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Power Allocation for Cache-Aided Small-Cell Networks with Limited Backhaul

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***Abstract*—Cache-aided small-cell network is becoming an effective method to improve the transmission rate and reduce the backhaul load. Due to the limited capacity of backhaul, less power should be allocated to users whose requested contents do not exist in the local caches to maximize the performance of caching. In this paper, power allocation is considered to improve the performance of cache-aided small-cell networks with limited backhaul, where interference alignment (IA) is utilized to manage interferences among users. Specifically, three power allocation algorithms are proposed. First, we come up with a power allocation algorithm to maximize the sum transmission rate of the network, considering the limitation of backhaul. Second, in order to have more users meet their rate requirements, a power allocation algorithm to minimizing the average outage probability is also proposed. In addition, in order to further improve the users' experience, a power allocation algorithm that maximizes the average satisfaction of all the users is also designed. Simulation results are provided to show the effectiveness of the three proposed power allocation algorithms for cache-aided small-cell networks with limited backhaul.**

***Index Terms*—Caching, interference alignment, limited backhaul, outage probability, power allocation, small-cell networks.**

I. INTRODUCTION

With the arrival of 5G mobile cellular network and the proliferation of smart mobile devices, the wireless mobile data increase unprecedentedly [1], [2]. Thus, the small-cell network is becoming the main method of realizing the traffic demand for the 5G mobile cellular networks [3]–[6]. However, small-cell networks cannot solve the problem of backhaul. With the rapid increase of mobile users and traffic, the pressure on the backhaul becomes more and more serious, leading to a decline in users' satisfaction. Thus, in order to solve this problem, proactive caching in small-cell base stations (SBSs) is attracting more and more interest [7]–[11]. Meanwhile, the shift of wireless traffic from locally generated speech to centrally created content also provides great opportunity for caching [12]. When caching is considered, the communication process is divided into two phases [13]. The first one is the placement phase, which is performed during the off-peak time with sufficient network resources. The subsequent one is the delivery phase, which is performed during the peak-traffic time with scarce network resources. Thus we can proactively cache some important contents in SBSs up to the storage memory limit with respect to a certain popularity profile during a content placement phase through backhaul [14]. During the content delivery phase, SBSs can directly transmit the contents to users without backhaul, if the users' requested contents already exist in the caches of the SBSs [15]. This allows caching to effectively shift the traffic of backhaul from peak to off-peak time, thereby reducing peak traffic and alleviating the backhaul load. Moreover, caching can also move the users' requested contents close to users in a smart way to reduce the access delay.

Plenty of research on caching has been done, which has mainly focused on the benefits of caching and optimizing the content placement to increase the local content delivery. In [13], a novel coded caching scheme was proposed to obtain both local and global caching gains, and thus can multiplicatively improve the peak rate. In [14], caching was utilized to improve the throughput as it can alleviate the backhaul load and do benefit for interference alignment (IA) technique. In [15], each transmitter equally cached some nonoverlapping subfiles of each file and transfers files by cooperating with each other to achieve interference cancellation. In [16], the storage-latency tradeoff in wireless interference networks was studied, where all the transmitters and receivers were equipped with caches. Nevertheless, it is difficult to predict the requested contents of all the users. In addition, the capacity of each cache is limited in order to save cost. Thus the requested contents of some users may not exist in the caches, and they can only be obtained via the limited backhaul.

On the other hand, interference also becomes much more serious in small-cell networks due to the intensive deployment of SBSs, which can restrict the system capacity and result in a decline in the system performance [17]–[19]. Thus, interference management is an important issue in cache-aided small-cell networks to increase the system throughput. Some initial works were done in the interference management of cache-aided networks. In [15], the interference channel is turned into broadcast channel, X channel, or hybrid channel to achieve interference management through a specific file splitting and placing strategy. In particular, IA can also be

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adopted in cache-aided networks to effectively mitigate the interference [14], [16], due to its high capability in interference management.

When IA is performed, the precoding matrices should be cooperatively designed to constrain interferences into the same subspaces at the unintended users, and each user can retrieve the desired signal by using the decoding matrix that is orthogonal to the direction of interferences [20]–[25]. The feasibility condition is one of the key problems for IA, through which the minimum number of antennas to perfectly eliminate the interferences can be determined [26], [27]. To further improve the performance of IA-based networks, power allocation (PA) schemes have been studied in [28]–[30]. Since IA can manage interference among users effectively, it has been successfully developed for many kinds of multi-input and multi-output (MIMO) wireless networks with excellent performance [31]–[33]. Nevertheless, there are still some challenges to utilize IA in practical systems, one of which is channel state information (CSI) [34]. In IA-based networks, the global CSI should be available at each node accurately to calculate the appropriate precoding matrices, which is difficult to achieve in practical scenarios. Thus the overhead of CSI feedback in IA networks is extremely high [35]. In order to solve this problem, we can exchange the local CSI at transmitters through backhaul links in [14], [19].

Due to its excellent performance, IA has also been applied to the cache-aided small-cell networks [14], [19]. In the system, the local CSI of each SBS can be exchanged at the central processor with the help of backhaul links. Thus, only local CSI should be fed back to each SBS, which makes IA much easier to achieve. However, CSI exchange takes up some of the capacity of backhaul, and will limit the transmission rate of the uncached contents through backhaul links. Therefore, in this paper, we study the PA schemes in cache-aided small-cell networks to further improve its performance, under the condition that the capacity of backhaul links is limited. In this case, the difference between the transmission of the cached contents and that of the uncached contents can be fully considered. Some initial work of this paper in conference version will be presented in [36]. The key contributions of our research are summarized as follows.

- IA is utilized in the cache-aided small-cell networks to manage interference among different cells, and the local CSI at each SBS can be exchanged through backhaul, which will make IA much easier to achieve. Nevertheless, the CSI exchange will take up some of the capacity of backhaul, which limits the transmission rate. Thus, in this paper, PA is studied, considering the effects on the backhaul due to the cached and uncached transmission.
- Owing to the difference between the transmission of the cached contents and that of the uncached contents, a PA algorithm that maximizes the sum rate is proposed to optimize the spectrum efficiency of the cache-aided small-cell network with limited backhaul.
- The minimal transmit power of each user to meet its rate requirement is derived, and the expression of the average outage probability is defined. Thus in order to satisfy the rate requirements of more users, a PA algorithm is proposed to minimize the average outage probability of the network.
- To further improve all the users' experience in the small-cell network, a PA algorithm is proposed to maximize the average satisfaction of the users, with its closed-form solutions derived.

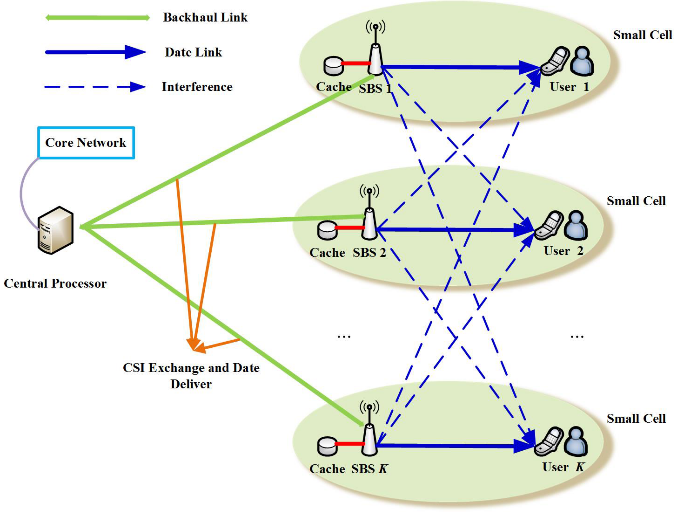

Fig. 1. Demonstration of cache-aided small-cell network with limited backhaul.

The rest of this paper is structured as follows. The system description is presented in Section II. Three different power allocation algorithms for cache-aided small-cell networks are proposed in Section III. Simulation results are presented and discussed in Section IV. Finally, conclusions are drawn in Section V.

Notation: $\mathbf{A}^\dagger$ represents the conjugate transpose of matrix $\mathbf{A}$. $\mathbb{C}^{M\times N}$ indicates the space of complex $M \times N$ matrices. $\mathcal{CN}(\mathbf{a}, \mathbf{A})$ corresponds to the complex Gaussian distribution with mean $\mathbf{a}$ and covariance matrix $\mathbf{A}$.

II. SYSTEM DESCRIPTION

In this section, the system model is first presented, followed by an introduction on IA and an analysis of the CSI exchange for the proposed scheme.

A. System Model

In this paper, we consider a cache-aided small-cell network with limited backhaul as shown in Fig. 1. There are one central processor at the macro-cell base station (MBS), K small-cell base stations (SBSs), and K corresponding users[1]. For simplicity, we assume that all the SBSs are equipped with M antennas and all the mobile users are equipped with N antennas. In addition, only one data stream is transmitted by each SBS to its corresponding user. As illustrated in Fig. 1, all the SBSs are connected to a central processor at the MBS via

[1] We assume that only one user is supported in a specific frequency band of each small cell. Nevertheless, more users can be served in each cell by orthogonal frequency-division multiple access (OFDMA) or other multiple-access methods.

their limited backhaul links and equipped with a cache. We assume that L $(L < K)$ users' requested contents do not exist in the local caches during a specific content-delivery phase. Thus, these contents need to be fetched from the core network via the limited backhaul links. On the contrary, the contents of the other $(K - L)$ users can be accessed directly from the local caches. In order to reduce the high overhead of global CSI feedback, we can exchange the local CSI of the users through the backhaul links [19], which will be discussed in detail in Section II-C. Thus, we assume that the total backhaul links of these SBSs have a fixed capacity of C, and part of it is utilized for data transmission, while the rest is leveraged for local CSI exchange.

With regard to the capacity of backhaul links, we assume that the capacity served for CSI exchange is C_c, and the remaining capacity used for date delivery is C_d, i.e.,

$$C = C_c + C_d. \tag{1}$$

Therefore, the sum deliver rate of these L uncached SBSs that obtain contents via limited backhaul is limited not to excess C_d. Consequently, we can assume that the sum transmission rate of these L corresponding users is also limited to C_d. While for the remaining $(K - L)$ mobile users, their requested contents are cached at their corresponding SBSs. Thus, these SBSs can transmit information directly to their corresponding users without rate limitation. In addition, the total transmit power of all the K SBSs is constrained to be a constant P_{max}, due to the fact that the small-cell network is connected to one specific power grid.

B. Interference Alignment

IA is an emerging linear precoding technique to effectively manage interference among users, and it is applied to cached-aided small-cell networks in this paper. When IA is performed, the recovered signal at the kth mobile user can be denoted as

$$y^{[k]} = \mathbf{u}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{v}^{[k]}x^{[k]} + \sum_{i=1, i\neq k}^{K} \mathbf{u}^{[k]\dagger}\mathbf{H}^{[ki]}\mathbf{v}^{[i]}x^{[i]} + \mathbf{u}^{[k]\dagger}\mathbf{z}^{[k]}, \tag{2}$$

where $\mathbf{H}^{[ki]}$ is the $N \times M$ channel coefficient matrix from the ith SBS to the kth user. Each element of $\mathbf{H}^{[ki]}$ is i.i.d. and following $\mathcal{CN}(0, 1)$. $\mathbf{v}^{[k]} \in \mathbb{C}^{M\times 1}$ is the unitary precoding vector at the kth SBS, and $\mathbf{u}^{[k]} \in \mathbb{C}^{N\times 1}$ is the decoding vector of the kth user. $\mathbf{z}^{[k]}$ is the $N \times 1$ additive white Gaussian noise (AWGN) vector with distribution $\mathcal{CN}(\mathbf{0}, \sigma^2)$ at the kth mobile user, where σ^2 is the noise power at the user.

When IA is feasible [26], the interferences in the cache-aided small-cell network can be perfectly eliminated if the following equations are satisfied [37].

$$\mathbf{u}^{[k]\dagger}\mathbf{H}^{[ki]}\mathbf{v}^{[i]} = 0, \ \forall i \neq k, \tag{3}$$

$$\text{rank}\left(\mathbf{u}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{v}^{[k]}\right) = 1. \tag{4}$$

Thus the desired signals of the kth user in the network can be rewritten as

$$y^{[k]} = h^{[k]}x^{[k]} + \bar{z}^{[k]}, \tag{5}$$

where $h^{[k]} = \mathbf{u}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{v}^{[k]}$, and $\bar{z}^{[k]} = \mathbf{u}^{[k]\dagger}\mathbf{z}^{[k]}$.

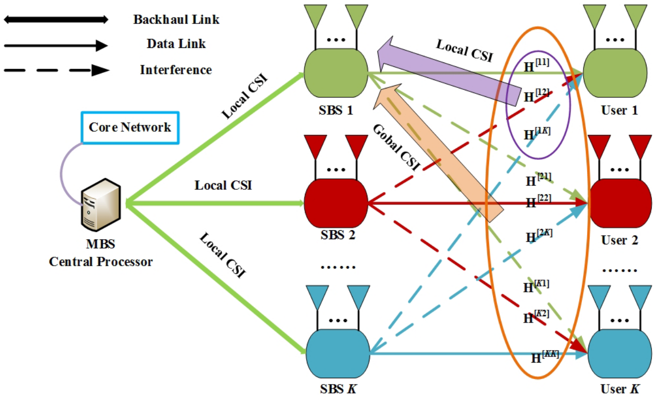

Fig. 2. Local CSI exchange via limited backhaul links

As mentioned before, only one data stream is transmitted from each SBS to its corresponding user. Thus the following condition (6) should be satisfied according to the feasibility of IA [26].

$$K \leq (M + N - 1) \tag{6}$$

Thus the transmission rate of the kth user in the cache-aided small-cell network with interference completely eliminated can be expressed as

$$R^{[k]} = \log_2\left(1 + \frac{\left|h^{[k]}\right|^2}{\sigma^2}P^{[k]}\right), \tag{7}$$

where $P^{[k]}$ is the transmit power of the kth SBS.

IA can eliminate the interference among users effectively. However, in conventional IA-based networks, the most challenging issue is that all the nodes in the network should have the knowledge of the accurate global CSI. Thus the overhead of CSI feedback is extremely high when the number of users is large, which becomes a bottleneck to realize IA in practical systems. Fortunately, only local CSI should be acquired at each SBS and exchanged via backhaul, which will be discussed in the next subsection.

C. CSI Exchange

The high overhead of CSI feedback is one of the key challenging issues to achieve IA. In the proposed scheme, the overhead of CSI feedback can be effectively reduced through local CSI exchange via backhaul, as shown in Fig. 2. In the scheme, the CSI from all the SBSs should be estimated at each mobile user [38], and only the local CSI at each user should be fed back to its corresponding SBS. Then the local CSI of all the SBSs are exchanged at the central pressor via the limited backhaul links, and thus all the SBSs have the knowledge of global CSI. In this way, the number of the channel matrices fed back to each SBS is equal to K. While in conventional IA-based networks, the global CSI should be fed back to all the SBSs, i.e., the number of the channel matrices fed back to each SBS is K^2. Therefore, the overhead of CSI feedback in cache-aided small-cell networks with IA can be reduced to $1/K$ of that in conventional IA-based wireless networks, which makes it much easier to achieve IA in the proposed scheme.

III. POWER ALLOCATION ALGORITHMS FOR CACHE-AIDED SMALL-CELL NETWORKS

In this section, three PA algorithms with different objective functions are proposed in cache-aided small-cell network with limited backhaul, to maximize the total transmission rate, minimize the average outage probability or maximize the average satisfaction, respectively.

A. PA Algorithm for Maximizing Sum Rate

The transmission rate is an important metric to measure the performance of a wireless system directly, and a PA algorithm for maximizing the sum rate (PAMSR) of all the users in the network is proposed in this subsection, through which the spectrum efficiency of the cache-aided small-cell network can be maximized.

As mentioned above, for the L uncached users, they should obtain the contents via the limited backhaul due to the fact that their requested contents do not exist in the caches of SBSs. Thus the rate constraint of these L users should be satisfied as

$$\sum_{l\in\Omega} R^{[l]} \leq C_d, \tag{8}$$

where Ω is the set of the L uncached users. In addition, the total transmit power of the K users is constrained to be a constant, i.e.,

$$\sum_{k=1}^{K} P^{[k]} = P_{max}. \tag{9}$$

In the proposed scheme, IA is adopted to manage interference among SBSs, and thus the sum rate of users in the small-cell network can be expressed as

$$R_{sum} = \sum_{k=1}^{K} \log_2\left(1+\left|h^{[k]}\right|^2 \frac{P^{[k]}}{\sigma^2}\right). \tag{10}$$

Based on the above assumptions, we can optimize the transmit power allocated to each SBS to maximize the sum transmission rate of the network, and the objective function can be expressed as

$$\begin{aligned}
\text{(P1)} \quad & \max_{P^{[1]},P^{[2]},\ldots,P^{[K]}} \sum_{k=1}^{K} \log_2\left(1+\left|h^{[k]}\right|^2 \frac{P^{[k]}}{\sigma^2}\right) \\
s.\ t. \quad & P^{[k]} \geq 0,\ \forall k = 1,\ldots,K \\
& \sum_{l\in\Omega} \log_2\left(1+\left|h^{[l]}\right|^2 \frac{P^{[l]}}{\sigma^2}\right) \leq C_d \\
& \sum_{k=1}^{K} P^{[k]} \leq P_{max}.
\end{aligned} \tag{11}$$

(P1) in (11) is a convex optimization problem, and it can be solved by applying Karush-Kuhn-Tucker (KKT) conditions as in Theorem 1.

Thorem 1: The closed-form solution of the optimization problem in (11) can be obtained as

$$\begin{cases}
P^{[k]} = \left(\dfrac{1}{\lambda_2 \ln 2} - \dfrac{\sigma^2}{\left|h^{[k]}\right|^2}\right)^+, \ \forall k \in \Omega', \\
P^{[l]} = \left((1-\lambda_1)\dfrac{1}{\lambda_2 \ln 2} - \dfrac{\sigma^2}{\left|h^{[l]}\right|^2}\right)^+, \ \forall l \in \Omega,
\end{cases} \tag{12}$$

where Ω' is the set of $(K-L)$ cached users, $x^+ = \max(x,0)$, λ_1 and λ_2 should satisfy

$$\begin{cases}
\displaystyle\sum_{l\in\Omega} \log_2\left(1+\left|h^{[l]}\right|^2 \frac{\left((1-\lambda_1)\dfrac{1}{\lambda_2 \ln 2} - \dfrac{\sigma^2}{\left|h^{[l]}\right|^2}\right)^+}{\sigma^2}\right) \leq C_d, \\
\displaystyle\sum_{l\in\Omega}\left((1-\lambda_1)\frac{1}{\lambda_2 \ln 2} - \frac{\sigma^2}{\left|h^{[l]}\right|^2}\right)^+ + \sum_{k\in\Omega'}\left(\frac{1}{\lambda_2 \ln 2} - \frac{\sigma^2}{\left|h^{[k]}\right|^2}\right)^+ = P_{max}.
\end{cases} \tag{13}$$

Proof: First, we put the objective function, and the inequality and equality constraints into one equation by using Lagrange coefficient as

$$\begin{aligned}
L = & -\sum_{k=1}^{K} \log_2\left(1+\left|h^{[k]}\right|^2 \frac{P^{[k]}}{\sigma^2}\right) \\
& + \lambda_1\left(\sum_{l\in\Omega} \log_2\left(1+\left|h^{[l]}\right|^2 \frac{P^{[l]}}{\sigma^2}\right) - C_d\right) \\
& + \lambda_2\left(\sum_{k=1}^{K} P^{[k]} - P_{max}\right) \\
& - \omega_1 P^{[1]} - \omega_2 P^{[2]} - \cdots - \omega_K P^{[K]}.
\end{aligned} \tag{14}$$

Then, the optimal values should satisfy the conditions in (15) (on the next page), according to which, we can obtain the closed-form solution of (P1) as (12), where λ_1 and λ_2 should satisfy (13). ∎

Observing the closed-form solution for (P1) in (12), we can find that it is similar to that of the PA problem in conventional IA networks. The noise level of the kth user is equal to $\frac{\sigma^2}{\left|h^{[k]}\right|^2}$, and we can conclude that, the higher the user's noise level is, the less transmit power this user will obtain. Nevertheless, the difference is that the sum rate of the L uncached users is limited in our proposed scheme, and the maximum water level of these L users is lower than or equal to that of the $(K-L)$ cached users, referring to the conventional water-filling strategy.

$$\begin{cases} (-1+0)\dfrac{\dfrac{\left|h^{[1]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[1]}\right|^2\dfrac{P^{[1]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_1=0, \\ (-1+0)\dfrac{\dfrac{\left|h^{[2]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[2]}\right|^2\dfrac{P^{[2]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_2=0, \\ \cdots\cdots \\ (-1+0)\dfrac{\dfrac{\left|h^{[k]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[k]}\right|^2\dfrac{P^{[k]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_k=0,\ \forall k\in\Omega^{'}, \\ \cdots\cdots \\ (-1+\lambda_1)\dfrac{\dfrac{\left|h^{[l]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[l]}\right|^2\dfrac{P^{[l]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_l=0,\ \forall l\in\Omega, \\ \cdots\cdots \\ \lambda_1\left(\displaystyle\sum_{l\in\Omega}\log_2\left(1+\left|h^{[l]}\right|^2\frac{P^{[l]}}{\sigma^2}\right)-C_d\right)=0, \\ \lambda_2\left(\displaystyle\sum_{k=1}^{K}P^{[k]}-P_{max}\right)=0, \\ \omega_k P^{[k]}=0,\ \forall k=1,\ldots,K, \\ \lambda_1,\lambda_2\geq 0. \end{cases} \tag{15}$$

B. PA Algorithm for Minimizing Average Outage Probability

The spectrum efficiency of the cache-aided small-cell network with limited backhaul can be optimized by the PAMSR algorithm in (11). However, when the rate requirement of each user is also considered, outage probability is more effective to reflect each user's satisfaction compared to spectrum efficiency. Outage probability simply implies the probability that the user's rate requirement cannot be met due to channel variations. When outage occurs, the quality of service (QoS) of this user will drop dramatically. Thus a PA algorithm for minimizing the average outage probability (PAMAOP) is proposed in this subsection.

We assume that the rate requirements of all the K users are $R_{tar}^{[1]}$, $R_{tar}^{[2]}$, …, $R_{tar}^{[K]}$. For the sake of simplicity, we also assume that the rate requirements of the L uncached users via backhaul links are lower than those of the $(K-L)$ cached users. This is reasonable, due to the fact that the delivery rate of the backhaul is limited.

To derive the PAMAOP algorithm, Proposition 1 is first presented to denote the minimal transmit power of the kth SBS that to meet the rate requirement of its corresponding mobile user.

Proposition 1: The minimal transmit power of the kth SBS to satisfy the rate requirement of its corresponding mobile user, $R_{tar}^{[k]}$, can be denoted as

$$P_{min}^{[k]}=\frac{\left(2^{R_{tar}^{[k]}}-1\right)\sigma^2}{\left|h^{[k]}\right|^2}. \tag{16}$$

Proof: When interferences are completely eliminated through IA, the transmission rate of the kth user in our proposed scheme can be expressed as (7). Besides, in order to meet its rate requirement, the transmission rate of the kth user should satisfy the following condition.

$$R^{[k]}\geq R_{tar}^{[k]}. \tag{17}$$

From (7) and (17), we can obtain

$$\log_2\left(1+\frac{\left|h^{[k]}\right|^2}{\sigma^2}P^{[k]}\right)\geq R_{tar}^{[k]}. \tag{18}$$

According to (18), we can obtain

$$P^{[k]}\geq\frac{\left(2^{R_{tar}^{[k]}}-1\right)\sigma^2}{\left|h^{[k]}\right|^2}=P_{min}^{[k]}. \tag{19}$$

Thus $P_{min}^{[k]}$ is the minimal value of the kth SBS's transmit power to meet its rate requirement $R_{tar}^{[k]}$. ■

According to its definition, the outage probability of the kth user can be expressed as

$$\Pr^{[k]}\{\text{outage}\}=\Pr\left\{R^{[k]}<R_{tar}^{[k]}\right\}. \tag{20}$$

Based on (20), the average outage probability of all the users can be defined as

$$\eta=\frac{1}{K}\sum_{k=1}^{K}\Pr\left\{R^{[k]}<R_{tar}^{[k]}\right\}. \tag{21}$$

From (21), we can know that the smallest value of η is 0 when rate requirements of all the users can be met, while its largest value is 1 when no rate requirement can be satisfied.

According to the definition of η in (21), the PAMAOP algorithm in cache-aided small-cell networks with limited backhaul can expressed as

$$\begin{aligned} \text{(P2)}\quad & \min_{P^{[1]},P^{[2]},\ldots,P^{[K]}}\ \frac{1}{K}\sum_{k=1}^{K}\Pr\left\{R^{[k]}<R_{tar}^{[k]}\right\} \\ s.\,t.\quad & P^{[k]}\geq 0,\ \forall k=1,\ldots,K \\ & \sum_{l\in\Omega}R^{[l]}\leq C_d \\ & \sum_{k=1}^{K}P^{[k]}\leq P^{max}. \end{aligned} \tag{22}$$

(P2) appears to be a complex combinatorial optimization problem, which is difficult to solve. Nevertheless, we can see that the purpose of the PAMAOP algorithm is to make more users meet their rate requirements. Thus we can solve the problem by allocating appropriate power to each user to maximize the number of users that can satisfy their own rate requirements.

Base on Proposition 1, we sort the minimal transmit powers of the K SBSs to meet their rate requirements in the ascending order. Then we give priority to the SBS whose minimal transmit power is the smallest of all. If its minimal transmit power is lower than the total power, we can allocate the minimal transmit power to this user to meet its rate requirement. In this way, more power will be left to make more users meet their rate requirements. Subsequently, we can allocate the remaining power to other users according to the above mentioned method, and so on, until all the remaining power is used up. Therefore, the average outage probability can be optimized to be minimal by this method due to the fact that more users can meet their rate requirements, which is summarized in Algorithm 1.

Algorithm 1 PAMAOP Algorithm

```
1: Calculate the minimal transmit power of all the SBSs to meet their rate requirements according to (16).
2: Sorting the minimal values of transmit power of the $K$ users in ascend order.
3: Choosing the $m$th user whose minimal value of transmit power is the smallest of all the remaining users.
4: if $m \in \Omega$, then
5:     if $P^{[m]} \leq P_{max}$ then
6:         if $R^{[m]} \leq C_d$ then
7:             We can allocate the minimal power to the $m$th user.
8:             $P_{max} = P_{max} - P^{[m]}$.
9:             $C_d = C_d - R^{[m]}$.
10:            Jump into step 3.
11:        else
12:            Choosing the $n$th user whose minimal value of transmit power is the smallest of all the remaining cached users.
13:            $P^{[m]} = P^{[n]}$, $m = n$.
14:            Jumping into step 21.
15:        end if
16:    else
17:        We should allocate the remaining power to maximize the sum rate of all the remaining users.
18:        Jumping into step 30.
19:    end if
20: else if $m \notin \Omega$, then
21:    if $P^{[m]} \leq P_{max}$ then
22:        We can allocate the minimal power to the $m$th user.
23:        $P_{max} = P_{max} - P^{[m]}$.
24:        Jump into step 3.
25:    else
26:        We should allocate the remaining power to maximize the sum rate of all the remaining users.
27:        Jumping into step 30.
28:    end if
29: end if
30: The solutions can be obtained.
```

C. PA Algorithm for Maximizing Average Satisfaction

In last subsection, the average outage probability is minimized according to Algorithm 1 for the proposed scheme. In the PAMOAP algorithm, the outage probability will become lower only when the rate requirements of more users can be fully met. Nevertheless, in practical systems, if the rate requirements of users cannot be all satisfied, we should try to maximize the rate of each user to guarantee the fairness, instead of only meeting the requirements of some of the users. Thus in this subsection, a PA algorithm for maximizing the average satisfaction (PAMAS) is proposed.

First, we define the average satisfaction of all the users as

$$\Lambda=\frac{1}{K}\sum_{k=1}^{K}\min\left(\frac{R^{[k]}}{R_{tar}^{[k]}},1\right)=\frac{1}{K}\sum_{k=1}^{K}\min\left(\frac{\log_2\left(1+\left|h^{[k]}\right|^2\frac{P^{[k]}}{\sigma^2}\right)}{R_{tar}^{[k]}},1\right). \tag{23}$$

The largest value of Λ is 1 when the rate requirements of all the users can be satisfied. From (16) and (23), we can also know that Λ will decrease if we allocate more power than $P_{min}^{[k]}$ to the kth user. This is because if the rate requirement of the kth user is already met, increasing $P^{[k]}$ will decrease the power allocated to other users. To maximize the average satisfaction, the objective function of the problem can be expressed as

$$\text{(P3)}\ \max_{P^{[1]},P^{[2]},\ldots,P^{[K]}}\ \frac{1}{K}\sum_{k=1}^{K}\min\left(\frac{\log_2\left(1+\left|h^{[k]}\right|^2\frac{P^{[k]}}{\sigma^2}\right)}{R_{tar}^{[k]}},1\right)$$

$$\begin{aligned} s.\,t.\quad & P^{[k]}\geq 0,\ \forall k=1,\ldots,K\\ & \sum_{l\in\Omega} R^{[l]}\leq C_d\\ & \sum_{k=1}^{K} P^{[k]}\leq P_{max}. \end{aligned} \tag{24}$$

(P3) is difficult to solve. In order to reduce the computational complexity, we discuss it in two cases as follows.

1) $P_{max} < \sum\limits_{k=1}^{K} P_{min}^{[k]}$:

When $P_{max} < \sum\limits_{k=1}^{K} P_{min}^{[k]}$, some of the users cannot meet their rate requirements. We should allocate the total transmit power P_{max} to all the users to maximize the value of Λ. In addition, the transmit power of the kth user cannot be higher than $P_{min}^{[k]}$, if we want to maximize of the average satisfaction. Thus, the PA problem can be represented as

$$\text{(P4)}\ \max_{P^{[1]},P^{[2]},\ldots,P^{[K]}}\ \frac{1}{K}\sum_{k=1}^{K}\frac{1}{R_{tar}^{[k]}}\log_2\left(1+\left|h^{[k]}\right|^2\frac{P^{[k]}}{\sigma^2}\right)$$

$$\begin{aligned} s.\,t.\quad & 0\ \leq P^{[k]}\leq P_{min}^{[k]},\ \forall k=1,2,\ldots,K\\ & \sum_{l\in\Omega} R^{[l]}\leq C_d\\ & \sum_{k=1}^{K} P^{[k]}\leq P_{max}, \end{aligned} \tag{25}$$

where Λ is not expressed as the representation in (24), due to the fact that the transmit power of each user is already limited to be lower than its minimal transmit power to satisfy its rate requirement.

2) $P_{max} \geq \sum\limits_{k=1}^{K} P_{min}^{[k]}$:
In this situation, all users can met their rate requirement, i.e., the value of the average satisfaction can be equal to 1 on the condition that at least minimal transmit power is allocated to each user according to (16). Thus we allocate P_{max} to all the users to maximize their sum rate with their rate requirements, and the objective function can be represented as

$$
\begin{aligned}
\text{(P5)} \max_{P^{[1]},P^{[2]},\ldots,P^{[K]}} & \frac{1}{K}\sum_{k=1}^{K}\log_2\left(1+\left|h^{[k]}\right|^2\frac{P^{[k]}}{\sigma^2}\right) \\
s.\,t. \qquad & P^{[k]} \geq P_{min}^{[k]},\ \forall k=1,2,\ldots,K \\
& \sum_{l\in\Omega} R^{[l]} \leq C_d \\
& \sum_{k=1}^{K} P^{[k]} \leq P_{max}
\end{aligned} \tag{26}
$$

Thus to obtain the closed-form solutions of the PAMAS algorithm, (P4) and (P5) should be solved. First, the closed-form solution of (P4) is derived in Theorem 2.

Theorem 2: The closed-form solution of (P4) in (25) can be represented as

$$
\begin{cases}
P^{[k]}=\min\left(\left(\dfrac{1}{KR_{tar}^{[k]}\lambda_2\ln 2}-\dfrac{\sigma^2}{\left|h^{[k]}\right|^2}\right)^{+},P_{min}^{[k]}\right), \\
\hfill \forall k\in\Omega' \\
P^{[l]}=\min\left(\left((\dfrac{1}{KR_{tar}^{[l]}}-\lambda_1)\dfrac{1}{\lambda_2\ln 2}-\dfrac{\sigma^2}{\left|h^{[l]}\right|^2}\right)^{+},P_{min}^{[l]}\right), \\
\hfill \forall l\in\Omega
\end{cases} \tag{27}
$$

where λ_1 and λ_2 should meet (28) (on the next page).

Proof: First, we put the objective function, the inequality constraints and the equality constraints into an equation by using Lagrange coefficient as

$$
\begin{aligned}
L = & -\frac{1}{K}\sum_{k=1}^{K}\frac{1}{R_{tar}^{[k]}}\log_2\left(1+\left|h^{[k]}\right|^2\frac{P^{[k]}}{\sigma^2}\right) \\
& +\lambda_2\left(\sum_{k=1}^{K}P^{[k]}-P_{max}\right) \\
& +\lambda_1\left(\sum_{l\in\Omega}\log_2\left(1+\left|h^{[l]}\right|^2\frac{P^{[l]}}{\sigma^2}\right)-C_d\right) \\
& -\omega_1P^{[1]}-\omega_2P^{[2]}-\cdots-\omega_KP^{[K]}.
\end{aligned} \tag{29}
$$

Then, we can obtain that the optimal values should satisfy the following equations according to the KKT conditions.

$$
\begin{cases}
\left(-\dfrac{1}{KR_{tar}^{[1]}}+0\right)\dfrac{\dfrac{\left|h^{[1]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[1]}\right|^2\dfrac{P^{[1]}}{\sigma^2}\right)ln2}+\lambda_2-\omega_1=0 \\
\left(-\dfrac{1}{KR_{tar}^{[2]}}+0\right)\dfrac{\dfrac{\left|h^{[2]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[2]}\right|^2\dfrac{P^{[2]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_2=0 \\
\cdots \\
\left(-\dfrac{1}{KR_{tar}^{[k]}}+0\right)\dfrac{\dfrac{\left|h^{[k]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[k]}\right|^2\dfrac{P^{[k]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_k=0,\ \forall k\in\Omega' \\
\cdots \\
\left(-\dfrac{1}{KR_{tar}^{[l]}}+\lambda_1\right)\dfrac{\dfrac{\left|h^{[l]}\right|^2}{\sigma^2}}{\left(1+\left|h^{[l]}\right|^2\dfrac{P^{[l]}}{\sigma^2}\right)\ln 2}+\lambda_2-\omega_l=0,\ \forall l\in\Omega \\
\cdots \\
\lambda_1\left(\sum\limits_{l\in\Omega}\log_2\left(1+\left|h^{[l]}\right|^2\dfrac{P^{[l]}}{\sigma^2}\right)-C-d\right)=0 \\
\lambda_2\left(\sum\limits_{k=1}^{K}P^{[k]}-P_{max}\right)=0 \\
\omega_kP^{[k]}=0,\ \forall k=1,\ldots,K \\
\lambda_1,\lambda_2\geq 0
\end{cases} \tag{30}
$$

Thus we can obtain the close-form solution of P(4) as (27), in which λ_1 and λ_2 should satisfy (28). ■

Then, the closed-form solution of (P5) in (26) is derived in Theorem 3.

Theorem 3: The closed-form solution of (P5) in (26) can be expressed as

$$
\begin{cases}
P^{[k]}=\left(\dfrac{1}{K\lambda_2\ln 2}-\dfrac{\sigma^2}{\left|\widehat{h}^{[k]}\right|^2}\right)^{+}+P_{min}^{[k]},\ \forall k\in\Omega', \\
P^{[l]}=\left(\left(\dfrac{1}{K}-\lambda_1\right)\dfrac{1}{\lambda_2\ln 2}-\dfrac{\sigma^2}{\left|\widehat{h}^{[l]}\right|^2}\right)^{+}+P_{min}^{[l]},\ \forall l\in\Omega,
\end{cases} \tag{31}
$$

where λ_1 and λ_2 should satisfy (32) (on the next page).

In (31), $\left|\widehat{h}^{[k]}\right|^2$ can be expressed as

$$
\left|\widehat{h}^{[k]}\right|^2=\frac{\left|h^{[k]}\right|^2}{1+\dfrac{\left|h^{[k]}\right|^2P_{min}^{[k]}}{\sigma^2}},\quad \forall k=1,2,\ldots,K. \tag{33}
$$

Proof: When $P_{max} \geq \sum\limits_{k=1}^{K} P_{min}^{[k]}$, all the users can meet their rate requirements. Therefore, we can suppose that the

$$\begin{cases} \sum_{l\in\Omega}\log_2\left(1+\left|h^{[l]}\right|^2 \frac{\min\left(\left(\left(\frac{1}{KR_{tar}^{[l]}}-\lambda_1\right)\frac{1}{\lambda_2\ln 2}-\frac{\sigma^2}{\left|h^{[l]}\right|^2}\right)^+, P_{min}^{[l]}\right)}{\sigma^2}\right)\le C_d, \\ \sum_{l\in\Omega}\min\left(\left(\left(\frac{1}{KR^{[l]}_{tar}}-\lambda_1\right)\frac{1}{\lambda_2\ln 2}-\frac{\sigma^2}{\left|h^{[l]}\right|^2}\right)^+, P^{[l]}_{min}\right)+\sum_{k\in\Omega'}\min\left(\left(\frac{1}{KR^{[k]}_{tar}\lambda_2\ln 2}-\frac{\sigma^2}{\left|h^{[k]}\right|^2}\right)^+, P^{[k]}_{min}\right)=P_{max}. \end{cases} \tag{28}$$

$$\begin{cases} \sum_{l\in\Omega}\log_2\left(1+\left|\widehat{h}^{[l]}\right|^2 \frac{\left(\left(\frac{1}{K}-\lambda_1\right)\frac{1}{K\lambda_2\ln 2}-\frac{\sigma^2}{\left|\widehat{h}^{[l]}\right|^2}\right)^+ + P_{min}^{[l]}}{\sigma^2}\right)\le C_d, \\ \sum_{\substack{k=1\\k\notin\Omega}}^{K}\left(\frac{1}{K\lambda_2\ln 2}-\frac{\sigma^2}{\left|\widehat{h}^{[k]}\right|^2}\right)^+ + \sum_{l\in\Omega}\left(\left(\frac{1}{K}-\lambda_1\right)\frac{1}{\lambda_2\ln 2}-\frac{\sigma^2}{\left|\widehat{h}^{[l]}\right|^2}\right)^+ = P_{max}-\sum_{k=1}^{K}P_{min}^{[k]}. \end{cases} \tag{32}$$

rate of the kth user is higher than the required rate, and we have

$$\begin{aligned} &\sum_{k=1}^{K}\log_2\left(1+\left|h^{[k]}\right|^2\frac{P^{[k]}}{\sigma^2}\right) \\ =&\sum_{k=1}^{K}\log_2\left(1+\left|h^{[k]}\right|^2\frac{\left(\widehat{P}^{[k]}+P_{min}^{[k]}\right)}{\sigma^2}\right) \\ =&\sum_{k=1}^{K}\log_2\left(\left(1+\frac{\left|h^{[k]}\right|^2 P_{min}^{[k]}}{\sigma^2}\right)\left(1+\frac{\sigma^2\left|h^{[k]}\right|^2}{\left|h^{[k]}\right|^2 P_{min}^{[k]}+\sigma^2}\frac{\widehat{P}^{[k]}}{\sigma^2}\right)\right) \\ =&\sum_{k=1}^{K}\log_2\left(1+\left|\widehat{h}^{[k]}\right|^2\frac{\widehat{P}^{[k]}}{\sigma^2}\right)+\text{constant}. \end{aligned} \tag{34}$$

Then the problem of (P5) can be represented as (35) according to (34).

$$\begin{aligned} \max_{P^{[1]},P^{[2]},\ldots,P^{[K]}}\ & \frac{1}{K}\sum_{k=1}^{K}\log_2\left(1+\left|\widehat{h}^{[k]}\right|^2\frac{\widehat{P}^{[k]}}{\sigma^2}\right)+\text{constant} \\ s.t.\quad & \widehat{P}^{[k]}\ge 0,\ \forall k=1,\ldots,K \\ & \sum_{l\in\Omega}\log_2\left(1+\left|h^{[l]}\right|^2\frac{\left(\widehat{P}^{[l]}+P_{min}^{[l]}\right)}{\sigma^2}\right)\le C_d \\ & \sum_{k=1}^{K}\widehat{P}^{[k]}\le P_{max}-\sum_{k=1}^{K}P_{min}^{[k]}, \end{aligned} \tag{35}$$

where $\left|\widehat{h}^{[k]}\right|$ can be denoted as (33). The objective function in (35) is similar to the PA problem for maximizing the sum transmission rate, and we can use the KKT conditions to obtain the solution. Thus the closed-form solution of (P5) when $P_{max}\ge\sum_{k=1}^{K}P_{min}^{[k]}$ can be expressed as (31), where λ_1 and λ_2 should meet (32). ■

Based on Theorem 2 and Theorem 3, we can summarized the PAMAS algorithm as Algorithm 2.

Algorithm 2 PAMAS Algorithm

```
1: Calculate $P_{min}^{[k]}$ according to (16), $k=1,\ldots,K$.
2: if $P_{max}<\sum_{k=1}^{K}P_{min}^{[k]}$ then
3:     Allocate optimal transmit power to each user according to Theorem 2.
4: else
5:     Allocate optimal transmit power to each user according to Theorem 3.
6: end if
7: The algorithm ends.
```

D. Comparison and Summary

In the cache-aided small-cell network with limited backhaul, based on power and rate constraints, three different PA algorithms are proposed for different purposes. In Section III-A, in order to improve the sum rate of the users, a PAMSR algorithm was designed. Then in Section III-B, a PAMAOP algorithm

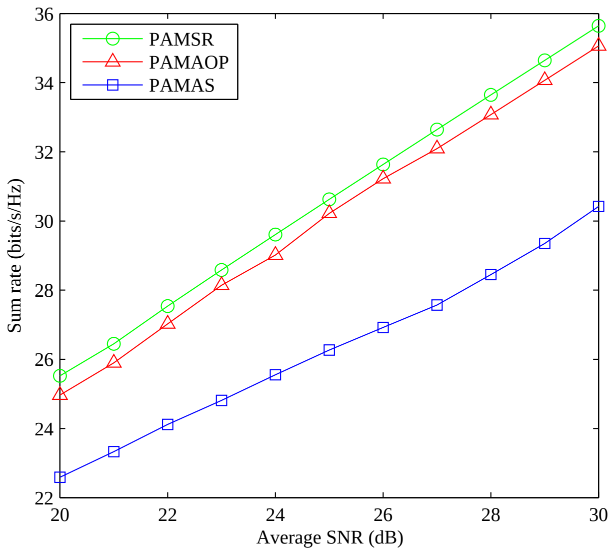

Fig. 3. Sum rate comparison of the three PA algorithms under different SNRs in a 5-user cache-aided small-cell network with limited backhaul, and $L = 2$.

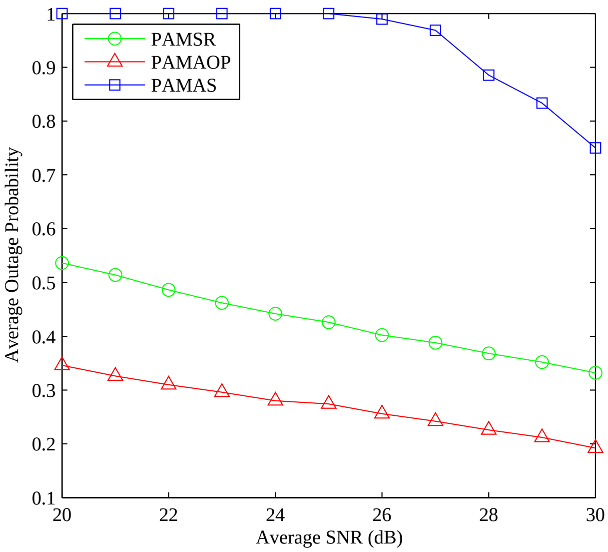

Fig. 4. Average outage probability comparison of the three PA algorithms under different SNRs in a 5-user cache-aided small-cell network with limited backhaul, and $L = 2$.

was proposed for minimizing the average outage probability. In addition, a PAMAS algorithm was proposed for maximizing the average satisfaction of users in Section III-C. For the PAMSR algorithm, it can improve spectrum efficiency of the network, while the PAMAOP algorithm can make more users meet their rate requirements. Nevertheless, the disadvantage of the PAMAOP algorithm is that the satisfaction of some users may be very low, although the requirements of the other users can be fully met. Compared to the PAMAOP algorithm, the PAMAS algorithm aims to make each user try to meet its rate requirement, and thus all the users can achieve relatively high performance. As analyzed above, all of these three algorithms have their unique advantages. Thus in practical scenarios, we can choose the appropriate PA algorithm to use according to the actual applications.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, simulation results are provided to show the performance of the proposed PA schemes for cache-aided small-cell networks. In the simulation, five SBSs and their corresponding mobile users are assumed to be in the network with limited backhaul. $M = N = 3$ antennas are equipped at each node of SBSs and mobile users. The total transmit power of the SBSs is constrained to 5W, i.e., $P_{max} = 5$W. In addition, the total capacity of the limited backhaul links for date transfer is 6 bits/s/Hz, i.e., $C_d = 6$bits/s/Hz. Without loss of generality, we assume that the 4th user and the 5th user can obtain their desired contents only via limited backhaul links due to that these contents are not cached in the corresponding SBSs, $L = 2$, and we have $R^{[4]} + R^{[5]} \leq 6$bits/s/Hz. The rate requirements of the five mobile users are assumed to be 12bits/s/Hz, 8bits/s/Hz, 6bits/s/Hz, 3bits/s/Hz, 1bits/s/Hz, respectively.

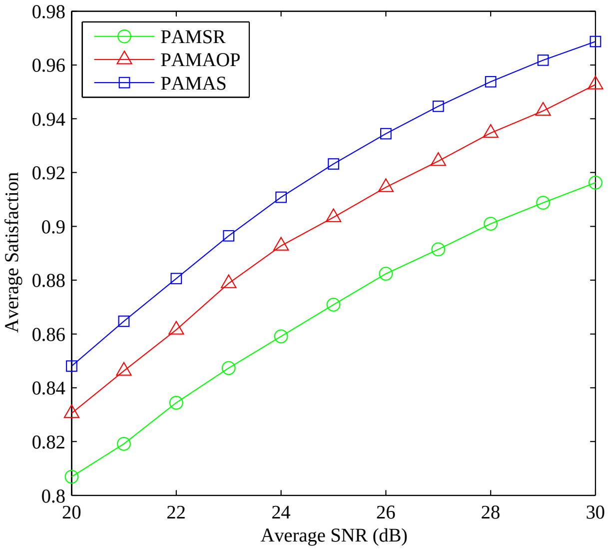

Fig. 5. Average satisfaction comparison of the three PA algorithms under different SNRs in a 5-user cache-aided small-cell network with limited backhaul, and $L = 2$.

First, the sum transmission rate, the average outage probability and the average satisfaction of the three proposed PA algorithms above are compared in Fig. 3, Fig. 4, and Fig. 5, respectively, with the average SNR ranging from 20 dB to 30 dB. In Fig. 3, the sum rate of these PA algorithms is compared. From the results, we can see that the sum rate of the network is optimized by the PAMSR algorithm, which is much higher than that of the other two algorithms. In addition, the sum rate of the PAMAOP algorithm is higher than that of the PAMAS algorithm, this is due to the fact that the power is allocated to the users whose rate requirements are easier to be satisfied with priority, and this can achieve relatively high sum rate. Then the average outage probability of the mobile users is compared in Fig. 4, with different PA algorithms. It is shown that the average outage probability of the PAMAOP algorithm is always much lower than the

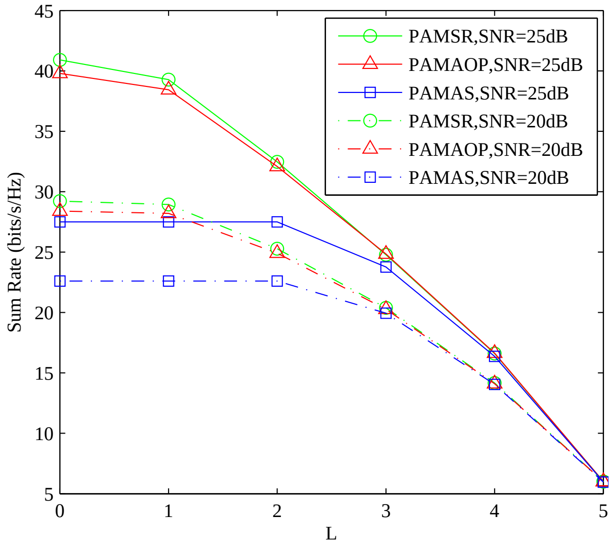

Fig. 6. Sum rate comparison of the three PA algorithms with different L in a 5-user cache-aided small-cell network with limited backhaul. SNR is set to 20dB and 25dB.

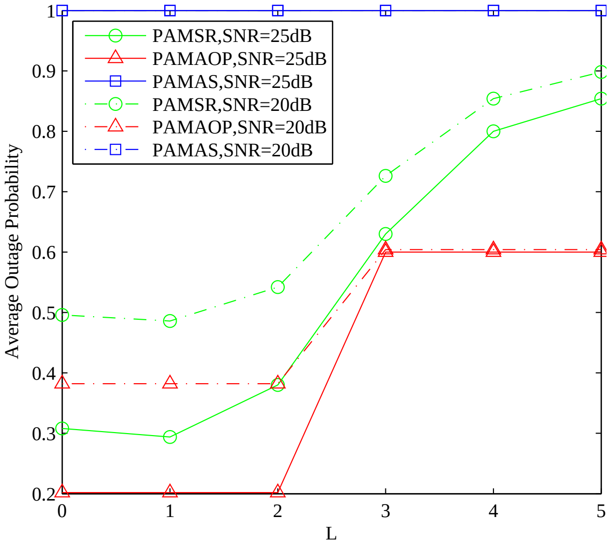

Fig. 7. Average outage probability comparison of the three PA algorithms with different L in a 5-user cache-aided small-cell network with limited backhaul. SNR is set to 20dB and 25dB.

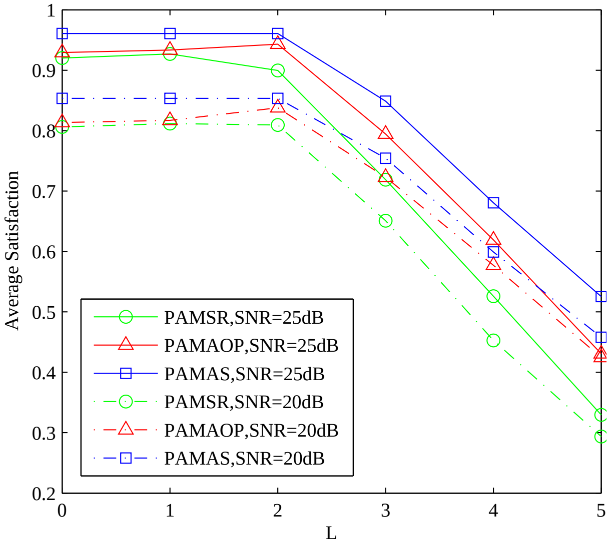

Fig. 8. Average satisfaction comparison of the three PA algorithms with different L in a 5-user cache-aided small-cell network with limited backhaul. SNR is set to 20dB and 25dB.

other two algorithms, because the average outage probability can be minimized by the PAMAOP algorithm according to (22). Besides, the average outage probability of the PAMAS algorithm is higher than the two others algorithms. This is due to the fact that the transmit power allocated to each user cannot approach its minimal required power, when $P_{max} < \sum_{k=1}^{5} P_{min}^{[k]}$, and thus all of the requirements of these users cannot be met in this case. In Fig. 5, the average satisfaction of the users is compared with different PA algorithms. From the results, we can see that the average satisfaction of the users with the PAMAS algorithm is always larger than that with the other two PA algorithms. This is because the average satisfaction can be optimized by the PAMAS algorithm according to Algorithm 2. Besides, the average satisfaction of the PAMSR algorithm is lowest, this is due to the fact that extremely high power can be allocated to the users with better channel but lower requirement by the PAMSR algorithm, which make the PA not fair among users.

Then the sum transmission rate, the average outage probability and the average satisfaction of the three proposed PA algorithm are compared in Fig. 6, Fig. 7, and Fig. 8, respectively, with the different number of uncached users, L. Two SNR values, 20dB and 25dB, are considered. The sum rate of the PA algorithms is considered in Fig. 6 with different L. From the results, we can see that when L becomes larger, less required contents are stored in the caches, and the sum rate of the network will be limited by the backhaul links. Specially, when L=5, no contents is stored in the edge caches, and the sum rate is limited to $C_d = 6$bits/s/Hz. In addition, we can see the when SNR becomes higher, the sum rate will become larger too. The average outage probability of the PA algorithms is compared in Fig. 7 with different L. From the results, we can know that the outage probability is becomes larger with larger L, due to the fact that more users will require data streams from the limited backhaul, and their requirements cannot be met. In Fig. 8, the average satisfaction of the mobile users is compared in Fig. 8 with different L. Form the results, it is shown that the average satisfaction will become smaller with larger L. This is because the less resource can be utilized to support the transmission of the users with only limited backhaul, when L becomes larger. In addition, from Fig. 6 to Fig. 8, we can also find that the relationship of the performance for these three algorithms is also consistent with the analysis in Fig. 3 to Fig. 5.

V. CONCLUSIONS

In this paper, we proposed a cache-aided small-cell scheme with limited backhaul, and IA was utilized to manage the interference among cells. In the scheme, the challenge of CSI of IA can be overcome by the local exchange via backhaul. Nevertheless, the CSI exchange takes up some of the resource of backhaul, and the rate of date delivery via backhaul is thus limited, which results in the difference in the transmission rate of the contents cached or uncached. Thus three PA algorithms were proposed to maximize the sum rate, to minimize the average outage probability, and to maximize the average satisfaction, respectively, considering the uniqueness of caching-aided small-cell networks. To make the algorithms easier to solve, their closed-form solutions were also derived. Finally, plenty of simulation results were provided to show the effectiveness of the proposed PA algorithms for the cache-aided small-cell networks.

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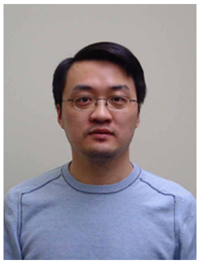

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