq R_0\right)$ denotes the probability that, after hitting the requested file f via Case k, a CR receives its desired file at a transmission rate $R_{k,f}$ higher than the threshold R_0. Explicitly, $D_{k,f}$ is the SDP of Case k when delivering file f. Clearly, hit ratio is jointly determined by SSP, SDP, and the content placement, whilst the bandwidth allocation determines the efficiency of content delivery. Hence, the overall offloading performance of the considered system would be significantly affected.

In the following, we derive hit ratio in closed form by formulating SSP and SDP, one after the other. For ease of analysis, we consider a CR located at the origin of the coordinate system as a typical CR. According to Slivnyak's theorem [18], we are allowed to carry out our analysis with respect to the overall offloading performance from the perspective of a typical CR.

A. Success Sensing Probability (SSP)

Again, SSP is the probability of a CR finding its requested file within the distributed caching system, either in a D2D or FD scenario.

1) **Case 1**: Assume that the typical CR requests file f. Since the location of CPs having the f-th file cached obeys a homogeneous PPP with density $q_f \lambda_p$, the probability density function (PDF) of the distance r_{0f} between the typical CR and the closest CP who caches the content f, is $f_{r_{0f}}(r) = 2\pi q_f \lambda_p r e^{-\pi q_f \lambda_p r^2}$ [18].

Observe that the SSP of Case 1 is given by the probability that the typical CR finds its target stored by the devices located within its CSR. Let s_0 indicate the radius of CSR. Hence, the SSP of Case 1 with file f being requested is

$$S_{1,f} = \int_0^{s_0} f_{r_{0f}}(r) \mathrm{d}r = 1 - \exp\left(-\pi q_f \lambda_p {s_0}^2\right). \tag{2}$$

Then the SSP of Case 1 is obtained as $S_1 = \sum_{f=1}^{F} p_f S_{1,f}$.

2) **Case 2**: In Case 2, in addition to being located within the CSR of the typical CR, at least one UE (CP or CR) can also sense the serving CP (termed CP_0). We refer to this relationship of the UEs as being *qualified*. If there is no qualified UE, the nearest CP having the requested file cached would be too far to be sensed, even upon invoking cooperation. The shaded region $\mathcal{S}$ of Fig. 2 represents the location range

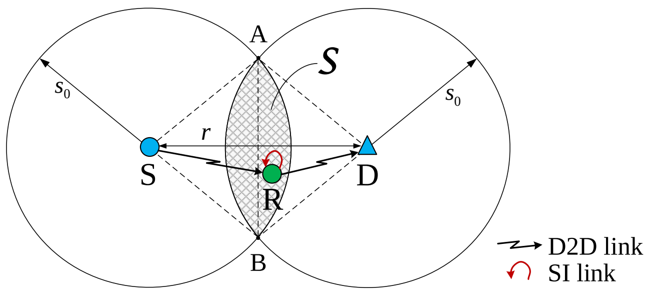

Fig. 2. A geometric illustration of Case 2, where S, R, and D indicates the serving CP, the selected FD relay, and the typical CR, respectively. The radius of the CSR is s_0. The shaded region implies the locations of all qualified UEs.

of all qualified UEs, where one of them is depicted as an example. The SSP of Case 2 with file f being requested is

$$S_{2,f} = \int_{s_0}^{2s_0} \left(1 - e^{-\lambda_0 |\mathcal{S}|}\right) f_{r_{0f}}(r)\mathrm{d}r, \tag{3}$$

where $|\mathcal{S}|$ indicates the area of region $\mathcal{S}$. Observing Fig. 2, $|\mathcal{S}|$ can be expressed as

$$\begin{aligned} |\mathcal{S}| &= \left(S_{\widehat{ABD}} - S_{\Delta ABD}\right) + \left(S_{\widehat{ABS}} - S_{\Delta ABS}\right) \\ &= 2{s_0}^2 \arccos\left(\frac{r}{2s_0}\right) - \frac{1}{2}r\sqrt{4{s_0}^2 - r^2}. \end{aligned} \tag{4}$$

Hence we obtain the SSP of Case 2 as $S_2 = \sum_{f=1}^{F} p_f S_{2,f}$. Finally, the overall SSP is $S = S_1 + S_2$.

B. Success Delivery Probability (SDP)

For the SDP $D_{k,f} \triangleq \Pr\left(R_{k,f} \geq R_0\right)$, it can be equivalently written as $\Pr\left(\gamma_{k,f} \geq \gamma_k\right)$. Here the transmission rate $R_{k,f}$ is given by $R_{k,f} = w_k \log_2\left(1 + \gamma_{k,f}\right)$, with $\gamma_{k,f}$ indicating the signal-to-interference-and-noise ratio (SINR) at the receiver of the typical CR, and $2^{R_0/w_k} - 1 \triangleq \gamma_k$ representing the equivalent SINR requirement related to Case k. Note that when multiple CRs are associated with the same CP via the same case, the CP would serve these CRs orthogonally. Let us consider a discrete-time system with the time being slotted equally and study a single slot of the network. Each file is transmitted in one slot. Below we will analyze the SDP for each case.

1) **Case 1***:* Specifically, the SINR at the typical CR receiver is given by $\gamma_{1,f} = \frac{P_t g_{0f} r_{0f}^{-\alpha}}{I_1 + N_0 w_1}$. Here g_{0f} denotes the channel gain between the serving CP and the typical CR, while I_1 is the interference inflicted by the active CPs that are also involved with Case 1, whose locations can be modeled by a homogeneous PPP Φ_1 with the intensity of $\lambda_r S_1$. The term $N_0 w_1$ denotes the noise power at the receiver, with N_0 indicating the noise power density. Further, we formulate the conditional SDP $\Pr\left(\gamma_{1,f} \geq \gamma_1 \left| r_{0f}\right.\right)$ as

$$\begin{aligned} &\Pr\left(\gamma_{1,f} \geq \gamma_1 \left| r_{0f}\right.\right) = \Pr\left(\frac{P_t g_{0f} r_{0f}^{-\alpha}}{I_1 + N_0 w_1} \geq \gamma_1 \left| r_{0f}\right.\right) \\ &\overset{(a)}{\approx} \Pr\left(g_{0f} \geq P_t^{-1} r_{0f}^{-\alpha} I_1 \gamma_1\right) \overset{(b)}{=} \mathbb{E}_{I_1}\left[e^{-P_t^{-1} r_{0f}^{\alpha} I_1 \gamma_1}\right] \\ &\overset{(c)}{=} \mathcal{L}_{I_1}\left(P_t^{-1} r_{0f}^{\alpha} \gamma_1\right), \end{aligned} \tag{5}$$

where step (a) is due to the consideration of an interference-limited region, step (b) is consistent with the small scale fading model of $g_{0f} \sim \exp(1)$, and step (c) represents the Laplace transform of the random variable I_1. More specifically, we have $I_1 = \sum_{i \in \Phi_1 \backslash \mathrm{CP}_0} P_t g_i r_i^{-\alpha}$, where g_i is the gain of the interference channel spanning from the i-th active CP involved with Case 1 to the typical CR, and r_i denotes the corresponding distance. The Laplace transform of I_1 is given by

$$\begin{aligned} \mathcal{L}_{I_1}(s) &= \mathbb{E}_{\Phi_1, g_i}\left[e^{-s\sum_{i \in \Phi_1 \backslash \mathrm{CP}_0} P_t g_i r_i^{-\alpha}}\right] \\ &= \mathbb{E}_{\Phi_1}\left[\prod_{i \in \Phi_1 \backslash \mathrm{CP}_0} \left(1 + sP_t r_i^{-\alpha}\right)^{-1}\right] \\ &= \exp\left\{-2\pi\lambda_r S\int_0^{\infty}\left(1 - \frac{1}{1 + sP_k x^{-\alpha}}\right) x\mathrm{d}x\right\} \\ &\overset{(a)}{=} \exp\left\{-2\pi^2\lambda_r S_1 (sP_t)^{\frac{2}{\alpha}} \csc\left(\frac{2\pi}{\alpha}\right)\alpha^{-1}\right\}, \end{aligned} \tag{6}$$

where step (a) is obtained from [19, Eq. 3.194.4]. By substituting $s = P_t^{-1} r_{0f}^{\alpha} \gamma_1$ into (6), we arrive at:

$$\mathcal{L}_{I_1}\left(P_t^{-1} r_{0f}^{\alpha} \gamma_1\right) = \exp\left\{-2\pi^2 \lambda_r S_1 \gamma_1^{2/\alpha} \csc\left(2\pi\alpha^{-1}\right)\alpha^{-1} r_{0f}^2\right\}. \tag{7}$$

Therefore, the SDP of Case 1 when delivering file f is

$$\begin{aligned} D_{1,f} &= \mathbb{E}_{r_{0f}}\left[\Pr\left(\gamma_{1,f} \geq \gamma_1 \left| r_{0f}\right.\right)\right] \\ &= 2\pi q_f \lambda_p \int_0^{s_0} \exp\left(-Ar^2\right) r dr \\ &\overset{(a)}{=} \frac{\pi q_f \lambda_p}{S_{1,f}} A^{-1}\left(1 - e^{-A{s_0}^2}\right), \end{aligned} \tag{8}$$

where $A = 2\pi^2 \lambda_r S_1 \gamma_1^{2/\alpha} \csc\left(2\pi\alpha^{-1}\right)\alpha^{-1} + \pi q_f \lambda_p$ is defined, and step (a) is obtained from [19, Eq. (3.326.2)].

2) **Case 2***:* We use the subscripts SR and RD to distinguish the first and the second stage of the cooperative transmission in Case 2, namely the source-relay and relay-destination links. As mentioned above, all the qualified UEs must be located in $\mathcal{S}$. Generally, there may exist multiple qualified UEs and one of them should be selected. For simplicity, we denote the selected UE as R_0 and the classic decode-and-forward (DF) protocol is applied. Hence the SINR at the typical CR receiver is $\gamma_{2,f} = \min\left(\gamma_{\mathrm{SR},f}, \gamma_{\mathrm{RD},f}\right)$, where $\gamma_{\mathrm{SR},f}$ and $\gamma_{\mathrm{RD},f}$ indicate the SINR of the first and second stage receivers, respectively. For ease of analysis, the locations of all active CPs and selected UEs involved with Case 2 are modeled by a homogeneous PPP Φ_2 with the intensity of $2\lambda_r S_2$. Notice that Φ_2 is non-overlapping with Φ_1 due to the orthogonal bandwidth allocation between Case 1 and Case 2.

For the first stage, the receiver's SINR is $\gamma_{\mathrm{SR},f} = \frac{P_t g_{\mathrm{SR}} r_{\mathrm{SR},f}^{-\alpha}}{I_{\mathrm{SR}} + g_{\mathrm{SI}} P_t + N_0 w_2}$, where g_{SR} is the channel gain between the serving CP and the selected UE, and g_{SI} specifies the channel gain of the SI link after applying SIC, with $g_{\mathrm{SI}} \sim \exp\left(1/\sigma_{\mathrm{SI}}^2\right)$ assumed and $1/\sigma_{\mathrm{SI}}^2$ corresponding to the SIC capability. For example, $\sigma_{\mathrm{SI}}^2 = -70$ dB indicates that the power of SI can be suppressed 70 dB on average after applying SIC. Furthermore, I_{SR} represents the power of the interference received at R_0 with $I_{\mathrm{SR}} = \sum_{i \in \Phi_2 \backslash \mathrm{CP}_0 \& \mathrm{R}_0} P_t g_{\mathrm{SR},i} r_{\mathrm{SR},i}^{-\alpha}$ defined, and $g_{\mathrm{SR},i}$ is the gain of the channel spanning from the i-th active node in Φ_2 to R_0, with $g_{\mathrm{SR},i} \sim \exp(1)$ assumed. Finally, $r_{\mathrm{SR},i}$ is the related distance. Specifically, the conditional SDP

$\Pr\left(\gamma_{\mathrm{SR},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right)$ is formulated as

$$\begin{aligned}
&\Pr\left(\gamma_{\mathrm{SR},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right) = \Pr\left(\frac{P_t g_{\mathrm{SR}} r_{\mathrm{SR},f}^{-\alpha}}{I_{\mathrm{SR}} + g_{\mathrm{SI}} P_t + N_0 w_2} \geq \gamma_2\right) \\
&\overset{(a)}{\approx} \Pr\left(g_{\mathrm{SR}} - r_{\mathrm{SR},f}^{\alpha}\gamma_2 g_{\mathrm{SI}} \geq {P_t}^{-1} r_{\mathrm{SR},f}^{\alpha}\gamma_2 I_{\mathrm{SR}}\right) \\
&\overset{(b)}{=} \mathbb{E}_{I_{\mathrm{SR}}}\left[\frac{1}{1+\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\exp\left(-P_t^{-1} r_{\mathrm{SR},f}^{\alpha}\gamma_2 I_{\mathrm{SR}}\right)\right] \\
&= \frac{1}{1+\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\mathcal{L}_{I_{\mathrm{SR}}}\left({P_t}^{-1} r_{\mathrm{SR},f}^{\alpha}\gamma_2\right),
\end{aligned} \tag{9}$$

where step (a) is valid due to the interference-limited consideration of the dense deployment of UEs, and step (b) is from the distribution of the composite random variable $Z \triangleq g_{\mathrm{SR}} + X$ with $X \triangleq -r_{\mathrm{SR},f}^{\alpha}\gamma_2 g_{\mathrm{SI}}$. The following remark gives the derivation of step (b).

Remark 1: As $g_{\mathrm{SR},f} \sim \exp(1)$ and $g_{\mathrm{SI}} \sim \exp\left(\frac{1}{\sigma_{\mathrm{SI}}^2}\right)$ are predefined, the cumulative distribution function (CDF) of the random variable X can be expressed as

$$\begin{aligned}
&F_X(x) = \Pr\left(-r_{\mathrm{SR},f}^{\alpha}\gamma_2 g_{\mathrm{SI}} \leq x\right) \\
&= \Pr\left(g_{\mathrm{SI}} \geq -\frac{x}{r_{\mathrm{SR},f}^{\alpha}\gamma_2}\right) = 1 - \Pr\left(g_{\mathrm{SI}} \leq -\frac{x}{r_{\mathrm{SR},f}^{\alpha}\gamma_2}\right) \\
&= \begin{cases} 1, & if\ x \geq 0 \\ \exp\left(\frac{x}{\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\right), & if\ x < 0 \end{cases}.
\end{aligned} \tag{10}$$

Consequently, the PDF of X is obtained as

$$f_X(x) = \begin{cases} 0, & if\ x \geq 0 \\ \frac{1}{\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\exp\left(\frac{x}{\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\right), & if\ x < 0 \end{cases}. \tag{11}$$

Accordingly, the PDF of the random variable Z is

$$\begin{aligned}
&f_Z(z) = \int_{-\infty}^{\infty} f_{g_{\mathrm{SR}}}(z-x) f_X(x)\mathrm{d}x \\
&= \begin{cases} \frac{1}{1+\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\exp(-z), & if\ z \geq 0 \\ \frac{1}{1+\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\exp\left(\frac{z}{\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\right), & if\ z < 0 \end{cases}.
\end{aligned} \tag{12}$$

Hence we obtain

$$\begin{aligned}
&\Pr\left(Z \geq P_t^{-1} r_{\mathrm{SR},f}^{\alpha}\gamma_2 I_{\mathrm{SR}}\right) \\
&= \frac{1}{1+\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\exp\left(-P_t^{-1} r_{\mathrm{SR},f}^{\alpha}\gamma_2 I_{\mathrm{SR}}\right),
\end{aligned} \tag{13}$$

which is in line with step (b) in (9).

In (9), the Laplace transform of I_{SR} can be further reformulated as

$$\begin{aligned}
&\mathcal{L}_{I_{\mathrm{SR}}}(s) = \mathbb{E}_{\Phi_2, g_{\mathrm{SR},i}}\left[e^{-s\sum_{i\in\Phi_2\backslash \mathrm{CP}_0 \& \mathrm{R}_0} P_t g_{\mathrm{SR},i} r_{\mathrm{SR},i}^{-\alpha}}\right] \\
&= \mathbb{E}_{\Phi_2}\left[\prod_{i\in\Phi_2\backslash \mathrm{CP}_0 \& \mathrm{R}_0}\left(1 + sP_t r_{\mathrm{SR},i}^{-\alpha}\right)^{-1}\right] \\
&= \exp\left\{-4\pi\lambda_r S_2 \int_0^{\infty}\left(1 - \frac{1}{1+sP_t x^{-\alpha}}\right) x\mathrm{d}x\right\} \\
&= \exp\left\{-4\pi^2\lambda_r S_2 (sP_t)^{2/\alpha}\csc\left(\frac{2\pi}{\alpha}\right)\alpha^{-1}\right\}.
\end{aligned} \tag{14}$$

Thus, the conditional SDP for the first stage becomes

$$\begin{aligned}
&\Pr\left(\gamma_{\mathrm{SR},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right) = \\
&\frac{1}{1+\sigma_{\mathrm{SI}}^2 r_{\mathrm{SR},f}^{\alpha}\gamma_2}\exp\left\{-4\pi^2\lambda_r S_2 {\gamma_2}^{2/\alpha}\csc\left(2\pi\alpha^{-1}\right)\alpha^{-1} r_{\mathrm{SR},f}^2\right\}.
\end{aligned} \tag{15}$$

For the second stage, the receiver's SINR is $\gamma_{\mathrm{RD},f} = \frac{P_t g_{\mathrm{RD}} r_{\mathrm{RD},f}^{-\alpha}}{I_{\mathrm{RD}} + N_0 w_2}$, where g_{RD} is the channel gain between the UE selected and the typical CR, I_{RD} represents the power of interference received at the typical CR with $I_{\mathrm{RD}} = \sum_{i\in\Phi_2\backslash \mathrm{CP}_0 \& \mathrm{R}_0} P_t g_{\mathrm{RD},i} r_{\mathrm{RD},i}^{-\alpha}$ defined, $g_{\mathrm{RD},i}$ is the channel gain between the i-th active node in Φ_2 and the typical CR, and $r_{\mathrm{RD},i}$ is the corresponding distance. Then the conditional SDP $\Pr\left(\gamma_{\mathrm{RD},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right)$ is formulated as

$$\begin{aligned}
&\Pr\left(\gamma_{\mathrm{RD},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right) = \Pr\left(\frac{P_t g_{\mathrm{RD}} r_{\mathrm{RD},f}^{-\alpha}}{I_{\mathrm{RD}} + N_0 w_2} \geq \gamma_2\right) \\
&\approx \Pr\left(g_{\mathrm{RD}} \geq {P_t}^{-1} r_{\mathrm{RD},f}^{\alpha}\gamma_2 I_{\mathrm{RD}}\right) \\
&= \mathbb{E}_{I_{\mathrm{RD}}}\left[\exp\left(-P_t^{-1} r_{\mathrm{RD},f}^{\alpha}\gamma_2 I_{\mathrm{RD}}\right)\right] \\
&= \mathcal{L}_{I_{\mathrm{RD}}}\left({P_t}^{-1} r_{\mathrm{RD},f}^{\alpha}\gamma_2\right),
\end{aligned} \tag{16}$$

where the Laplace transform of I_{RD} is given by

$$\begin{aligned}
&\mathcal{L}_{I_{\mathrm{RD}}}(s) = \mathbb{E}_{\Phi_2, g_{\mathrm{RD},i}}\left[e^{-s\sum_{i\in\Phi_2\backslash \mathrm{CP}_0 \& \mathrm{R}_0} P_t g_{\mathrm{RD},i} r_{\mathrm{RD},i}^{-\alpha}}\right] \\
&= \mathbb{E}_{\Phi_2}\left[\prod_{i\in\Phi_2\backslash \mathrm{CP}_0 \& \mathrm{R}_0}\left(1 + sP_t r_{\mathrm{RD},i}^{-\alpha}\right)^{-1}\right] \\
&= \exp\left\{-4\pi\lambda_r S_2 \int_0^{\infty}\left(1 - \frac{1}{1+sP_t x^{-\alpha}}\right) x\mathrm{d}x\right\} \\
&= \exp\left\{-4\pi^2\lambda_r S_2 (sP_t)^{2/\alpha}\csc\left(\frac{2\pi}{\alpha}\right)\alpha^{-1}\right\}.
\end{aligned} \tag{17}$$

Hence, we have the conditional SDP for the second stage as follows

$$\begin{aligned}
&\Pr\left(\gamma_{\mathrm{RD},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right) = \\
&\exp\left\{-4\pi^2\lambda_r S_2 {\gamma_2}^{2/\alpha}\csc\left(2\pi\alpha^{-1}\right)\alpha^{-1} r_{\mathrm{RD},f}^2\right\}.
\end{aligned} \tag{18}$$

When multiple qualified UEs exist, a specific one should be selected. For the DF relaying protocol, a popular optimization criterion is the maximization of the end-to-end signal-to-noise ratio (SNR) [20], which becomes an SINR-based selection in the presence of interferers. However, when both the relay and interferer locations obey a PPP, a closed-form analysis of above optimization criterion becomes intractable [21], since a closed-form expression for the interference distribution only exists for specific path loss exponents under specific network dimensions. Therefore, we opt for considering the performance of a tractable worst case scenario. More specifically, the selected UE is located farthest both from the serving CP and from the typical CR at the same time, indicating that $r_{\mathrm{SR},f} = s_0$ and $r_{\mathrm{RD},f} = s_0$. This is indeed the worst possible option for a location-based relay selection scheme aiming for maximizing the minimum of the source-relay distance and relay-destination distance. Based on this selection criterion, the relay selected is geographically located within the region $\mathcal{S}$ in Fig. 2, while the selected UE considered in our analysis should be located at point A or B. Under this consideration, the SDP of Case 2 when delivering file f is given by

$$\begin{aligned}
&D_{2,f} = \mathbb{E}_{r_{\mathrm{SD},f}}\left[\Pr\left(\gamma_{2,f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right)\right] \\
&= \mathbb{E}_{r_{\mathrm{SD},f}}\left[\Pr\left(\gamma_{\mathrm{SR},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right)\Pr\left(\gamma_{\mathrm{RD},f} \geq \gamma_2 \left| r_{\mathrm{SD},f} \right.\right)\right] \\
&\overset{(a)}{=} \frac{e^{-B{s_0}^2}}{1+\sigma_{\mathrm{SI}}^2 s_0^2\gamma_2},
\end{aligned} \tag{19}$$

where step (a) is obtained by considering $r_{\mathrm{SR},f} = r_{\mathrm{RD},f} = s_0$, and $B = 8\pi^2\lambda_r S_2 {\gamma_2}^{2/\alpha}\csc\left(2\pi\alpha^{-1}\right)\alpha^{-1}$ is defined.

Finally, substituting (2), (3), (8) and (19) into (1), we express the hit ratio of the overall caching system in closed form as

$$\begin{aligned}
\rho = \sum_{f=1}^{F} p_f \pi q_f \lambda_p &\left(\frac{1-e^{-A{s_0}^2}}{A}\right. \\
&\left.+ \frac{e^{-B{s_0}^2}}{1+\sigma_{\mathrm{SI}}^2 s_0^2\gamma_2}\int_{s_0}^{2s_0}\left(1 - e^{-\lambda_0|\mathcal{S}|}\right) 2re^{-\pi q_f\lambda_p r^2}\mathrm{d}r\right).
\end{aligned} \tag{20}$$

V. Numerical and Simulation Results

For our numerical evaluations, unless otherwise stated, the baseline setting of simulation environments is as follows. The intensity of UEs in the network is $\lambda_0 = 10^3\ nodes/\text{km}^2$, and the factor dividing CRs and CPs equals to $\delta = 0.5$. The path loss exponent is $\alpha = 3.7$, the total bandwidth assigned for the D2D caching network is $\text{W}_0 = 20$ MHz, and the bandwidth sharing factor is fixed at $\theta = 0.2$. The transmission power of UEs is set to $P_t = 23$ dBm, the SIC capability of each UE is set to $1/\sigma_{\text{SI}}^2 = 70$ dB, and the radius of CSR is fixed as $s_0 = 50$ m. We consider a file library consisting of $F = 50$ files, and each CP can store $N = 5$ files. The Zipf exponent of the file popularity distribution is set to $\epsilon = 0.7$. The rate threshold of UEs receiving the target content is fixed at $R_0 = 100$ Kbps. A pair of content placement strategies are considered, namely the file popularity based random caching (FPRC), where the caching probability is proportional to the file popularity; and the uniform random caching (URC), where the caching probability is the same for all files. For Monte Carlo simulations, we consider a $2\ \text{km} \times 2\ \text{km}$ square area, and the noise power density is set to be $N_0 = -174\ \text{dBm/Hz}$. All simulation results are obtained by performing 10^4 Monte Carlo trials. In our simulations, the relay is selected based on the criterion of maximizing the minimum of the source-relay distance and relay-destination distance.

Figure 3 shows both the numerical and simulation results for SSP as well as for hit ratio with respect to the Zipf exponent ϵ. In specific, we denote $\rho_k \triangleq \sum_{f=1}^{F} p_f S_{k,f} D_{k,f}$ as the hit ratio contributed by Case k ($k = 1$ or 2), and $\rho_1 + \rho_2 = \rho$. In Fig. 3, the numerical results of SSP exactly match the simulation results. As for hit ratio, the numerical lines are slightly below the simulation based curves, since a relay at the maximum distance from both the source and from the destination (i.e., point A or B in Fig. 2) is considered in our derivations, while the relay selected in the simulations is geographically located within the region $\mathcal{S}$ shown in Fig. 2 but it is not necessarily located at point A or B. We also observe that when the file catalogue becomes more skewed because ϵ increases, the performance gains attained by Case 2 are reduced, since the contents tend to become available within a relatively smaller range.

In Fig. 4, we investigate the impact of the SIC capability on the proposed policy. Here a half-duplex (HD) based policy is considered, where the content sensing and delivery rely on HD cooperation. Furthermore, a non-relaying (nonR) policy is also considered, which is essentially same to that in [4] and [5]. The effects of self offloading are not included here. As shown in Fig. 4, the proposed policy outperforms the benchmarks even for a moderate SIC capability. However, when the SIC capability becomes low, the proposed policy is outperformed by its HD counterpart, but it maintains its superiority over the nonR regime. Note that keeping the SIC capability above 20 dB is indeed feasible for FD devices [7]. Moreover, the proposed policy associated with the URC strategy is much degraded. It becomes even worse than its HD counterpart using the FPRC strategy. Hence, it is crucial to carefully formulate the content placement in order to reap the benefit of the FD functionality.

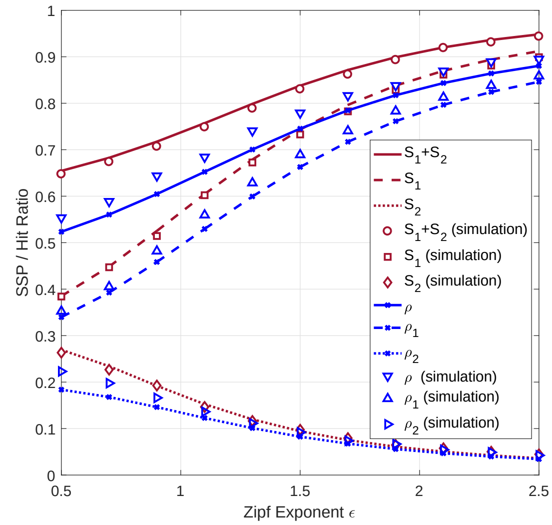

Fig. 3. Impact of Zipf exponent ϵ on the SSP and on the hit ratio achieved by the proposed policy associated with the FPRC strategy.

Figure 5 shows the overall hit ratio of the proposed policy for different CSR radius s_0. It is shown that hit ratio first increases for both cases and then declines upon increasing s_0. This observation can be explained as follows. The value of s_0 corresponds to the content sensing capability at the individual devices. When s_0 is too small, even though the content within an extended range can be perceived by invoking our policy, the SSP is still moderate, hence leading to a low hit ratio. By contrast, when s_0 is fixed at a pretty large value, although more CRs become capable of sensing and fetching the content via direct links, they are prone to hostile large scale fading, hence degrading the performance of content delivery.

Finally, Fig. 6 compares the results of the proposed policy to that of a nonR policy with respect to the storage capacity N. Clearly, the hit ratio of the two schemes has been remarkably improved upon increasing of N. Although our policy outperforms the benchmarks, the performance gap shrinks gradually as the storage capacity is increased.

VI. Conclusions

A novel D2D caching policy has been proposed for joint cooperative content sensing and delivery by exploiting FD communications. Based on the stochastic geometry aided modeling of the network, we have derived hit ratio in closed form, which jointly considers the impact of both the SSP and of the SDP. The accuracy of our analysis has been validated by Monte Carlo simulations. Our numerical results have shown that the proposed policy achieves a higher offloading success ratio than the existing approaches, even in the face of a moderate SIC capability. Furthermore, the offloading performance of the proposed policy can be potentially further improved by carefully setting the radius of CSR, which is directly related to the transmit power of D2D nodes.

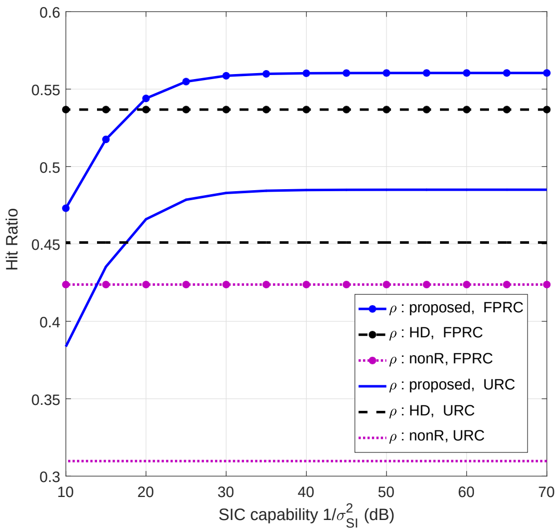

Fig. 4. Impact of SIC capability $1/\sigma^2_{\mathrm{SI}}$ on hit ratio with different policies.

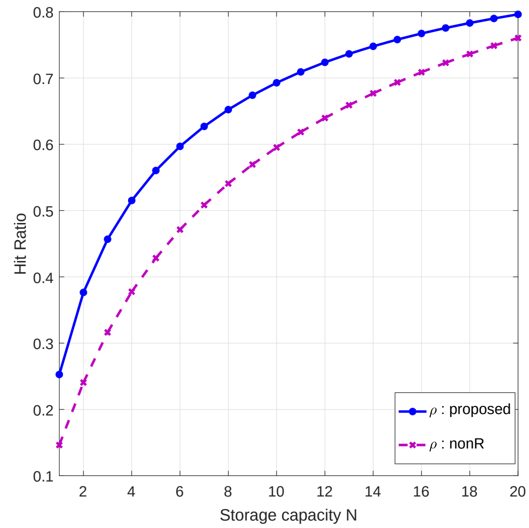

Fig. 6. Impact of storage capacity N on hit ratio, where $s_0 = 50$ m and FPRC strategy is applied.

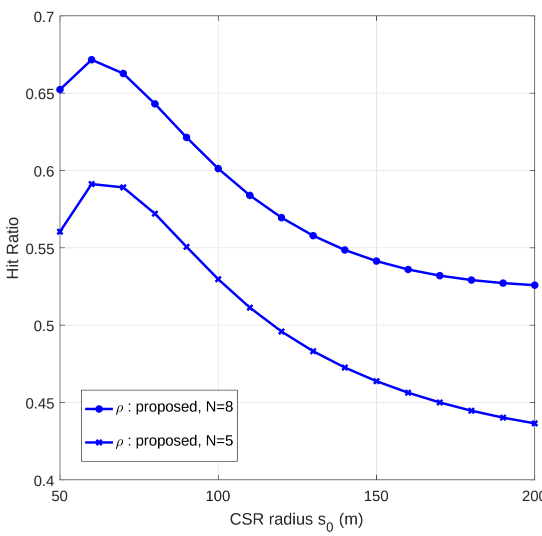

Fig. 5. Impact of CSR radius s_0 on hit ratio where FPRC strategy is applied.

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