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Coverage analysis of cache-enabled small cell networks with stochastic geometry methods

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Abstract

Caching popular content in the storage of small cells is deemed as an efficient way to decrease latency, offload backhaul and satisfy user's demands. In order to investigate the performance of cache-enabled small cell networks, coverage probability is studied in both single-point transmission and cooperative multipoint (CoMP) transmission scenarios. Meanwhile, the caching distribution modeled as Zipf and uniform distribution are both considered. Assuming that small base stations (SBSs) are distributed as a homogeneous Poisson point process (HPPP), the closed-form expressions of coverage probability are derived in different transmission cases. Simulation results show that CoMP transmission achieves a higher coverage probability than that of single-point transmission. Furthermore, Zipf distribution-based caching is more preferable than uniform distribution-based caching in terms of coverage probability.

Keywords caching, coverage probability, single-point transmission, CoMP transmission, stochastic geometry

1 Introduction

The demand for mobile data is increasing rapidly with emerging applications and services [1], which brings a great challenge to the cellular network in the future. Although technologies such as cooperative communication, cognitive radio, interference management are of some benefit to improve the user's quality-of-experience (QoE), the quality-of-service (QoS) of multimedia service is still inadequate. One particular way of dealing with the above problems is to cache the files in the storage of each SBSs in the network [2–3]. Specifically, caching shows an advantage in reducing the duplicate file transmissions and allowing users to get access to the favorable nodes (e.g., SBSs) with caching ability. Further, caching can also reduce the backhaul link loss and lower latency as well as network congestion [4].

The idea of caching at SBSs, relays or users has been highlighted in previous works. To the best of our knowledge, Ref. [5] is the first work to utilize stochastic geometric approaches to analyze caching at SBSs. Then followed in Ref. [6], the cost for the user to retrieve the requested file from the cache-enabled SBS is considered. Unlike Refs. [5–6], in Ref. [7], Yang et al. analyze cache-based content delivery in three-tier heterogeneous networks. Recently, in Ref. [8], Chen et al. conduct a comprehensive analysis on the successful probability in cluster-centric small cell networks, where CoMP technique with either joint transmission (JT) or parallel transmission (PT) is utilized to deliver content to the served user. However, some weak assumptions are made in this work. For instance, SBSs are grouped into disjoint clusters which means that each CoMP cluster exclusively serves one user at one time. Besides, the background thermal noise is neglected. In summary, most of the previous works consider caching in the single-point transmission case while there is a wide gap for the study of performance analysis of caching in CoMP transmission case.

In this paper, we investigate the problem of caching in small cell networks from a stochastic geometry perspective. By considering the distribution of SBSs as a HPPP, we analyze the coverage probability in both single-point transmission and CoMP-JT transmission cases. With

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caching ability at SBSs, the coverage probability is derived as the probability that the serving SBS(s) satisfies the signal to interference ratio (SINR) target and has the requested file simultaneously, which leads to a function of SINR target, SBS intensity, caching probability. Furthermore, Zipf and uniform distribution-based caching strategies are compared by the analysis of coverage probability.

The rest of this paper is organized as follows. The system model is presented in Sect. 2. In Sect. 3, coverage probability is analyzed in both single-point transmission and CoMP transmission scenarios. Then, the results are validated via numerical simulations in Sect. 4. Finally, conclusions are drawn in Sect. 5.

2 System model

We consider a cellular network where SBSs are located according to a HPPP $\Phi = \{a_k, k \in \mathbb{N}^+\}$ of intensity λ, where a_k represents the kth closest SBS to the origin. Each SBS is equipped with unlimited capacity to cache file $f \in \mathcal{F} = \{f_1, f_2, ..., f_F\}$ with caching probability p_f. Thereby, SBSs caching file f construct a novel HPPP $\Phi_f = \{b_i, i \in \mathbb{N}^+\}$ with density $p_f \lambda$ [9]. Here, b_i represents the ith closest SBS of the new HPPP Φ_f to the origin. Without loss of generality, we refer to the user located at the origin as the typical user.

At each transmission, each SBS transmits with constant transmit power value of 1. The standard power loss propagation model is used with path loss exponent $\alpha > 2$. Furthermore, we consider a Rayleigh fading channel in which the channel gain from SBS z ($z \in \Phi$ or $z \in \Phi_f$) to the typical user is h_z, which is an exponential distribution with mean 1. Besides, r_z represents the distance between the SBS z and the typical user. Hence, the received power at the typical user from the SBS z is $h_z r_z^{-\alpha}$. The noise is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2.

According to Ref. [4], it has been proved that only a small portion of the files are frequently requested by the majority of users. Particularly, the popularity of file f can be modeled by the Zipf distribution as follows

$$q_f = \frac{\dfrac{1}{f^\delta}}{\sum_{j=1}^{F} \dfrac{1}{j^\delta}} \tag{1}$$

where F is the total number of files, and $\delta > 0$ reflects the skew of the popularity distribution.

In this paper, in order to investigate the impact of caching distribution on coverage probability, we assume that the SBSs cache file following two different distributions:

1) Zipf distribution. We assume that the skewness parameter of Zipf distribution is γ. Under the Zipf distribution-based caching strategy, the popular files are cached by more SBSs.

2) Uniform distribution. Uniform distribution is a model that the SBSs cache the file with equal probability. Thus, caching probability of file f is

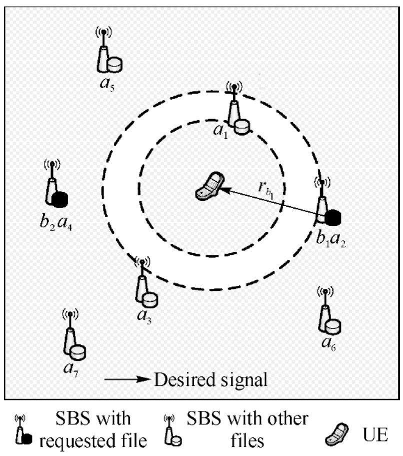
$$p_f = \frac{1}{F} \tag{2}$$

3 Coverage probability analysis

In this section, the coverage probability is analyzed with respect to two transmission scenarios: single point transmission and CoMP transmission, which are shown in Fig. 1. Here, the coverage probability is defined as the probability that the SINR at the typical user exceeds the minimal SINR target T as well as the requested file is included in the cache of the serving SBS(s) [5].

3.1 Single point transmission

In the single point transmission, the typical user is exclusively associated to the closest SBS with the requested file. As depicted in Fig. 1(a), the serving SBS b_1 is not the closest SBS to the typical user, therefore the shadow part indicating the interference from other SBSs to the typical user is divided into two parts.



(a) Single point transmission