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Research Article

Probabilistic Caching Placement in the Presence of Multiple Eavesdroppers

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The wireless caching has attracted a lot of attention in recent years, since it can reduce the backhaul cost significantly and improve the user-perceived experience. The existing works on the wireless caching and transmission mainly focus on the communication scenarios without eavesdroppers. When the eavesdroppers appear, it is of vital importance to investigate the physical-layer security for the wireless caching aided networks. In this paper, a caching network is studied in the presence of multiple eavesdroppers, which can overhear the secure information transmission. We model the locations of eavesdroppers by a homogeneous Poisson Point Process (PPP), and the eavesdroppers jointly receive and decode contents through the maximum ratio combining (MRC) reception which yields the worst case of wiretap. Moreover, the main performance metric is measured by the average probability of successful transmission, which is the probability of finding and successfully transmitting all the requested files within a radius R. We study the system secure transmission performance by deriving a single integral result, which is significantly affected by the probability of caching each file. Therefore, we extend to build the optimization problem of the probability of caching each file, in order to optimize the system secure transmission performance. This optimization problem is nonconvex, and we turn to use the genetic algorithm (GA) to solve the problem. Finally, simulation and numerical results are provided to validate the proposed studies.

1. Introduction

The arrival of big data era has led to a growing communication business, and the demand for wireless data rates becomes higher and higher. In order to reduce the transmission load and capacity crunch, caching is emerging as an important technology in the next generating wireless networks. The main idea behind caching is to store parts of the popular contents in caching helpers' memory and leverage the locally stored content to reduce transmission links, thereby reducing the transmission load and speeding up the transmission of requested content. And the different cache strategies have been well studied [1–9]. Specifically in [1], the authors considered a cluster-centric small-cell networks with combined design of cooperative caching and transmission policy and proposed a combined caching scheme to increase the local content diversity. The distributed caching placement has been studied in [2, 3], and in [3], the authors proposed to combine two recent schemes, distributed caching of content in small cells and cooperative transmissions from nearby base stations/BSs to achieve unprecedented content delivery speeds while reducing backhaul cost and delay. The probabilistic caching placement was studied in [4–7]. Departing from the conventional cache hit optimization in cache-enabled wireless networks, the authors in [4] considered an alternative optimization approach for the probabilistic caching placement in stochastic wireless D2D caching networks, proposed the cache-aided throughput, and provided a closed-form approximation of cache-aided throughput. Different from [4], the authors in [5] studied a probabilistic small-cell caching strategy and considered two kinds of network architectures: the small-cell base stations (SBSs) are always active and the SBSs are activated on demand by mobile users (MUs). The authors in [6, 7] proposed to use different optimization strategies to optimize the probabilistic caching placement. In addition, in paper [8], the analysis, design, and optimization of geographic caching were presented; and in paper [9], a hybrid caching scheme was studied which was jointly optimized with the transmission schemes to achieve a fine balance between the signal cooperation gain and the caching diversity gain.

The emergence of cache and wireless devices has solved a lot of problems, such as reducing transmission load, traffic, and energy consumption of the backhaul. The existing works on the wireless caching and transmission mainly focus on the communication scenarios without eavesdroppers, for instance, [4–9]. But when the eavesdroppers appear, it is of vital importance to investigate the physical-layer security for the wireless caching aided networks. In recent years, some researchers also have took into account the problem of secure caching, such as [10–13]. Specially, in [10], the problem of secure caching in the presence of an external wiretapper for both centralized and decentralized cache placement was analyzed. In [11], unmanned aerial vehicles assisted secure transmission for scalable videos in hyperdense networks via caching was studied. The authors in [12] studied a cooperative network with caching relays to reduce the transmission links overheard by the eavesdropper. Moreover, a novel hybrid cache placement was proposed to cache the popular contents, and the closed expressions of the secrecy outage probability and average secrecy capacity were obtained. The authors in [13] studied a framework of communication, caching, and computing- (3C-) oriented small-cell networks with interference alignment, in which caching and computing are exploited to simplify the network topology, improve the throughput, reduce the backhaul load, and guarantee the quality of experience of users.

The works about the physical-layer security have been studied such as the works in [14–16]. In [14], Wyner proved that the secure communication is feasible without cryptography technology as long as the eavesdropper's instantaneous channel is worse than the legitimate user's instantaneous channel. Based on Wyner's wiretap channel model, the authors in [15] studied the secrecy capacity over Gaussian channel. And the knowledge about the wireless information-theoretic security has been studied in [16]. In addition, the secrecy performance of wireless communication has been studied in [17–19]. Specifically in [17], the impact of cochannel interference and wiretap on the security performance of multiple amplify-and-forward (AF) relaying networks has been studied. In [18], the physical-layer security of a multiantenna transmission system in the presence of Poisson distributed eavesdroppers was analyzed, and the two different cases including the eavesdroppers being colluding and noncolluding were also analyzed in the paper. The relaying techniques for enhancing the physical-layer security have been studied in [19–26].

According to the above analysis, the main idea of this paper is to design, analyze, and optimize the probabilistic caching placement based on the security of transmission. Without loss of generality, the locations of relays are modeled by a homogeneous PPP. Moreover, considering the randomness of eavesdroppers' positions, we also model the locations of eavesdroppers by a homogeneous PPP, and the eavesdroppers jointly receive and decode contents through MRC reception which yields the worst case of wiretap. In addition, the main performance metric is measured by the average probability of successful transmission; the analytical result and analytical lower bound of the average probability of successful transmission are presented in the performance analysis. Due to the nonconvex nature and the complication of the average probability of successful transmission, it is too complicated to get a closed-form solution. Therefore, the GA is used to find the optimal solution instead of deriving a closed-form solution. And in order to better evaluate the proposed caching placement, we use the most popular content (MPC) caching placement as a standard for comparison, where the method of MPC caching placement is to cache the most popular contents in all relays. Finally, the numerical and simulation results are provided to validate the proposed studies.

The novelties and main contributions of this paper can be summarized as follows:

(i) Based on the security of transmission, the probabilistic caching placement is designed in the presence of multiple eavesdroppers which follow the homogeneous PPP.

(ii) The main performance metric is measured by the average probability of successful transmission, and both the analytical result and the analytical lower bound of the average probability of successful transmission are presented. Moreover, GA is used to optimize the average probability of successful transmission to maximize the system performance.

(iii) The simulation results are provided to demonstrate the studies that the optimized probabilistic caching placement is superior to the MPC caching placement, and the system secure performance can be improved by increasing the transmit power, the cache size, and the intensity of relays but will deteriorate with larger intensity of eavesdroppers.

The rest of this paper is organized as follows. In Section 2, we introduce the system model and study the probabilistic caching placement and the file transmission. In Section 3, the system performance is analyzed. And the optimization of probabilistic caching placement is presented in Section 4. The numerical and simulation results are provided in Section 5. The conclusions are presented in Section 6.

Notations. In this paper, we use P_i^{find} and P_i^{suc} to represent the probability of finding the requested file i and the successful probability of transmitting the file i, respectively. Moreover, we use $\overline{P}_{\text{suc}}$ to represent the average probability of successful transmission and use $\overline{P}_{\text{low}}^{\text{suc}}$ to represent the lower bound of average probability of successful transmission.

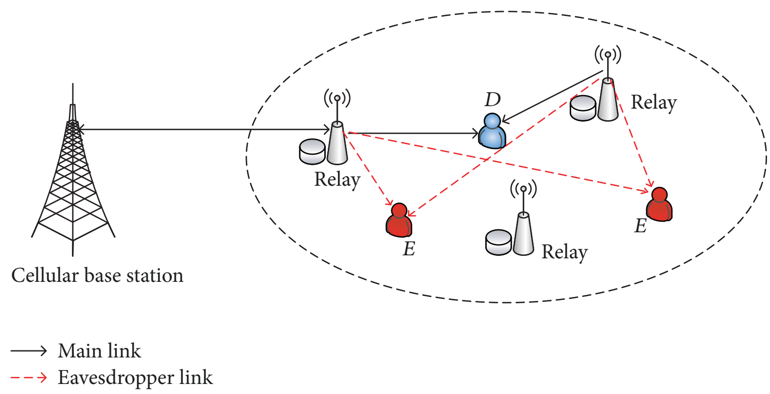

Figure 1: System model.

2. System Model

Figure 1 depicts the system model of a wireless caching network, which comprises a cellular base station (BS), a random legitimate user (D), multiple DF relays $\{R_k \mid k = 1, 2, \ldots, K\}$ with cache capacity, and multiple eavesdroppers $\{E_l \mid l = 1, 2, \ldots, L\}$ which can overhear messages and bring out the issue of information security [27–30]. Without loss of generality, the locations of relays are modeled by the homogeneous PPP Φ_r with intensity λ_r and the eavesdroppers' positions also follow the homogeneous PPP Φ_e with intensity λ_e.

In this system model, we consider BS has no direct link with D and eavesdroppers [31–33], the transmission is performed only via relays [34–36], and all relays can successfully send the files in their local cache to D within radius R. For legitimate D, if the requested file can be found in relays, the nearest relay directly transfers the file to D; otherwise, the file will be transmitted from BS to the nearest base station and then transmitted to D. Moreover, all wireless links are subjected to Rayleigh flat fading channel with a path loss governed by the exponent $\alpha > 2$ [37–39].

2.1. Cache Placement. We assume that there are N files that have been requested to D, which all have the same size. The case of unequal size will not be considered in this paper, but we can always assume that any file can be divided into blocks of the same size, so the similar analysis also can still be applied. In this paper, the files are characterized by their popularity, namely, the probability that a file is requested by the user. The request probability follows the Zipf distribution, which has been widely used in the literature [1–9]; that is, the request probability of ith file is

$$f_i = \frac{i^{-\gamma}}{\sum_{j=1}^{N} j^{-\gamma}}, \tag{1}$$

where γ is the Zipf parameter with the popularity skewness. According to the request probability, we can find that $f_1 \geq f_2 \geq \cdots \geq f_N$ and $\sum_{i=1}^{N} f_i = 1$.

In this paper, we consider each relay has the same cache memory size C_R ($C_R < N$) and the unit of storage/size is file. Because relays cannot store all files ($KC_R < N$), relays need to judiciously choose which files to store. Thus, we apply the probabilistic caching placement to the file's cache placement and by optimizing the cache placement to prove the system performance.

In the probabilistic model, the contents are independently placed in the cache memories of different relays, according to the same distribution. Therefore, if each relay caches ith file with a certain probability q_i ($0 \leq q_i \leq 1$) independently, we denote by $\mathbf{q} = [q_1, \ldots, q_N]$ the caching probabilities of file $i \in [1, N]$, and due to the cache storage limit, we have

$$\sum_{i=1}^{N} q_i \leq C_R. \tag{2}$$

In this paper, in order to alleviate the traffic and decline the transmission links, our goal is to find an optimal local caching strategy to optimize the system performance. Therefore, we only consider the secure transmission in local devices.

2.2. File Transmission. When a file request occurs, and there is at least one relay that stored the requested file within the radius r, the request would be satisfied and the relay would directly transmit the file to D. If there is more than one relay which has the requested file, the file will be transmitted from the nearest one. In the case where the requested file can not be found in relays, the file must be forwarded from core network to D assisted by nearest relay. Because we only consider the secure transmission in local devices, in the following, we will only analyze the local transmission.

We assume the channel state information (CSI) is known to D; therefore, when D sends the request, the nearest relay R_k ($k \in K$) which has cached the requested file directly transmits the file to D. According to [18], the received SNR at D can be shown as follows:

$$\mathsf{SNR}^D = \rho \eta_d, \tag{3}$$

where $\rho = p_r/\sigma^2$, p_r is the transmit power at relay, σ^2 is the noise power, $\eta_d \triangleq |h_{R_k,D}|^2 r_{R_k,D}^{-\alpha}$ is the channel gains for D, $h_{R_k,D}$ denotes the channel parameters of $R_k \rightarrow D$, and $r_{R_k,D}$ represents the distance from D to the nearest relay R_k.

The received SNR at a random eavesdropper E_l is given by

$$\mathsf{SNR}^{E_l} = \rho \eta_{e_l}, \tag{4}$$

where $\eta_{e_l} \triangleq |h_{R_k,E_l}|^2 r_{R_k,E_l}^{-\alpha}$, h_{R_k,E_l} denotes the channel parameters of $R_k \to E$, and r_{R_k,E_l} represents the distance from R_k to E_l.

3. Performance Analysis

In this section, we will analyze the cache hit probability and the average probability of successful transmission, and the average probability of successful transmission is defined as the main performance metric. Moreover, the analytical result and the analytical lower bound of the average probability of successful transmission are presented in this section.

3.1. Cache Hit Probability. In this paper, we define the cache hit probability as a probability that the user D successfully finds the requested file in a given area. From the system model, we know that relays are modeled by a PPP Φ_r with intensity λ_r, so the relays caching the ith file also follow a PPP with density $q_i\lambda_r$. According to the notion of stochastic geometry, in a given area within the radius r, the expected number of relays caching the ith file can be calculated as

$$E[K] = q_i \lambda_r \pi r^2. \tag{5}$$

And from [3–7], we find that, for a PPP distribution with density λ, the probability that there are n nodes in an area within the radius r is

$$F(n, r, \lambda) = \frac{\left(\pi r^2 \lambda\right)^n}{n!} e^{-\pi r^2 \lambda}. \tag{6}$$

Therefore, if we assume user D is located at the origin and find the requested file in an area within the radius R, the probability of finding at least one relay caching the ith file within a radius R is

$$P_i^{\text{find}} = 1 - F\left(0, R, q_i \lambda_r\right) = 1 - e^{-\pi q_i \lambda_r R^2}. \tag{7}$$

3.2. Probability of Successful Transmission. In this paper, we define the probability of successful transmission as the probability of finding and then successfully transmitting the requested file within a radius R. In order to analyze the probability of successful transmission, we firstly analyze the secrecy capacity which is the difference between the capacities of the legitimate channel C_D and the equivalent wiretap channel C_E. Based on the system model, the secrecy capacity can be expressed as [40–43]

$$C_s = \left[\log_2\left(1 + \mathsf{SNR}^D\right) - \log_2\left(1 + \mathsf{SNR}^E\right)\right]^+, \tag{8}$$

where $[x]^+$ returns $\max(0, x)$, $\mathsf{SNR}^E = \rho\eta_e$, and $\eta_e = \sum_{E_l \in \Phi_e} \eta_{e_l}$ is equivalent wiretap channel gain.

Therefore, when the ith file is requested by D, we use r_i to represent the distance to the nearest relay which has cached ith file. The probability of successful transmission can be shown as follows [44–47]:

$$\begin{aligned} P_i^{\text{suc}} & \\ &= \Pr\left\{\left[\log_2\left(1 + \mathsf{SNR}^D\right) - \log_2\left(1 + \mathsf{SNR}^E\right)\right] > R_s\right\} \\ &= \Pr\left\{\eta_d > M + \tau\eta_e\right\} \\ &= E_{r_i}\left[\int_0^\infty \int_{M+\tau y}^\infty f_{\eta_d}(x) f_{\eta_e}(y)\, d(x)\, d(y)\right], \end{aligned} \tag{9}$$

where R_s is the target secrecy rate, $M = (2^{R_s} - 1)/\rho$, $\tau = 2^{R_s}$, and f_{η_e} and f_{η_d} are the probability distribution function (PDF) of η_e and η_d, respectively.

Because eavesdroppers jointly receive and decode contents with MRC reception, we have $\eta_e = \sum_{E_l \in \Phi_e} \eta_{e_l}$. But since the randomness of eavesdroppers' positions, the exact closed-form expression for the PDF of η_e is difficult to obtain. However, by using the result from [48] and applying the PDF of η_d as $f_{\eta_d}(x) = r_i^\alpha e^{-r_i^\alpha x}$, we can calculate the successful probability of transmitting ith file P_i^{suc} as follows:

$$\begin{aligned} P_i^{\text{suc}} &= E_{r_i}\left[e^{-r_i^\alpha M} \int_0^\infty e^{-r_i^\alpha \tau y} f_{\eta_e}(y)\, dy\right] \\ &= E_{r_i}\left[e^{-r_i^\alpha M} \mathscr{L}_{\eta_e}(s)\right] = \int_0^\infty e^{-r_i^\alpha M} \mathscr{L}_{\eta_e}(s) f_{r_i} d_{r_i}, \end{aligned} \tag{10}$$

where $s = r_i^\alpha \tau$ and $\mathscr{L}_{\eta_e}(s)$ is the Laplace transform of η_e. According to [48], we have

$$\begin{aligned} \mathscr{L}_{\eta_e}(s) &= E_{\Phi_e}\left[e^{-s\eta_e}\right] = E_{\Phi_e}\left[\exp\left(-s \sum_{e_l \in \Phi_e} \eta_{e_l}\right)\right] \\ &= E_{\Phi_e}\left[\prod_{e_l \in \Phi_e} E_{|h_{e_l}|}\left(\exp\left(-s\left|h_{e_l}\right|^2 r_{e_l}^{-\alpha}\right)\right)\right] \\ &\overset{(a)}{=} \exp\left\{-E_{|h_{e_l}|}\left(\left(\int_0^\infty \lambda_e\left(1 - \exp\left(-s\left|h_{e_l}\right|^2 r_{e_l}^{-\alpha}\right)\right) 2\pi r_{e_l} d_{r_{e_l}}\right)\right\} \\ &\overset{(b)}{=} \exp\left(-\lambda_e \pi E_{h_{e_l}}\left[\left|h_{e_l}\right|^{4/\alpha}\right] \Gamma\left(1 - \frac{2}{\alpha}\right) s^{2/\alpha}\right), \end{aligned} \tag{11}$$

where step (a) holds for the probability generating functional lemma (PGFL) over PPP [48], step (b) holds for the integration formula $\int_0^\infty x^m \exp(-\beta x^n) d_x = \Gamma(\gamma)/(n\beta^\gamma)$, $\gamma = (m+1)/n$, $E_{h_{e_l}}[|h_{e_l}|^{4/\alpha}]$ can be calculated as

$$E_{h_{e_l}}\left[\left|h_{e_l}\right|^{4/\alpha}\right] = \int_0^\infty x^{2/\alpha} f_{|h_{e_l}|^2}(x)\, d_x = \Gamma\left(1 + \frac{2}{\alpha}\right), \tag{12}$$

and $f_{|h_{e_l}|^2}(x) = e^{-x}$ is the PDF of wiretap channel gain $|h_{R_k,E_l}|$. Therefore, substitute

$$\mathscr{L}_{\eta_e}(s) = \exp\left(-\beta s^{2/\alpha}\right), \tag{13}$$

where $\beta = \lambda_e \pi \Gamma(1 + 2/\alpha)\Gamma(1 - 2/\alpha)$. In this paper, we assume conditioning on $r_i \le R$ as a result of the maximum distance, and the PDF of r_i is given by

$$f_{r_i} = \begin{cases} \dfrac{2\pi q_i \lambda_r r_i}{1 - e^{-\pi q_i \lambda_r R^2}} e^{-\pi q_i \lambda_r r_i^2} & 0 \le r_i \le R \\ 0 & r_i > R. \end{cases} \tag{14}$$

Substituting (13) and (14) in (10), the successful probability of transmitting the file i is given by

$$P_i^{\text{suc}} = \int_0^\infty \exp\left(-r_i^\alpha M - \beta\tau^{2/\alpha} r_i^2\right) \times \frac{2\pi q_i \lambda_r r_i}{1 - e^{-\pi q_i \lambda_r R^2}} \exp\left(-\pi q_i \lambda_r r_i^2\right) d_{r_i}. \quad (15)$$

3.3. The Average Probability of Successful Transmission. In this paper, we define the average probability of successful transmission as the probability of finding and then successfully transmitting all the requested files within a radius R. Therefore, based on the above analysis, the average probability of successful transmission is given by

$$\begin{aligned}\overline{P}_{\text{suc}} &= \sum_{i=1}^{N} f_i P_i^{\text{find}} P_i^{\text{suc}} = \sum_{i=1}^{N} f_i \left(1 - e^{-\pi q_i \lambda_r R^2}\right) \\ &\times \int_0^\infty \exp\left(-r_i^\alpha M - \beta\tau^{2/\alpha} r_i^2\right) \\ &\times \frac{2\pi q_i \lambda_r r_i}{1 - e^{-\pi q_i \lambda_r R^2}} \exp\left(-\pi q_i \lambda_r r_i^2\right) d_{r_i},\end{aligned} \quad (16)$$

following constraints

$$\sum_{i=1}^{N} q_i \le C_R, \qquad q_i \in [0, 1], \; i \in [1, N]. \quad (17)$$

From (16), we can find $\overline{P}_{\text{suc}}$ is a function of various factors, for example, r_i, α, R_s, q_i, R, λ_r as well as λ_e. For any given r_i, α, R_s, R, λ_r, and λ_e, $\overline{P}_{\text{suc}}$ solely depends on the caching probability q_i. But since the complication of $\overline{P}_{\text{suc}}$, it is complicated to obtain a closed-form expression for $\overline{P}_{\text{suc}}$. Thus, in this subsection, we derive its analytical lower bound. The analytical lower bound presents a conservative estimation of $\overline{P}_{\text{suc}}$. If the lower bound is higher than the success threshold, the exact $\overline{P}_{\text{suc}}$ can be definitely guaranteed. The details about the analytical lower bound are shown as follows. We rewrite (10) as

$$\begin{aligned}P_i^{\text{suc}} &= E_{r_i}\left[\exp\left(-r_i^\alpha M\right) \exp\left(-\beta\tau^{2/\alpha} r_i^2\right)\right] \\ &= E_{r_i}\left[\exp\left(-r_i^\alpha M\right)\right] E_{r_i}\left[\exp\left(-\beta\tau^{2/\alpha} r_i^2\right)\right].\end{aligned} \quad (18)$$

According to Jensen's inequality, we have

$$P_i^{\text{suc}} \ge \exp\left(-M E_{r_i}\left[r_i^\alpha\right]\right) \exp\left(-\beta\tau^{2/\alpha} E_{r_i}\left[r_i^2\right]\right). \quad (19)$$

Based on the PDF of r_i in (14), $E_{r_i}[r_i^\alpha]$ can be calculated as

$$\begin{aligned}E_{r_i}\left[r_i^\alpha\right] &= \int_0^\infty r_i^\alpha \frac{2\pi q_i \lambda_r r_i}{1 - e^{-\pi q_i \lambda_r R^2}} \exp\left(-\pi q_i \lambda_r r_i^2\right) d_{r_i} \\ &= \frac{\pi q_i \lambda_r}{1 - e^{-\pi q_i \lambda_r R^2}} \times \frac{\Gamma(1 + \alpha/2)}{\left(\pi q_i \lambda_r\right)^{1+\alpha/2}}.\end{aligned} \quad (20)$$

$E_{r_i}[r_i^2]$ can be calculated as

$$\begin{aligned}E_{r_i}\left[r_i^2\right] &= \int_0^\infty r_i^2 \frac{2\pi q_i \lambda_r r_i}{1 - e^{-\pi q_i \lambda_r R^2}} \exp\left(-\pi q_i \lambda_r r_i^2\right) d_{r_i} \\ &= \frac{\Gamma(2)}{\pi q_i \lambda_r \left(1 - e^{-\pi q_i \lambda_r R^2}\right)}.\end{aligned} \quad (21)$$

Substituting (20) and (21) in (19), we can obtain the closed-form expression of the lower bound $P_{i_{\text{low}}}^{\text{suc}}$ as

$$\begin{aligned}P_{i_{\text{low}}}^{\text{suc}} &= \exp\left(-\frac{M\pi q_i \lambda_r}{1 - e^{-\pi q_i \lambda_r R^2}} \times \frac{\Gamma(1 + \alpha/2)}{\left(\pi q_i \lambda_r\right)^{1+\alpha/2}}\right) \\ &\times \exp\left(-\frac{\beta\tau^{\alpha/2}\Gamma(2)}{\pi q_i \lambda_r \left(1 - e^{-\pi q_i \lambda_r R^2}\right)}\right).\end{aligned} \quad (22)$$

Therefore, the closed-form expression of the lower bound $P_{\text{low}}^{\text{suc}}$ is given by

$$\begin{aligned}\overline{P}_{\text{low}}^{\text{suc}} &= \sum_{i=1}^{N} f_i P_i^{\text{find}} P_{i_{\text{low}}}^{\text{suc}} \\ &= \sum_{i=1}^{N} f_i \left(1 - e^{-\pi q_i \lambda_r R^2}\right) \\ &\times \exp\left(-\frac{M\pi q_i \lambda_r}{1 - e^{-\pi q_i \lambda_r R^2}} \times \frac{\Gamma(1 + \alpha/2)}{\left(\pi q_i \lambda_r\right)^{1+\alpha/2}}\right) \\ &\times \exp\left(-\frac{\beta\tau^{2/\alpha}\Gamma(2)}{\pi q_i \lambda_r \left(1 - e^{-\pi q_i \lambda_r R^2}\right)}\right).\end{aligned} \quad (23)$$

4. Optimization of Probabilistic Caching Placement

From the performance analysis, it can be seen that the caching parameter q_i affects the system secure performance significantly. Therefore, in this section, the optimization of probabilistic caching placement is to find the optimal caching probability q_i^* ($i \in [1, N]$). But due to the nonconvex nature and the complication of $\overline{P}_{\text{suc}}$, it is too complicated to get a closed-form solution of q_i^*. Based on the above considerations, we utilize the GA to find the optimal solution of q_i^* instead of deriving a closed-form solution. The details about the optimization of genetic algorithm are shown in Algorithm 1.

Notation. N denotes the number of total files, λ_r denotes the intensity of relays, λ_e denotes the intensity of eavesdroppers, p_r denotes the transmit power at relay, and $p_{r_{\min}}$ and $p_{r_{\max}}$ represent the minimum of transmit power and the maximum of transmit power, respectively. In addition, q^* represents the optimal caching probability of the ith file, $\overline{P}_{\text{suc}}^*$ represents the average probability of all files successful transmission, and LB and UB represent the lower bound and upper bound of variables, respectively.

Input: input parameters $N, \lambda_r, \lambda_e, p_r, p_{r_{\min}}, p_{r_{\max}}$
Output: output the optimal caching probability $\mathbf{q}^* = [q_1^*, \ldots, q_N^*]$
and the average probability of success transmission $\overline{P}_{\text{suc}}^*$
(1) Initialize $\overline{P}_{\text{suc}} = zeros(0)$
(2) $j = 1$
(3) **for** $p_r = p_{r_{\min}} : p_{r_{\max}}$ **do**
(4) $[\mathbf{x}, fval] = ga\_main(N, \lambda_r, \lambda_e, p_r)$
(5) $\mathbf{q}^*(j,:) = \mathbf{x}(end - 3)$
(6) $\overline{\mathbf{P}}_{\text{suc}}^*(j) = -fval$
(7) $j = j + 1$
(8) **end for**
(9) **function** $ga\_main(N, \lambda_r, \lambda_e, p_r)$
(10) ObjectiveFunction=@$ga\_fitness$
(11) $nvars = N + 3$
(12) Initialize LB and UB
(13) ConstraintFunction=@$ga\_constraint$
(14) $[q_i^*, fval] =$
$ga(ObjectiveFunction, nvars, [\,], [\,], [\,], [\,],$
$LB, UB, \ldots, ConstraintFunction, options)$
(15) **return** $[q_i^*, fval]$
(16) **end function**
(17) **function** $ga\_fitness(\mathbf{x})$
(18) $\mathbf{q}_i^* = \mathbf{x}(1 : end - 3)$
(19) $p_r = \mathbf{x}(end)$
(20) calculate $f_i, P_i^{\text{find}}, P_i^{\text{suc}}$
(21) $\overline{P}_{\text{suc}}^* = \sum_{i=1}^{N} f_i P_i^{\text{find}} P_i^{\text{suc}}$
(22) $y = -\overline{P}_{\text{suc}}^*$
(23) **return** y
(24) **end function**

Algorithm 1: Optimization of probabilistic caching placement.

In Algorithm 1, the function ga_main (lines (9)–(16)) is the calling function of GA. The main intension of the function ga_main is to define the number of variables (line (11)), initialize lower bound and upper bound (line (12)), and call the fitness function and constraint function of GA to return the optimal q_i^* and the minimum $fval$ (line (14)). The fitness function of GA is presented from lines (17) to (24). The main ideas of the fitness function are to take one input vector $\mathbf{x}$, where $\mathbf{x}$ has as many elements as number of variables, then compute the value of the function, and return that scalar value in its one return argument y. It is worth noting that all variables consist of the caching probability of N files, the intensity of relays λ_r, the intensity of eavesdroppers λ_e, and the transmit power of relays p_r, so the length of $\mathbf{x}$ is equal to $N + 3$, where $\mathbf{x}$ is the vector of all variables. But because there are only N files, we can get that the length of $\mathbf{q}$ should be equal to $length(\mathbf{x}) - 3$. Moreover, because the function of GA is to find the minimum value, we define argument y as the negative of $\overline{P}_{\text{suc}}^*$. Similarly, the GA function assumes the constraint function will take one input $\mathbf{x}$, where $\mathbf{x}$ has as many elements as number of variables in the problem. Furthermore, the constraint function computes the values of all the inequality and equality constraints and designs two vectors c and ceq, respectively, where $c = \text{sum}(\mathbf{x}(1 : end - 3)) - C_R$ and $ceq = [\,]$. The details about the algorithm optimization and the associated analysis can be found in the literature, such as the works [49–52].

5. Numerical and Simulation Results

In this section, the numerical and simulation results are presented to verify the system secure performance in the presence of multiple eavesdroppers and illustrate the effect of key system parameters. In addition, the system performances are compared with the traditional MPC caching placement. Without loss of generality, the secrecy data rate R_s is set to 0.1 bps/Hz, and the noise power is set to one.

As shown in Figure 2, this figure depicts the effect of the number of files N on the average probability of successful transmission, where $p_r = 30$ dB, $C_R = 5$, $\alpha = 2.1$, $\gamma = 0.5$, $R = 100$, $\lambda_r = 4 \times 10^{-3}$, and $\lambda_e = 1 \times 10^{-5}$. From this figure, we can see that the average probability of successful transmission decreases as N increases. And when the number of files N is equal to C_R, the average probability of successful transmission of MPC caching placement is equal to the analytical result of probabilistic caching placement and the analytical lower bound of probabilistic caching placement. However, when N is larger than C_R, the performance of probabilistic caching placement is better than MPC caching placement, and with increasing N, MPC caching placement

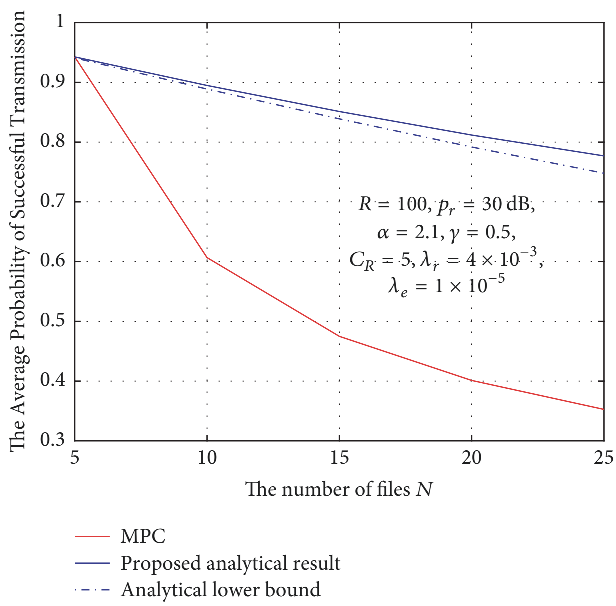

Figure 2: Effect of N on the average probability of successful transmission.

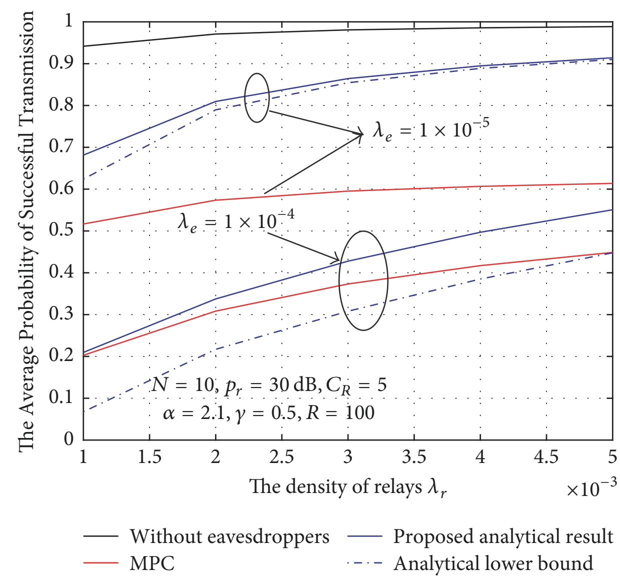

Figure 4: Impact of λ_r and λ_e on the average probability of successful transmission.

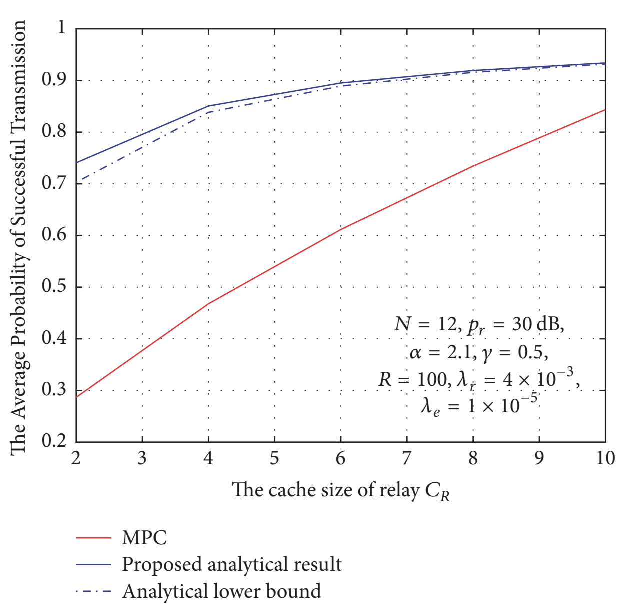

Figure 3: Effect of C_R on the average probability of successful transmission.

deteriorates more rapidly than the probabilistic caching placement. The reason is that the MPC caching placement combines all signals to exploit the signal cooperation gain, but the proposed probabilistic caching placement achieves the balance between the signal cooperation gain and the caching diversity gain.

Figure 3 shows the effect of the cache size of relay C_R on the average probability of successful transmission, where $N = 12$, $p_r = 30\,\text{dB}$, $\gamma = 0.5$, $R = 100$, $\alpha = 2.1$, $\lambda_r = 4 \times 10^{-3}$, and $\lambda_e = 1 \times 10^{-5}$. As observed from the figure, the average probability of successful transmission becomes better as C_R increases, and it is also obvious that the performance of probabilistic caching placement is always higher than MPC caching placement. Moreover, from the picture, we can see that as C_R increases, the analytical result of probabilistic caching placement and the analytical lower bound of probabilistic caching placement are quite closer. And the average probability of successful transmission of probabilistic caching placement and MPC caching placement becomes closer as the value of C_R increases.

Figure 4 shows the effect of the intensity of relays λ_r and the intensity of eavesdroppers λ_e on the average probability of successful transmission, where $N = 10$, $p_r = 30\,\text{dB}$, $C_R = 5$, $\alpha = 2.1$, $\gamma = 0.5$, and $R = 100$. As observed from the figure, the average probability of successful transmission becomes better as λ_r increases, and the average probability of successful transmission with $\lambda_e = 1 \times 10^{-5}$ is higher than that with $\lambda_e = 1 \times 10^{-4}$. Thus, we can find when the value of λ_e increases, the average probability of successful transmission will decrease. In addition, from the figure, we also can find that the analytical result and analytical lower bound of probabilistic caching placement are quite closer with increasing λ_r. And when $\lambda_e = 1 \times 10^{-4}$, the difference between the analytical result and analytical lower bound is more obvious than $\lambda_e = 1 \times 10^{-5}$. Moreover, when $\lambda_e = 1 \times 10^{-5}$, the analytical result and analytical lower bound of probabilistic caching placement are both higher than MPC caching placement. However when $\lambda_e = 1 \times 10^{-4}$, the analytical lower bound of probabilistic caching placement is lower than MPC. But we also can find the difference between the analytical result and the analytical lower bound of probabilistic caching placement becomes quite closer with increasing λ_r. It is worth noting that the performance without considering security is superior to the performance of considering secure transmission, but in the actual situation, eavesdroppers exist, and we cannot just

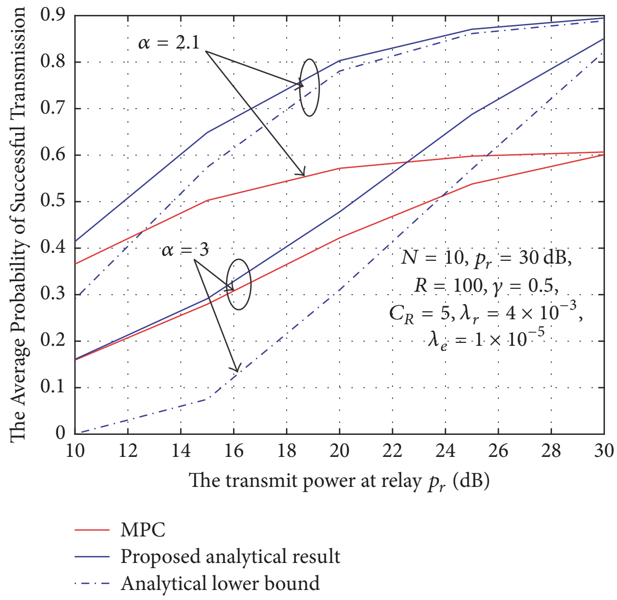

FIGURE 5: Impact of p_r and α on the average probability of successful transmission.

consider the performance of main channel, and we also need to consider the eavesdropper's channel.

Figure 5 shows the effect of the transmit power at relay p_r and the path loss α on the average probability of successful transmission, where $N = 10$, $C_R = 5$, $\gamma = 0.5$, $R = 100$, $\lambda_r = 4 \times 10^{-3}$, and $\lambda_e = 1 \times 10^{-5}$. From this figure, we can find that the average probability of successful transmission increases as p_r increases. Moreover, the analytical result and the analytical lower bound of probabilistic caching placement is quite closer with increasing p_r. In addition, the analytical result of probabilistic caching placement is always higher than MPC caching placement. And for the probabilistic caching placement, with $\alpha = 2.1$, the associated average probability of successful transmission is better than that with $\alpha = 3$, so we can obtain that the average probability of successful transmission deteriorates with larger α. Furthermore, when $\alpha = 3$ and $p_r \leq 12$ dB, the average probability of successful transmission of probabilistic caching placement is almost equal to MPC caching placement. But when $p_r \geq 12$ dB, the average probability of successful transmission of probabilistic caching placement is always higher than MPC caching placement. The reason is that increasing the value of transmit power p_r can exploit the signal cooperation gain and the caching diversity gain, but the MPC caching placement only can utilize the signal cooperation gain, and the probabilistic caching placement can exploit both the signal cooperation gain and the caching diversity gain.

6. Conclusions

In this paper, we designed, analyzed, and optimized the probabilistic caching placement in the presence of multiple eavesdroppers. And the average probability of successful transmission was defined as the main performance metric, which is the probability of finding and then successfully transmitting all the requested files within a radius R. Moreover, the analytical result and the analytical lower bound of average probability of successful transmission were both presented. But due to the nonconvex nature and the complication of average probability of successful transmission, the GA was used to find the optimal solution instead of deriving a closed-form solution. Finally, simulation results were provided to support the studies that the proposed probabilistic caching placement is superior to the MPC caching placement. In addition, the system secure performance can be improved by increasing the value of p_r, C_R, and λ_r but will deteriorate with larger N and λ_e.

Data Availability

The authors state the data availability in this manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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