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Jiachen Yang*, Chaofan Ma, Jiabao Man, Huifang Xu, Gan Zheng, and Houbing Song

Abstract: The proliferation of mobile devices that support the acceleration of data services (especially smartphones) has resulted in a dramatic increase in mobile traffic. Mobile data also increased exponentially, already exceeding the throughput of the backhaul. To improve spectrum utilization and increase mobile network traffic, in combination with content caching, we study the cooperation between primary and secondary networks via content caching. We consider that the secondary base station assists the primary user by pre-caching some popular primary contents. Thus, the secondary base station can obtain more licensed bandwidth to serve its own user. We mainly focus on the time delay from the backhaul link to the secondary base station. First, in terms of the content caching and the transmission strategies, we provide a cooperation scheme to maximize the secondary user's effective data transmission rates under the constraint of the primary users target rate. Then, we investigate the impact of the caching allocation and prove that the formulated problem is a concave problem with regard to the caching capacity allocation for any given power allocation. Furthermore, we obtain the joint caching and power allocation by an effective bisection search algorithm. Finally, our results show that the content caching cooperation scheme can achieve significant performance gain for the primary and secondary systems over the traditional two-hop relay cooperation without caching.

Key words: cooperative cognitive radio network; content caching; power allocation

1 Introduction

Recent developments in mobile devices for smartphones and tablets have driven access to

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multimedia content at any time, resulting in an explosive increase in data traffic. Cisco expects that traffic demand will grow monthly by 2019[1]. In addition, massive mobile data traffic requires more spectrum for efficient transmission. However, available spectrum resources are suffering from an extreme shortage. Cognitive Radio (CR) technology is an emerging technology that has the potential to address network frequency requirements[2]. On the basis of the properties of available side information and the priori rules of off-spectrum enabling, the authors summarized three spectrum sharing methods in non-cooperative CR: overlay, underlay, and interweave overlay[3]. The limited spectrum resources inspire us to find a more reasonable method, namely, the CR Network (CRN)[4], to make the best use of the spectrum. Unlike the traditional wireless networks that allocate radio

resources statically, the CRN can realize dynamic allocation of the spectrum resource. The CRN helps in using the spectrum bands that have not been fully exploited and achieves the improved performance of the system. With dynamically allocated spectrum resource, the CRN poses sophisticated optimization problems that need to be addressed to improve the radio resource efficiency. Many studies have been conducted on how to maximize the spectrum resource usage. In Ref. [5], the optimization techniques to maximize spectrum resource usage are applied to centralized and decentralized CRNs. With the ever-growing complexity of ultra-dense heterogeneous networks and the continuous fluctuation of network environments, self-organization approaches are applied to achieve this network paradigm and facilitate spectrum sensing, spectrum management, and sharing[6]. Cooperative CRN (CCRN) is a promising technology to solve the spectrum scarcity problem by improving spectrum utilization efficiency in wireless networks. Cooperation among the CRNs is introduced to increase the data transmission throughput and accelerate the data transmission. In this strategy, the Secondary User (SU) can be used as a relay for the Primary Users (PUs) when the PUs can access the SUs and the channels between the primary transmitter and PUs are weak, thereby achieving a win-win strategy for both users[7–9]. In Ref. [10], a resource allocation strategy for cooperative multi-relay CRNs is considered in which the SUs can serve as the relay of the PUs. In Ref. [11], a power-optimized scheme for collaborative spectrum sensing among secondary nodes is proposed to achieve the optimal optimization of the secondary nodes. In Ref. [12], an objective of maximizing energy efficiency to achieve better power allocation is considered in decode and forward relaying for CCRNs. Unlike the above works, in Ref. [13], both information and energy cooperation in CRNs are considered, and this joint consideration creates even stronger incentives to cooperate and substantially improves the radio resource efficiency. Most studies focused on providing more spectrum access opportunity for SUs and high transmission rates for both PUs and SUs.

Zhang et al.[14] proposed multi-hop routing algorithms that reduce the probability of spectrum handoff and rerouting upon PUs' arrival. The simultaneous consideration of both primary and secondary activities in the actual spectrum accessing in CRNs is taken into account in Ref. [15]. However,

most existing researches consider only the information and energy cooperation in CCRN and ignore the time delay because the primary data need to be fetched first from the Primary Base Station (PBS) to the Secondary Base Station (SBS) and then delivered to the PU. Cai et al.[16] investigated a cross-layer routing method for a multi-channel multi-hop CRN to minimize the delay from the source to a common destination, and in Ref. [17] they proposed a cross-layer distributed opportunistic routing protocol, in which the spectrum sensing and the relay selection are jointly considered to decrease the purpose of decreasing the delivery delay from source to destination. Motivated by this problem and the recent advances in wireless edge caching[18, 19], we aim to exploit caching capability at the SBS, which pre-fetches some popular files for the PUs so that it does not need to acquire it from the PBS, thus eliminating the delay due to transmission from the PBS to the SBS and save more energy to serve SUs. The literature on edge caching is rich. In Ref. [18], joint caching placement was investigated in femto base stations with limited cache storage. In Ref. [19], the caching scheme that stores the Most Popular Contents (MPC) based on Zero-Forcing BeamForming (ZFBF) transmission to achieve cooperation gain is studied. However, few studies employ the edge caching technique to improve the performance of CRNs, especially CCRN. Caching in CRNs is investigated in Ref. [20], where data retrieval probability is derived, but primary-secondary cooperation is not considered and the cooperation caching scheme in CCRNs is still not investigated.

In this paper, we consider the content cooperation between the primary and secondary systems in CCRN. First, a simple CCRN system model is considered. Then, on the basis of the system model, combined with the limited cache capacity and the transmit power, we formulate an optimal problem that aims to maximize SUs' transmission rate under the constraint of the minimum data transmission rate for PU. To solve the formulated problem, we provide an effective bisection algorithm.

To more clearly show the detailed improvements made in this paper compared with previously published conference papers, we list the following improvements. First, on the basis of the proposed theoretical basis of CCRNs, we added the necessary caching cooperation theory. To be specific, we introduced the theory of content caching and introduced

the application of content caching in CCRNs. Second, a more comprehensive and systematic introduction to the research significance and the detailed related work was presented, aiming to indicate the role of content caching. On the basis of the research conducted for this paper, future work was also summarized. Third, in accordance with the characteristics of the Rayleigh fading channel, the original calculation formula is more specifically expressed to clearly represent the variable characteristics. For the presented algorithm, further algorithm complexity is analyzed in detail. In addition to introducing the overall performance, we also considered the impact of additional key parameters on the content caching scheme in CCRN and added numerous simulation experiments to verify the performance of the cooperation scheme. Furthermore, a detailed analysis of the experimental results was presented.

The rest of this paper is organized as follows: The related works are reviewed in Section 2. The system models are introduced in detail in Section 3, including the network, caching, and transmission models. The formulation and derivation of the caching and power allocation are presented in Section 4. In Section 5, an effective bisection algorithm is designed. Simulation results and analysis are shown in Section 6. We conclude this paper and introduce future work in Section 7.

2　Related Work

This section introduces the approaches used to improve the spectrum efficiency in CCRN.

In recent years, researchers have dedicated great efforts to researching CCRNs from different aspects, such as information, throughput, and energy cooperation. Cai et al.[21] proposed a distributed data collection algorithm for CCRN without the time synchronization requirement to address the problem of time synchronization and fairness. Simeone et al.[22] studied a cooperation scheme wherein the PUs maximized transmission rates with the help of SUs, and in return some time slots are exploited to SUs, which competed for transmissions following a distributed power control mechanism. Xu and Li[23] presented multi-channel cellular networks based on OFDMA in CCRNs to address the resource allocation problem. Li et al.[24] considered the problem of multi-hop relay selection according to a network formation game on the basis of combined cooperation in both the time and

the frequency domains in CCRNs, which proved that cooperative multi-hop relaying can significantly benefit both the primary and secondary systems. Cao et al.[25] utilized the polarization character of electromagnetic waves in CCRN and maximized a weighted sum throughput of PUs and SUs via multi-timescale dynamic Markov decision process under energy constraints. Wang et al.[26] focused on a two-phase overlay cognitive two-way relay network. However, in the aforementioned literature, the cooperation schemes are based on the two-way relay cooperation, which the SBS first acquires the PU's information from the PBS and then transmits it to the PU. These schemes are not considered the optimum cooperation schemes due to the delay from the first access to required information.

Motivated by the relatively inexpensive network resources of storage capacity, the edge caching technique is considered one of the most effective techniques in reducing data access delay. This technique proactively fetches data at nearby base stations during off-peak times and contributes to the reduction in delay for users and backhaul usage. Edge caching technique has been well exploited in different wireless networks. In Ref. [18], Shanmugam et al. exploited caching on a femto base station to alleviate traffic pressure on backhaul links and focused on minimizing file downloading time by optimizing the content placement problem in a wireless network. Zhou et al.[27] studied cache-enabled heterogeneous cellular networks by considering the multicast capacity and proposed a stochastic content multicast scheduling algorithm to jointly optimize the average delay and the power costs subjected to a multiple access constraint. Content caching in device-to-device networks was proposed in Ref. [28]. The authors focused on the relationship between asymptotic scaling characteristics and content popularity statistics, and obtained an optimal scaling behavior via distributed caching scheme. Although the caching technique has been studied in traditional networks, the application of the caching technique in CRNs has not been clearly studied. Zhao et al.[20] applied caching in CRNs to reduce total cost under delay constraints. A services routing based caching scheme is proposed in Ref. [29], which can greatly lighten the load on the data center and maintain the advantages of global intelligent computing of traditional cloud computing. Although the issues of caching in CCRN have been investigated in several studies, our scheme is different from these studies

because the SBS exploits the time diversity of the secondary network and proactively improves the transmission rates of both systems based on the joint optimal content placement and power allocation.

3 System Model

3.1 Network model

In this article, we consider the cooperation between a primary system and a secondary system in a basic four-node CRN via content caching. The system model is shown in Fig. 1. We consider a primary system that includes one PBS and one PU and also considers a secondary system that includes one SU and one SBS. All devices except the SBS with multiple antennas are single antenna. In addition, we assume that the SBS has a limited cache capacity to store the primary and secondary content. Therefore, the SBS can simultaneously serve PUs and SUs with appropriate power using ZFBF[19, 30]. The SBS is considered capable of sensing the spectrum environment. When the PBS is not serving the PU, the licensed spectrum that belongs to the primary system can be shared to the secondary system. In addition, we consider all channels are quasi-static; thus, the channel gain remains constant during a period of time.

3.2 Transmission model

In CCRN, we consider that the available licensed bandwidth is unitized to 1 MHz and the time duration that a primary user is allowed to transmit a requested file over bandwidth is T. In terms of the cached primary and secondary content, a time slot T is divided into

Fig. 1   CCRN system model.

three parts: the first part is t_p, indicating the time taken by the uncached primary content for the PU; the second part is t_s, which is the time occupied by the uncached secondary content for the SU; and the last part is $T - t_p - t_s$, which indicates the time when the SBS simultaneously transmits the primary and secondary content. Taking this fact into account, we assume that the primary file cannot be successfully sent to the PU. We assume that the PBS transmit power and the SBS transmit power are P_p and P_s, respectively. The SBS also reasonably allocates a certain amount of power to serve the PU and its own users. Let x_p and x_s denote the signal of a requested file transmitted by the PBS and the SBS. The received signals at the PU from the PBS and the SBS are given by

$$y_p = \sqrt{P_p h_p} |d_p|^{-\frac{\alpha}{2}} x_p + \eta_p \qquad (1)$$

$$y_{sp} = \sqrt{\beta P_s h_{sp}} |d_{sp}|^{-\frac{\alpha}{2}} x_p + \eta_{sp} \qquad (2)$$

and the received signal at the SU is

$$y_s = \sqrt{(1-\beta) P_s h_s} |d_s|^{-\frac{\alpha}{2}} x_s + \eta_s \qquad (3)$$

where h_p and d_p are the channel fading coefficient and the distance from the PBS to the PU, respectively; h_{sp} and h_s are the channel fading coefficients from the SBS to the PU and its own SU, respectively; and d_{sp} and d_s denote the distances of the SBS to the PU and its own SU, respectively. The terms η_p, η_{sp}, and η_s represent Gaussian noise distributed with zero mean at the PU and SU, respectively. β denotes the ratio of the SBS power allocated to serve the PU, while the remaining portion of $(1-\beta)$ is reserved to serve the SU. For the sake of simplicity, we assume that the fading channels among the PBS, the SBS, the PU, and the SU are quasi-static Rayleigh with unit mean power. To achieve cooperation gain, we consider the MPC caching strategy. Specifically, the SBS equipped with multiple antennas can use the ZFBF approach to simultaneously serve the PUs and SUs over the licensed bandwidth[30]. Without loss of generality, the licensed bandwidth is normalized to 1 MHz. On the basis of the cached content of the PU and SU, we divide the transmission model into four types.

Type 1: When the primary and secondary files that are requested by the PU and SU are cached in the SBS, the SBS can simultaneously serve the PU and SU over the whole time T using ZFBF. The transmission data for PU and SU are respectively expressed as

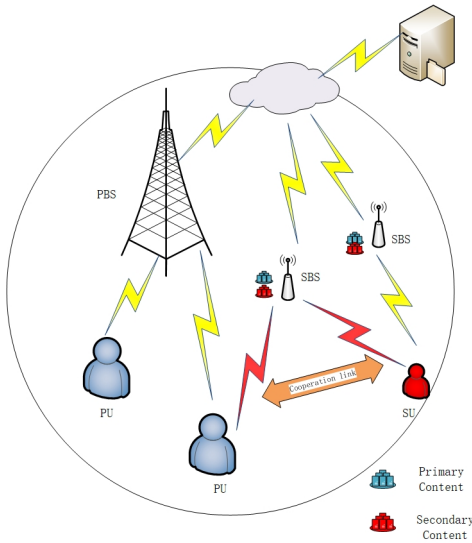$$R_1^p = R_p \cdot \Pr(T \log_2(1 + \frac{\beta P_s |h_{sp}|^2 d_{sp}^{-\alpha}}{H_0}) \geqslant S_p) \qquad (4a)$$

$$R_1^s = R_s \cdot \Pr(T\log_2(1 + \frac{(1-\beta)P_s|h_s|^2 d_s^{-\alpha}}{H_0}) \geqslant S_s)$$

(4b)

where H_0 is the noise power.

Type 2: When the primary content requested by the PU is cached in the SBS in advance and the secondary file is not cached in the SBS, the SBS needs a period t_s $(0 \leqslant t_s \leqslant T)$ to obtain the secondary file from the content server. The remaining time $(T - t_s)$ is used to transmit the PU's and SU's data. The transmission data for PU and SU are respectively given by

$$R_2^p = R_p \cdot \Pr((T - t_s)\log_2(1 + \frac{\beta P_s|h_{sp}|^2 d_{sp}^{-\alpha}}{H_0}) \geqslant S_p)$$

(5a)

$$R_2^s = R_s \cdot \Pr((T - t_s)\log_2(1 + \frac{(1-\beta)P_s|h_s|^2 d_s^{-\alpha}}{H_0}) \geqslant S_s)$$

(5b)

Type 3: Similarly, when the primary content requested by the PU is uncached content, the SBS takes t_p $(0 \leqslant t_p \leqslant T)$ time to obtain the file. The requested secondary file has been cached in the SBS. Therefore, the remaining time $(T - t_p)$ is used to transmit the PU's and the SU's data. The transmission data for PU and SU are respectively given by

$$R_3^p = R_p \cdot \Pr((T - t_p)\log_2(1 + \frac{\beta P_s|h_{sp}|^2 d_{sp}^{-\alpha}}{H_0}) \geqslant S_p)$$

(6a)

$$R_3^s = R_s \cdot \Pr((T - t_p)\log_2(1 + \frac{(1-\beta)P_s|h_s|^2 d_s^{-\alpha}}{H_0}) \geqslant S_s)$$

(6b)

Type 4: Both requests from the PU and SU are not cached at the SBS. Thus, the cooperation period $(T - t_s - t_p)$ is utilized to transmit the data of PU and SU by the SBS with different power allocation. The transmission data for PU and SU are respectively expressed as

$$R_4^p = R_p \cdot \Pr((T - t_s - t_p)\log_2(1 + \frac{\beta P_s|h_{sp}|^2 d_{sp}^{-\alpha}}{H_0}) \geqslant S_p)$$

(7a)

$$R_4^s = R_s \cdot \Pr((T - t_s - t_p)\log_2(1 + \frac{(1-\beta)P_s|h_s|^2 d_s^{-\alpha}}{H_0}) \geqslant S_s)$$

(7b)

In this paper, the effective transmission rate expression can be converted to a more specific form due to the Rayleigh fading channel. To clarify this matter, Eq. (4a) is used as an example to write the expression

of the transformation,

$$R_1^p = R_p \cdot e^{-\xi_1^p}$$

(8)

where $\xi_1^p = ((2^{\frac{S_p}{T}} - 1) \cdot H_0 \cdot d_{sp}^{\alpha})/(\beta \cdot P_s)$, and the rest of the equations are similar to this conversion.

3.3　Caching model

We consider that the primary and the secondary systems are different; thus, the PUs and the SUs are interested in different video contents. For instance, the users served by small cells prefer traditional videos, while users of the mactocell prefer modern videos. Generally, the cached video files are common popular files. Thus, the privacy and security of the cached primary and secondary files are not considered in this article, and the files involved in the privacy security are protected by encryption; this matter is not within the scope of this article. We denote the library of files requested by the PU and SU as $F_p \triangleq \{1, 2, 3, \ldots, M\}$ and $F_s \triangleq \{1, 2, 3, \ldots, N\}$, respectively. For simplicity, we assume that primary and secondary content have the same size. Without loss of generality, we suppose that the popularities of primary and secondary content follow the Zipf law, which is widely used in Refs. [19, 31] and are given by $f_i^p = \frac{i^{-\gamma_p}}{\sum\limits_{n=1}^{M} n^{-\gamma_p}}$ $(i \in F_p)$ and $f_j^s = \frac{j^{-\gamma_s}}{\sum\limits_{n=1}^{N} n^{-\gamma_s}}$ $(j \in F_s)$, where γ_p and γ_s denote the popularity of the primary and secondary files, respectively. The Zipf distribution describes the probability distribution of file popularity and satisfies the tailing feature. The specific distribution model is shown in Fig. 2.

Figure 2 shows that the probability of requesting files is more concentrated when the file concentration
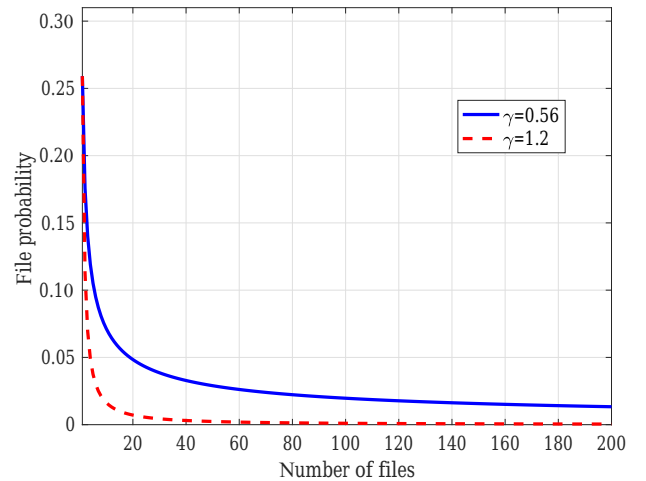

Fig. 2　Zipf probability distribution curve.

is larger. Specifically, when $\gamma = 1.2$, the requested file is basically concentrated on file numbers 1 to 20.

We also assume that both the primary and the secondary file popularities are descending in the index, i.e., $f_1^p \geqslant f_2^p \geqslant \cdots \geqslant f_M^p$ and $f_1^s \geqslant f_2^s \geqslant \cdots \geqslant f_N^s$, with $\sum_{i=1}^{M} f_i^p = 1$ and $\sum_{j=1}^{N} f_j^s = 1$, respectively. The primary and the secondary content that are stored in the content server are obtained by the wireless backhaul. In this paper, we consider SBS can pre-cache some popular files of the primary and secondary systems in off-peak period to serve the PU and SU. In return, the SBS gains more transmission time to access the primary spectrum to serve primary and secondary requests, which leads to a win-win situation for both systems. The primary and secondary content employ the MPC caching scheme according to the file popularity. We assume that the capacity C_o of the SBS's total cache capacity is used to the primary content to serve the PU while the remaining capacity of $(C - C_o)$ is reserved to store its own content.

4 Problem Formulation

In this paper, we aim to jointly optimize the caching capacity and power allocation strategies of the SBS to maximize the utility of the SBS, which is denoted as the total effective data transmission rates served by the SBS. Mathematically, on the basis of the above model analysis, we can formulate the problem as

$$\max_{C_o, \beta} \quad R^S(C_o, \beta) \overset{\Delta}{=} p_p \cdot p_s \cdot R_1^S + p_p \cdot R_2^S +$$
$$p_s \cdot R_3^S + R_4^s,$$
$$\text{s.t.,} \quad R^P(C_o, \beta) \overset{\Delta}{=} (p_p \cdot p_s \cdot R_1^P + p_p \cdot R_2^P +$$
$$p_s \cdot R_3^P + R_4^p) \geqslant R_{\text{th}},$$
$$0 \leqslant t_s \leqslant T, 0 \leqslant t_p \leqslant T, \ 0 \leqslant t_s + t_p \leqslant T,$$
$$0 \leqslant C_o \leqslant C, 0 \leqslant \beta \leqslant 1 \quad (9)$$

where $p_p \overset{\Delta}{=} \sum_{i=1}^{C_o} f_i^p$ and $p_s \overset{\Delta}{=} \sum_{j=1}^{C-C_o} f_j^s$ are the probabilities of the caching primary and secondary content, respectively. The $R_1^P \overset{\Delta}{=} R_1^p + R_4^p - R_2^p - R_3^p$ and $R_1^S \overset{\Delta}{=} R_1^s + R_4^s - R_2^s - R_3^s$, $R_2^P \overset{\Delta}{=} R_2^p - R_4^p$ and $R_2^S \overset{\Delta}{=} R_2^s - R_4^s$, $R_3^P \overset{\Delta}{=} R_3^p - R_4^p$ and $R_3^S \overset{\Delta}{=} R_3^s - R_4^s$ are the merging rates for the PU and SU, respectively. The first constraint indicates that the effective transmission rate of the primary user is greater than the demand threshold R_{th}. The second and third constraints denote that the content transmission time from the content

service to the SBS for both the PU and the SU through the backhaul link cannot exceed the whole time slot T. The fourth constraint represents that the cache capacity and the power consumption should be in a reasonable range.

Multiple variables are involved in the above problem, and we first study the property of caching placement C_o given power allocation β. We can easily see that the cache allocation C_o is an integer variable and different values determine the amount of primary and secondary files. For a given β, to find an optimal threshold C_o that satisfies PUs' target transmission rate, one can exploit the exhaustive search with $O(C)$ computational complicity. However, an efficient approach is not available. To address this challenge, we introduce a continuous variable $q = C_o/C, 0 \leqslant q \leqslant 1$. After we obtain an optimal q, then the optimal value C_o can be approximated by

$$C_o = \lceil qC \rceil \quad (10)$$

where $\lceil \cdot \rceil$ is the ceiling function.

The cumulative distribution function of the file popularity distribution of primary and secondary p_p and p_s following approximation of the sum of Zipf probabilities[31, 32] is useful.

$$p_p = \sum_{i=1}^{C_o} f_i^p \approx \frac{C_o^{1-\gamma_p} - 1}{M^{1-\gamma_p} - 1},$$
$$p_s = \sum_{j=1}^{C-C_o} f_j^s \approx \frac{(C - C_o)^{1-\gamma_s} - 1}{N^{1-\gamma_s} - 1} \quad (11)$$

Then, with Eqs. (10) and (11) substituted into $R^S(C_o, \beta)$, the effective data transmission of PU is given by

$$R^S(q, \beta) \overset{\Delta}{=} \frac{(qC)^{1-\gamma_p} - 1}{M^{1-\gamma_p} - 1} \cdot \frac{((1-q)C)^{1-\gamma_s} - 1}{N^{1-\gamma_s} - 1} \cdot$$
$$R_1^S + \frac{(qC)^{1-\gamma_p} - 1}{M^{1-\gamma_p} - 1} \cdot R_2^S +$$
$$\frac{((1-q)C)^{1-\gamma_s} - 1}{N^{1-\gamma_s} - 1} \cdot R_3^S + R_4^s \quad (12)$$

Formula (12) is a complex polynomial for caching allocation q and power ratio β. Thus, we study its convexity below.

We can find that for a given power ratio β, $R^S(q)$ is a concave function with regard to q, which can be proofed by the first and the second derivatives of $R^S(q)$. Next, we study the properties of $R^S(q, \beta)$ about β. To be specific, for any given caching allocation q, $R^S(q, \beta)$ is increasing in regard to β, and the objective function $R^S(q, \beta)$ is decreasing in β according to Eqs.

(4a) – (7a) and (4b) – (7b), respectively. The character is straightforward and the proof is omitted.

Complexity Analysis: According to Algorithm 1, the complexities of the search algorithm are $O(\log_2 \frac{\rho^U - \rho^L}{\varepsilon})$, where ε is convergence accuracy.

5   Bisection Algorithm

This section presents an effective algorithm to cope with the complicated problem. On the basis of the above analysis, we design the one-dimensional bisection search algorithm to solve problem (9), which maximizes the objective function of (9) while achieving the target data transmission of the primary network. The main idea is motivated by the basis bisection algorithm for solving the quasiconvex optimization problem. Generally speaking, we first consider the fact that the constraint $R^P(q, \beta) \geqslant R_{\text{th}}$ should hold with equality e.g., $R^P(q, \beta) = R_{\text{th}}$ to maximize the objective. Then, for a given power allocation β, we obtain the corresponding optimal caching allocation $\bar{q}$ by setting the first derivative as zero, and the optimal q^* that maximizes $R^P(q)$ is given by $q^* = \min(\bar{q}, 1)$. Next, combined with the optimal cache proportion, the minimum power portion β for satisfying the constraint $R^P(q, \beta) = R_{\text{th}}$ is obtained by the proposed bisection search algorithm. Finally, we obtain a joint optimal cache placement q and power ratio β for problem (9) by implementing our proposed scheme. The bisection algorithm is formally presented in Algorithm 1.

6   Simulation Results

In this section, the simulation results are presented to estimate the performance of the proposed caching cooperation scheme in CCRN and the impact of system parameters. We use the MATLAB simulation tool to complete the simulation, and the experimental parameters are shown in Table 1.

In Fig. 3, we plot the PU's rates for the transmission of its own content as a function of caching portion q

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Algorithm 1 A bisection search algorithm to solve problem (9)

1: Set the boundary values β^U, β^L for β
2: Given $\beta = (\beta^U + \beta^L)/2$, we find the optimal q^* by solving the first derivative to be zero;
3: If $R^P(\beta) < R_{\text{th}}$, set $\beta^L = \beta$; otherwise, set $\beta^U = \beta$;
4: Repeat Steps 2&3 until the solution is found and return the optimal β^* and the corresponding caching allocation q^*.

Table 1   Simulation parameters.

| Simulation parameter	Value
Primary content library, F_p	500
Secondary content library, F_s	300
Cache capacity of SBS, C	100
Number of antenna for SBS, N_a	2
Transmit power of PBS, P_p	40 dBm
Transmit power of SBS, P_s	13 dBm
Path loss exponent, α	3
Primary content popularity, γ_p	0.8
Secondary content popularity, γ_s	1.1
Noise power, H_0	−104 dBm
Distance of SBS to PU, d_{sp}	200 m
Distance of SBS to SU, d_s	300 m
Transmission time Slot, T	10 s
Rate requirement of PU, R_p	2 Mbps
Effective data rate requirement of PU, R_{th}	1.8 Mbps
Rate requirement of SU, R_s	1 Mbps
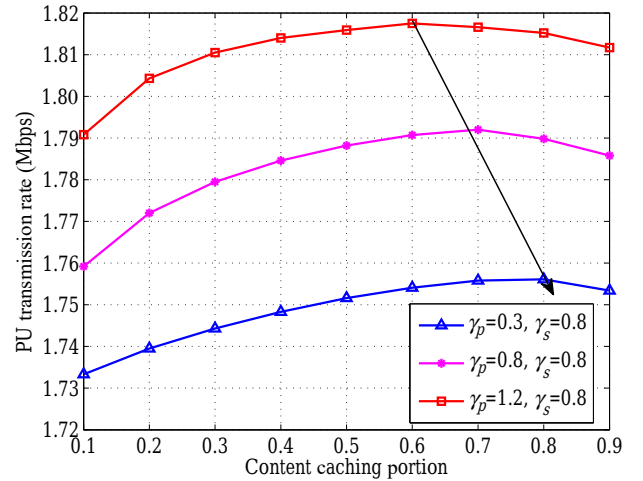
Fig. 3 Impact of PU transmission rates over Zipf parameters γ_p.

for three different values of the primary file popularity γ_p. We assume that the fixed power allocation β is 0.3. The optimum caching ratio for the primary content gradually reduces with increasing γ_p. Similarly, the achievable transmission rate of the primary user increases with γ_p because the PU's most popular content is more concentrated when the file popularity is increasing, which contributes to requiring small caching storage to cache the PU's most popular content. The remaining additional cache capacity can be utilized for the SU's content, thereby greatly improving the cooperation gains of the SBS.

Figure 4 shows the effective data transmission rates of PU as a function of caching portion q for three different distances between the SU and the SBS. We
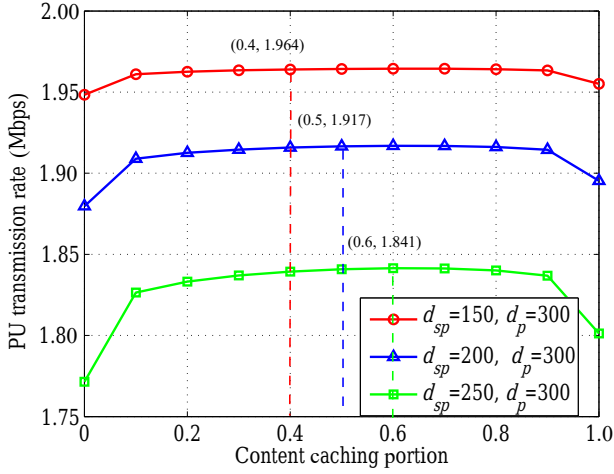
Fig. 4 Impact of PU transmission rates over the distance between SBS to the PU d_{sp}.

also assume that the fixed power allocation β is 0.3. The content popularity of the primary and secondary content is set to the same value, $\gamma_p = \gamma_s = 0.8$. The optimum caching ratio for the primary content gradually reduces with increasing distance. In addition, the achievable transmission rate of the primary user decreases with increasing d_{sp} because the signal fading and the transmission delay will increase with the increase in the transmission distance, which leads to a decrease in the simultaneous transmission time. Thus, the effective transmission rate is reduced. The fading caused by the transmission distance needs to be compensated through the larger caching capacity.

Figure 5 illustrates the content transmission rates regions of both PU and SU for different cooperation schemes. The proposed cooperation
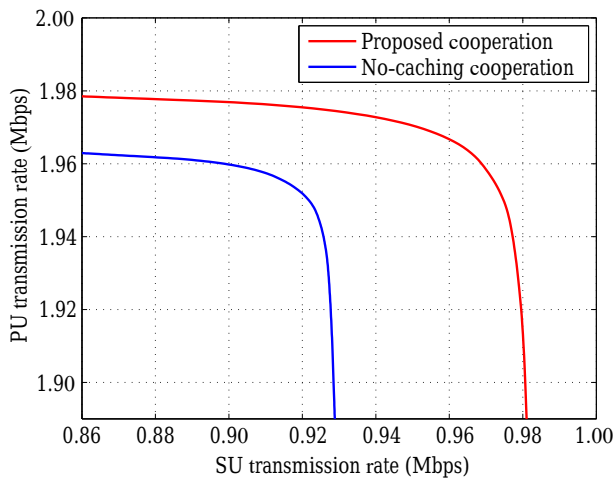
scheme outperforms the traditional relay cooperation scheme, in which the achievable rate region of the proposed scheme is greatly enlarged due to the content caching cooperation because the SBS can directly transmit the cached content to the PU and SU, thereby saving more transmission time to access the licensed bandwidth for the SBS to achieve more cooperation gains.

Figure 6 shows the impact of caching capacity C on the SU's achievable effective data transmission rates when the PU's required effective data transmission rates is achieved for both caching and relay cooperation schemes. As expected, the achievable rate R^S increases with the cache capacity C because as C increases, more required content for PU and SU can be directly and simultaneously transmitted, thereby reducing the transmission delay. Moreover, the effective transmission rate R^S increases obviously when the capacity is small. By contrast, the rates of SU tend to be constant when the file is large enough because the MPC for both PU and SU can be cached when the cache capacity is large enough. The proposed cooperation scheme outperforms the traditional relay cooperation scheme.

Figure 7 indicates that the effect of SBS transmit power on the achievable probability of SUs under the condition of successful transmission probability of the primary system. The effective data transmission rate that the SU can achieve also gradually increases with the SBS transmits power increases. Compared with the no-caching cooperation scheme, given that cache-enabled cooperation can directly deliver the content
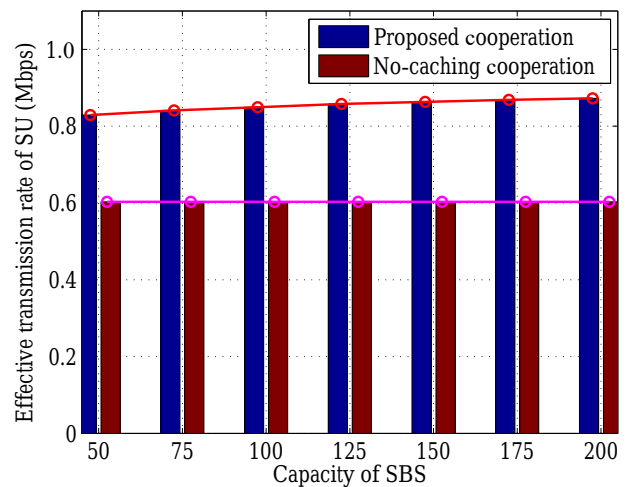

Fig. 5 SU and PU transmission rates regions of the different cooperation schemes.

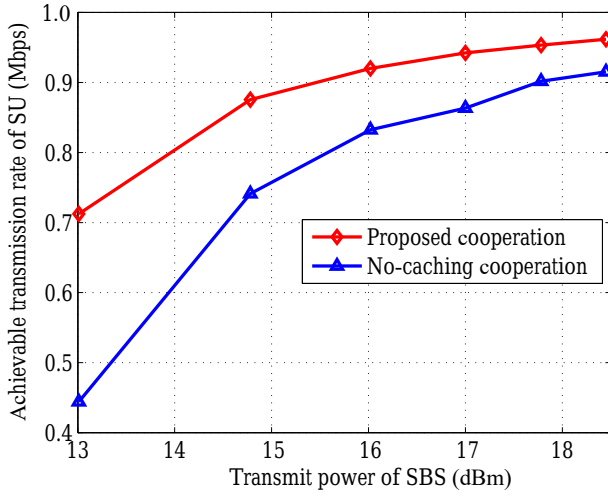**Fig. 6 Effective transmission rates for different SBS's capacity.**

Fig. 7   Effective transmission rates for different transmit power of SBS P_s.

to the PU through content caching, the effective data transmission rate that the SU can achieve is larger. In addition, when the transmit power of the SBS is low, the performance between the cache cooperative transmission and the no-caching cooperation is large. When the transmit power is increased, the effective data transmission rates achieved by the two schemes become increasingly small because the primary system reduces the dependency on the caching cooperation when the transmission power is large. Thus, the SBS can satisfy the PU by a sufficiently large transmission power and the remaining additional power for the SU transmission.

7   Conclusion and Future Work

In this paper, the content caching cooperation strategy in CCRN was studied with the aim to achieve mutual benefits for both systems. We jointly optimized the allocation of cache capacity and power to maximize the effective data rates of SU under the constraint of the PU's target effective data rate. In addition, we presented a dichotomy algorithm to achieve an optimal allocation. Simulation results indicated that the performance of content caching CCRN is better than that of the traditional relay cooperation scheme. Content caching in CCRN can be partially improved in further research. For instance, when more than a time period, a new file library needs to be updated for the corresponding primary and secondary content, further enhancing the various effects. The most popular prediction of file popularity is also necessary for CCRN, and the prediction of file popularity can be completed with the development of machine learning and big data.

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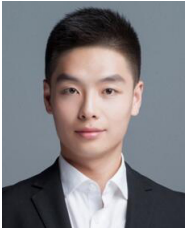
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