Hybrid Wireless Edge Caching for Relaying with Spatial Randomness

Eleni Demarchou, Constantinos Psomas, and Ioannis Krikidis
KIOS Research Center for Intelligent Systems and Networks
Department of Electrical and Computer Engineering, University of Cyprus, Cyprus
e-mail: {edemar01, psomas, krikidis}@ucy.ac.cy

***Abstract*—This paper employs wireless edge caching at relay nodes and proposes a cooperative hybrid caching placement scheme. The trade-off between the conventional caching schemes of most popular content (MPC) and largest content diversity (LCD) is investigated considering two degrees of flexibility. Specifically, we consider two design variables i.e, the number of relays employing the MPC scheme as well as the percentage of the storage dedicated to MPC. The caching policy is studied by considering spatially random relays and by using tools from stochastic geometry, we present a closed form expression for the success probability. Finally, we provide the optimal combination of MPC and LCD, which maximizes the success probability and show the gains achieved by our proposed scheme against conventional solutions.**

***Index Terms*—Wireless edge caching, cooperative relays, decode-and-forward, stochastic geometry.**

I. Introduction

Over the last decade, there's been an ever increasing data traffic to a growing number of devices in wireless networks. According to Cisco, by 2021 more than the three quarters of the monthly data traffic will be due to video streaming [1]. This implies that a tremendous number of network subscribers will require a larger amount of data at a faster rate. In this context, researchers have proposed to exploit the predictability of the users' file demands and add storage units in the network e.g., at the access points, in order to cache the most requested videos [2]. In that way, a user's requests will be dealt with at a closer distance which will result in a higher spectral efficiency as well as traffic offloading.

The main issue that needs to be addressed is the network's caching policy i.e., which files should be stored and where in the network, based on a given library consisting of the popular files of the network. In [3], the authors follow the most popular content (MPC) policy, where each small base station (BS) stores the most popular files. On the other hand, the authors in [4], investigate a probabilistic caching policy to maximize the number of satisfied requests; they show that when a user is covered by more than one BS, caching the most popular files everywhere is not always optimal. Thus, by caching different files at each cache-enabled node, a larger content diversity (LCD) is achieved. In addition, the authors in [5] study groups with different file preferences and derive the optimal group caching policy, considering the concept of cooperative caching. Moreover, the authors in [6], study a device-to device assisted cellular network, and provide the optimal caching placement that maximizes the offloading probability. Despite maximizing the number of satisfied requests is important, it does not guarantee that the files will be successfully obtained from the users. As such, the optimal caching placement should also consider both large-scale and small-scale attenuations. For this purpose, the cooperative caching is introduced, where the MPC scheme is used to achieve cooperation gain, while the LCD is used to increase the data offloading. In [7], cooperative caching helpers are deployed and the trade-off between the MPC and the LCD is presented as well as the optimal balance between the two. The authors in [8], study the optimal caching strategy that minimizes the download delay by employing cooperative BSs and considering the backhaul link delay. Furthermore, in [9], the authors consider cache-enabled small BSs, where each one dedicates a part of its available storage to cache files according to the MPC scheme and the rest according to the LCD scheme. By considering cooperative transmissions, they derive the optimal amount of storage, which should be devoted to MPC to maximize the user's quality of service. The same caching scheme is also considered in [10] for collaborative relaying; where the relays' locations are considered to be fixed and known. Even though the caching cooperation has been investigated in several studies, cooperative cache-enabled relays with spatial randomness has been overlooked.

This paper considers relays with caching capabilities and investigates a hybrid caching placement scheme of the conventional MPC and LCD schemes. Similarly to [9], [10], a variable part of the available storage of the relays is devoted to the MPC scheme to achieve cooperation gain. However, we do not apply the MPC scheme at all the relays of the network but introduce a new variable that defines the number of relays, which combine both MPC and LCD, while the remaining relays employ only the LCD scheme. In this way, we enable an additional degree of flexibility in the network, which handles more efficiently the total caching storage. In contrast to [10], we study spatially distributed relays and by using tools from stochastic geometry, we provide closed form expressions for the success probability. Furthermore, we consider a special case scenario, where the number of relays is fixed, and obtain the optimal caching design parameters that maximize the success probability. The numerical results provided, demonstrate the significant gains that can be achieved through the proposed caching scheme.

Notation: $\lceil x \rfloor$ refers to the round operation i.e., the nearest integer to x; $\mathbb{P}(X)$ represents the probability of the event X

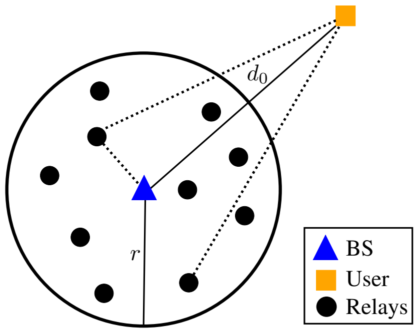

Fig. 1. A single cell structure consisting of one Bs, one user and a cluster of relays located inside a disk of radius r.

with expected value $\mathbb{E}(X)$; $\gamma(\cdot,\cdot)$ is the lower incomplete Gamma function and $\Gamma(\cdot)$ is the complete Gamma function.

II. System Model

Consider a single cell wireless network consisting of a BS, a user and a set of relays. The relays are spatially distributed according to a homogeneous Poisson point process (PPP) Φ with density λ in a disk of radius r; the BS is located in the centre of this disk. The distance between the i-th relay and the BS is denoted by d_i, $i \in \Phi$, and the distance between the user and the BS is denoted by d_0. We assume that $d_0 \gg r$ and thus the distance between the i-th relay and the user is approximately d_0 [11]. We study the downlink scenario where the direct link from the BS to the user is considered to be unavailable, for instance due to deep shadowing [12]. On the other hand, the relays can establish connectivity with the user and thus the user is served either directly by the relays (one-hop link) or by the BS via the relay nodes (two-hop link) as shown in Fig. 1. All the links in the network experience additive white Gaussian noise (AWGN) and normalized Rayleigh fading. Therefore, the power of the channel coefficients is exponentially distributed with unit variance. We denote by h_i and c_i the power of the channel coefficients of the links between the i-th relay and the user, and the i-th relay and the BS, respectively. In addition, all wireless links suffer from path-loss effects following a power-law distribution d^{-a}, where d is the Euclidean distance between the two connected nodes and $a > 2$ is the propagation exponent. Therefore, the signal-to-noise ratio (SNR) experienced at the user is given by

$$\text{SNR}_u = \frac{P_R h_i d_0^{-a}}{\sigma^2}, \tag{1}$$

where σ^2 is the power of the AWGN and P_R is the relays' transmission power. Similarly, the SNR at the i-th relay is expressed as

$$\text{SNR}_i = \frac{P_B c_i d_i^{-a}}{\sigma^2}, \tag{2}$$

where P_B is the BS's transmission power, where $P_B \geq P_R$. We denote by $\mathcal{F} = \{f_1, f_2, \dots, f_N\}$ a finite file library consisting of the N most popular files of the network each of equal size. The files are sorted in descending order according to their popularity and their probability distribution function (PDF) is given by the Zipf law

$$p_v = \frac{v^{-\gamma}}{\sum_{n=1}^{N} n^{-\gamma}}, \tag{3}$$

where v refers to the file's f_v popularity rank, $1 \leq v \leq N$, and γ is the Zipf exponent indicating the steepness of the PDF. The user requests a file according to (3) and successfully decodes it, if its spectral efficiency satisfies a predefined threshold rate R_F (bits/sec/Hz). Thus, the key metric is the success probability, defined as the probability of the user receiving its requested file with rate at least R_F.

III. Hybrid Edge Caching for Relaying

In this section, we present a new caching scheme that introduces a new degree of flexibility on the conventional combination of MPC and LCD caching strategies. Based on the proposed caching policy we derive the success probability using tools from stochastic geometry. Moreover, we study the special case where the number of relays is fixed and provide the optimal policy for the maximum success probability.

A. Hybrid caching

Each relay is equipped with a storage unit dedicated for file caching and is able to cache up to S files, where $S < N$. The BS has immediate access to all the N most popular files of the network. Similar to [9], [10], our caching strategy combines both MPC and LCD schemes. In MPC scheme the relays store the $M = \lceil \rho S \rfloor$[1] most popular files, where $0 \leq \rho \leq 1$. On the other hand, in LCD scheme, the relays take turns to fill their storage with different files. However, in contrast to [9], [10], we consider a hybrid caching placement by adding a new design variable $0 \leq \delta \leq 1$ to the caching placement.

Specifically, the relays are separated into two groups, G_1 and G_2, with densities $\lambda_1 \triangleq \delta\lambda$ and $\lambda_2 \triangleq (1-\delta)\lambda$, respectively (thinning operation) [13]. In this way, all relays in G_1 combine both MPC and LCD caching policies, while the relays of G_2 follow the LCD scheme. Thus, each relay in G_1 stores the M most popular files and then fills the rest of its available storage $(1-\rho)S$, with the next sequence of popular files, i.e, the first relay caches the files $S_1 = \{f_1, \dots, f_M, f_{M+1}, \dots, f_S\}$ and the j-th relay caches the files $S_j = \{f_1, \dots, f_M, f_{(j-1)(S-M)+M+1}, \dots, f_{j(S-M)+M}\}$. Finally, the relays in G_2 without caching any common file, they also take turns to fill their storage, each with the next group of popular files.

Since all relays in G_1 store the same M most popular files, they can cooperate to satisfy a request with rank $1 \leq v \leq M$. As such, the relays employ distributed beamforming, where, a global knowledge of the channels state information is assumed. Note that when $\rho = 0, \delta = 1$, all relays employ the LCD scheme and when $\rho = 1$, $\delta = 1$, all relays employ the MPC scheme; when a single relay exists in the network, it employs

[1]Note that the round operation is chosen against ceiling and floor operations to establish a more balanced caching scheme, without promoting neither MPC nor LCD, achieving better storage management.

TABLE I

RANKS OF THE FILES STORED IN EACH RELAY

G_1	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	11	12	13	14	15
G_2	16	17	18	19	20	21	22	23	24	25
	26	27	28	29	30	31	32	33	34	35
	36	37	38	39	40	41	42	43	44	45

the LCD scheme irrespective of the value of ρ. An example of our caching policy is shown in Table I, where we consider five relays with $\rho = 0.5$, $\delta = 0.4$, $N = 100$ files and $S = 10$ files. For this scenario, if the requested file has rank $1 \leq v \leq 5$, both of the relays in G_1 will transmit it to the user.

Based on the proposed caching scheme, we present the *network's protocol* which is as follows:

- The user places a request for a file from the network's library $\mathcal{F}$.
- If the requested file is stored more than once, then all the relays in G_1 transmit simultaneously the requested file to the user (cooperative beamforming).
- If the requested file is only cached once, then the relay which has the file will transmit it to the user.
- In case where the requested file is not cached, the BS transmits the file to the user via a randomly selected relay, using the decode-and-forward (DF) protocol i.e., in two time slots [12]. In the first slot, the BS transmits the file to a random relay; if it successfully decodes the file, it will forward it to the user in the second slot, otherwise the relay remains idle. Note that the transmission from the BS to the user is chosen to be weak compared to the direct links from the relays, since the main focus of this work is to introduce the design parameter δ and show the significant gains it provides to the system's performance.

B. Performance Analysis

We now turn our attention to the network's performance. First, we need to derive the hit and coverage probabilities of the user, in order to extract the success probability $\mathcal{P}_s$. The hit probability is the probability that the user's requested file is cached in the relays. Thus, when a file is cached according to the MPC scheme i.e., rank $v \leq M$, the hit probability is

$$\mathcal{P}_h^M(\rho,\delta) = (1-\Pi(0,\lambda_1))\sum_{v=1}^{M} p_v, \tag{4}$$

where p_v is given by (3) and refers to the user's request. Since MPC is employed by the relays in G_1, the term $(1-\Pi(0,\lambda_1))$ expresses the probability that G_1 is non-empty, and

$$\Pi(k,\lambda) = \frac{\exp(-\lambda\pi r^2)(\lambda\pi r^2)^k}{k!}, \tag{5}$$

with $\Pi(0,0) = 1$ [13]. When the file is cached according to the LCD scheme, we have three cases to consider. First we examine the case where the requested file has rank $v > M$, with $0 < \delta < 1$. Here, given that m and l relays are employed in G_1 and G_2 respectively, we have a total of $(m+l)S$ storage slots. The mM slots are dedicated for caching the M most popular files in the m relays (G_1). The remaining slots will fill with the files $[f_{M+1}, \dots, f_{(m+l)S-mM+M}]$. Next, we consider the case where G_1 is empty i.e., $\delta = 0$. In this case, only the relays in G_2 are employed filling their cache using the LCD scheme. Finally, we consider the case where G_2 is empty i.e., $\delta = 1$, which is similar with the first case with $l = 0$. Consequently, the hit probability of the LCD scheme is the summation of the three cases as follows

$$\begin{aligned}\mathcal{P}_h^L(\rho,\delta) = &\sum_{m=1}^{\infty}\Pi(m,\lambda_1)\sum_{l=1}^{\infty}\Pi(l,\lambda_2)\sum_{v=M+1}^{\min\{C(m,l),N\}} p_v \\ &+\Pi(0,\lambda_1)\sum_{l=1}^{\infty}\sum_{v=1}^{\min\{lS,N\}} p_v\Pi(l,\lambda_2) \\ &+\Pi(0,\lambda_2)\sum_{m=1}^{\infty}\sum_{v=M+1}^{\min\{C(m,0),N\}} p_v\Pi(m,\lambda_1),\end{aligned} \tag{6}$$

where $C(j,k) = S(j+k)+M(1-j)$, p_v is given by (3) and $\Pi(k,\lambda)$ is given in (5). Thus, the hit probability of the user is

$$\mathcal{P}_h(\rho,\delta) = \mathcal{P}_h^M(\rho,\delta) + \mathcal{P}_h^L(\rho,\delta), \tag{7}$$

where $\mathcal{P}_h^M(\rho,\delta)$ and $\mathcal{P}_h^L(\rho,\delta)$ are given by (4) and (6) respectively. Next, we derive the coverage probability of the user, defined as $\mathbb{P}(\log_2(1+\mathrm{SNR_u}) \geq \mathrm{R_F})$. The coverage probability of the user will be derived for three different transmission schemes i.e., only one relay transmits to the user, multiple relays cooperate to simultaneously transmit a file to the user, and the BS transmits the file to the user through DF relaying. We provide the following two lemmas.

Lemma 1. *The coverage probability of the user when establishing direct connectivity with the relays is given by*

$$\mathcal{P}_{cov}^S(R_F) = \exp\left(-\Xi(R_F)\right), \tag{8}$$

for the case where a single relay transmits to the user, and

$$\mathcal{P}_{cov}^M(R_F) = 1 - \sum_{k=1}^{\infty}\frac{\gamma\left(k,\Xi(R_F)\right)}{\Gamma(k)}\Pi(k,\lambda_1), \tag{9}$$

for the case where multiple relays transmit to the user, where $\Xi(R_F) = N_0\frac{2^{R_F}-1}{P_R d_0^{-\alpha}}$ *and* $\Pi(k,\lambda)$ *is given in (5).*

Proof. See Appendix A. □

Lemma 2. *The coverage probability of the user when receiving from the BS through a random relay using the DF protocol is given by [11]*

$$\mathcal{P}_{cov}^{\mathrm{DF}}(R_F) = \frac{2\mathcal{P}_{cov}^S(2R_F)}{r^2}\int_0^r x\exp\left(-\frac{2^{2R_F}-1}{P_B x^{-\alpha}}\right)dx, \tag{10}$$

where $\mathcal{P}_{cov}^S(R_F)$ *is given by (8).*

Proof. See Appendix B. □

By using the hit and coverage probabilities, we can obtain the success probability $\mathcal{P}_s$, defined as the probability that the user will receive its requested file with at least the threshold spectral efficiency R_F. Thus, according to the network protocol the success probability is given in the next proposition.

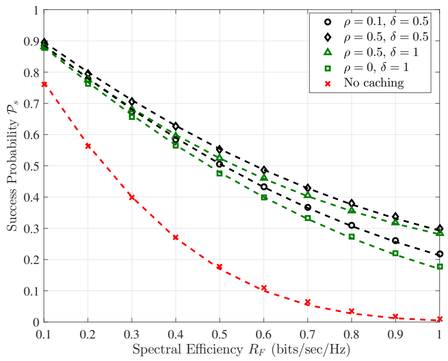

Fig. 2. Success probability versus spectral efficiency; dashed lines represent analytical results.

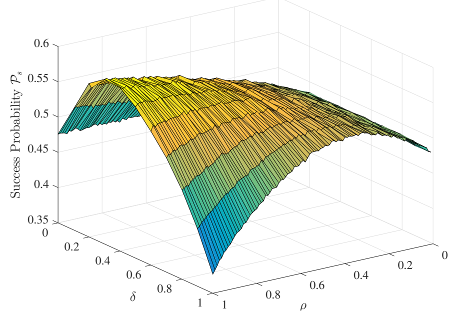

Fig. 3. Success probability for $R_F = 0.5$ bits/sec/Hz.

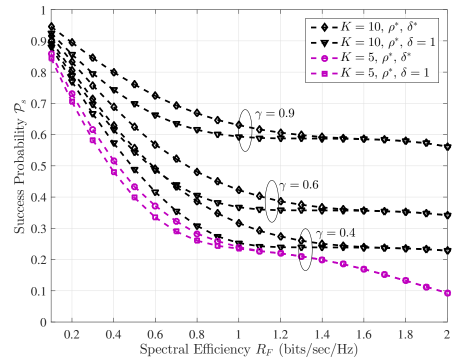

Fig. 4. Success probability $\mathcal{P}_s$ obtained from the optimal combination of ρ and δ.

Proposition 1. *The success probability when the direct link between the user and the BS is unavailable is given by*

$$\mathcal{P}_s(R_F,\rho,\delta) = \mathcal{P}_h^M(\rho,\delta)\mathcal{P}_{cov}^M(R_F) + \mathcal{P}_h^L(\rho,\delta)\mathcal{P}_{cov}^S(R_F) + (1-\mathcal{P}_h(\rho,\delta))\mathcal{P}_{cov}^{\mathrm{DF}}(R_F), \quad (11)$$

where $\mathcal{P}_h^M(\rho,\delta)$, $\mathcal{P}_h^L(\rho,\delta)$ and $\mathcal{P}_h(\rho,\delta)$ are given by (4), (6) *and* (7)*, respectively; $\mathcal{P}_{cov}^S(R_F)$ and $\mathcal{P}_{cov}^M(R_F)$ are given in Lemma 1 and $\mathcal{P}_{cov}^{\mathrm{DF}}(R_F)$ is given in Lemma 2.*

C. Special case - a fixed number of relays

Due to the complexity of the above expressions, we consider a special case scenario to study the optimization of the considered design parameters. Thus, we assume that the total number of relays employed in the network is a fixed integer K with $KS \leq N$, and our aim is to maximize the success probability. Since $\mathcal{P}_{cov}^{\mathrm{DF}}(R_F) \leq \mathcal{P}_{cov}^S(R_F) \leq \mathcal{P}_{cov}^M(R_F)$ for any threshold R_F, the probability where the 'no caching' case will achieve the maximum success probability between the three is zero. Thus, the success probability is maximized by employing LCD or MPC everywhere, or by a combination of both schemes. Based on the aforementioned, the success probability when K relays are employed is given by

$$\bar{\mathcal{P}}_s(R_F,K,\rho,\delta) = \underbrace{\mathcal{P}_z(M)}_{\mathcal{P}_h^M}\left(\underbrace{1-\frac{\gamma\left(\lceil\delta K\rfloor,\Xi(R_F)\right)}{\Gamma(\lceil\delta K\rfloor)}}_{\mathcal{P}_{cov}^M}\right) + \underbrace{\left(\mathcal{P}_z(C(\lceil\delta K\rfloor,\lceil(1-\delta)K\rfloor)) - \mathcal{P}_z(M)\right)}_{\mathcal{P}_h^L}\underbrace{\exp\left(-\Xi(R_F)\right)}_{\mathcal{P}_{cov}^S} + \left(1-\underbrace{\mathcal{P}_z(C(\lceil\delta K\rfloor,\lceil(1-\delta)K\rfloor))}_{\mathcal{P}_h}\right)\mathcal{P}_{cov}^{\mathrm{DF}}(R_F), \quad (12)$$

where $\delta \geq 1/K$ and $\mathcal{P}_z(Q) = \sum_{v=1}^{Q} p_v \approx \frac{Q^{1-\gamma}-1}{N^{1-\gamma}-1}$ [14]. The success probability given in (12) is the objective function that we need to maximize and so we formulate the following optimization problem

$$\max_{\rho,\delta} \quad \bar{\mathcal{P}}_s(R_F,K,\rho,\delta)$$
$$\text{subject to} \quad 0 \leq \rho \leq 1,$$
$$1/K \leq \delta \leq 1.$$

For the maximization of the success probability, we used the alternating optimization method, where one variable is optimized by keeping the second fixed and alternating until it converges to the global maximum [15]. Specifically, we used an iterative algorithm, which uses the derivatives of $\bar{\mathcal{P}}_s$ with respect to ρ and δ. The algorithm sets as starting optimal values $\rho' = 0$ and $\delta' = 1/K$, finds the root of each derivative at each step and sets ρ' and δ' equal to the derived roots for the next iteration. The cases where $\frac{d\bar{\mathcal{P}}_s}{d\rho}\big|_{\rho=1} \geq 0$ or $\frac{d\bar{\mathcal{P}}_s}{d\delta}\big|_{\delta=1} \geq 0$ imply that the success probability is an increasing function and thus $\rho' = 1$ and $\delta' = 1$, respectively. Finally, as these values are continuous, the final optimal values are updated as $\rho^* = \lceil\rho' S\rfloor/S$ and $\delta^* = \lceil\delta' K\rfloor/K$ since the amount of both files and relays is integer.

IV. Numerical Results

In this section, computer simulations are carried out to validate our analytical expressions and evaluate the performance of the proposed scheme. Unless otherwise stated, we use the following parameters i.e., $r = 10$ m, $d_0 = 5r$, $N = 1000$ files, $\gamma = 0.4$, $S = 100$ files, $\sigma^2 = 0$ dB, $P_R = 40$ dB, $P_B = 43$ dB, $\alpha = 2.5$, and $\lambda = 0.05$. The scheme presented in [9], [10] corresponds to $\delta = 1$ and is used as a reference scheme.

Fig. 2 plots the success probability versus the spectral efficiency, for different caching schemes. As can be seen, in all schemes, as the threshold rate increases the success probability decreases. This is because for higher R_F, the coverage probability is lower leading to a lower $\mathcal{P}_s$. The case where 'no caching' is employed i.e., $\mathcal{P}_h = 0$, it provides the lower bound for the success probability. Moreover, comparing the four different combinations of ρ and δ, we can see that for low values of R_F, all four schemes have the same performance. On the other hand, for high R_F values, the LCD scheme has lowest performance, while better success probability is obtained from the hybrid schemes. This is because the LCD scheme does not provide any cooperation gain which is needed at high R_F values. Finally, we can see a perfect match between the analytical results (dashed lines) and the simulation results (markers) which validates our analysis. In Fig. 3, the success probability is shown for $R_F = 0.5$ for all combinations of ρ and δ. The observations derived from Fig. 2 can be also validated here. We can see that the caching scheme with full MPC ($\rho = 1$, $\delta = 1$) gives the worst results followed by the full LCD scheme ($\delta = 0$), while the highest success probability is obtained at $\rho = 1$ and $\delta \approx 0.3$.

Fig. 4 deals with the optimal combination of ρ and δ, which maximizes the success probability under the special case scenario of fixed K. The success probability is depicted versus the threshold spectral efficiency, for different values of the Zipf exponent $\gamma \in \{0.4, 0.6, 0.9\}$. First, we consider the case where $K = 10$. As can be seen, for higher values of γ, the success probability increases since the most popular files are requested and these files have been cached. In addition, in all three cases, the proposed caching scheme outperforms compared to the benchmark caching policy, while at high threshold rates with $\rho = \delta = 1$ the two schemes converge. This happens because higher thresholds demand large SNR values, which are achieved through cooperation. Furthermore, the case where $K = 5$ relays is also presented. As expected, it outperforms in comparison with the case where $K = 10$, since there is less storage available and less cooperation gain.

V. Conclusion

This paper investigated the performance of cache-enabled relays in a single cell scenario. We considered a hybrid caching placement that enables two degrees of flexibility to combine the conventional MPC and LCD strategies. By using a stochastic geometric mathematical framework, we provided closed form expressions for the success probability. Furthermore, we derived the optimal combinations of ρ and δ that maximize the success probability. Our results show that the proposed scheme provides significant gains to the network's performance. In our future work, we will generalize the proposed scheme for multi-cell communication systems considering more sophisticated relaying schemes.

Appendix

A. Proof of Lemma 1

The coverage probability of the user connected to the i-th relay, $i \in \Phi$, denoted as $\mathcal{P}_{cov}^S$, is given by

$$\mathbb{P}\left(\mathrm{SNR_u} > 2^{\mathrm{R_F}} - 1\right) = \mathbb{P}\left(h_i > \Xi(R_F)\right) = \exp\left(-\Xi(R_F)\right), \quad (13)$$

where $h_i \sim \exp(1)$ and $\Xi(R_F) = \sigma^2 \frac{2^{R_F}-1}{P_R d_0^{-\alpha}}$. In the case where K relays, $K > 1$, transmit simultaneously to the user, the coverage probability $\mathcal{P}_{cov}^M$ can be evaluated as

$$\mathbb{P}\left(\sum_{i=1}^{K} h_i > \Xi(R_F) \;\middle|\; K\right) \overset{(a)}{=} \left(1 - \frac{\gamma\left(K, \Xi(R_F)\right)}{\Gamma(K)} \;\middle|\; K\right)$$
$$= 1 - \sum_{k=1}^{\infty} \frac{\gamma\left(K, \Xi(R_F)\right)}{\Gamma(K)} \Pi(k, \lambda_1), \quad (14)$$

where $\sum_{i=1}^{K} h_i$ is a Gamma random variable with shape parameter K and thus (a) follows by the cumulative distribution function $F(y, K) = \frac{\gamma(K,y)}{\Gamma(K)}$. Finally, since the K relays belong to G_1 with density λ_1, we uncondition on K by using $\Pi(k, \lambda_1)$ given in (5).

B. Proof of Lemma 2

Since the relays employ the DF protocol, the coverage probability of the user depends on the chosen relay being in coverage. Thus, we first derive the coverage probability of a relay randomly chosen by the BS. From (2) and since $c_i \sim \mathrm{Exp}(1)$, the coverage probability can be obtained as [11]

$$\mathbb{P}\left(c_i \geq \sigma^2 \frac{2^{R_F} - 1}{P_B d_i^{-\alpha}}\right) = \mathbb{E}\left[\exp\left(-\sigma^2 \frac{2^{R_F} - 1}{P_B d_i^{-\alpha}}\right)\right]$$
$$= \int_x \exp\left(-\sigma^2 \frac{2^{R_F} - 1}{P_B x^{-\alpha}}\right) f_d(x) dx$$
$$= \frac{1}{\pi r^2} \int_0^{2\pi} \int_0^r x \exp\left(-\sigma^2 \frac{2^{R_F} - 1}{P_B x^{-\alpha}}\right) dx\, d\theta, \quad (15)$$

where $f_d(x) = 1/\pi r^2$ is the PDF of the random variable d_i. The result follows by multiplying (8) by (15) and replacing R_F with $2R_F$, due to the use of the DF policy i.e., two channel uses are required due to half-duplex constraint [12].

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