Performance Evaluation of Content Caching in CoMP Enabled-Small Cell Networks

Junseop Ahn and Hong-Shik Park

***Abstract*—In this paper, we present a detailed comparison of two content caching strategies in the case of Coordinated Multi-Point (CoMP) enabled small cell networks: Probabilistic Randomized Caching (PRC) and Popular Content and Content Diversity based Caching (PC + CDC). We analyze the effect of hit ratio assisted by CoMP according to cache size, content popularity distribution, and small cell base station (SBS) density. Our analysis shows that hit ratio of caching with CoMP outperforms that of caching without CoMP and PC + CDC shows better performance in the given cache size, content popularity distribution, and SBS density. In particular, we can infer that the content popularity distribution and cache size are influential factors for increasing hit ratio of caching in CoMP enabled small cell networks and SBS density and content diversity based caching strategy are significant factors for better hit ratio gain in CoMP scenario.**

***Index Terms*—Small cell networks, cooperation, CoMP, probabilistic randomized caching, and popular content and content diversity based caching.**

I. Introduction

Recently, owing to the tremendous amount of mobile data traffic consumption, 5G cellular network is facing new challenges to address the problem. As one of the most promising solutions such as Massive MIMO, Carrier aggregation, Data offloading, and Coordinated Multi-Point (CoMP) transmission and so on, caching contents like multimedia traffic at the network edge, especially at the small cell base station, is attracting great attention. Ref. [1] Herein, small cell networking represents deploying low powered and short coverage small cell base stations (SBSs) underlying macro cellular network and its caching is to store the contents that users request at a storage which is equipped in the SBS. In order to achieve 5G requirement such as high throughput and very low latency, the small cell networking forum/research groups are trying to deploy SBSs hyper-densely compared with current small cell environment where deployed only at the hot-spot or coverage hole and cache the contents in SBSs as close as possible to the users.[2]-[6].Thus, there has been many researches about caching at the SBSs recently for achieving 5G requirement by means of off-loading macro cellular traffic and reducing backhaul traffic..

There are several tutorial papers about caching in 5G wireless networks in [3] and [5]. Authors in [3] have explained inevitability of caching the content at the network edge in 5G and concerned about where to cache, what to cache, and how to cache. In addition, the paper [3] proposed edge caching scheme based on the concept of information centric networking for enhancing spectral efficiency and energy efficiency and authors in [5] proposed proactive caching in SBSs and D2D for reducing backhaul bottleneck.

On the other hand, authors [7] numerically analyzed tradeoffs between the outage probability and average contents delivery rate with signal-to-interference and noise ratio (SINR), small cell base station density, target file bit rate, storage size and content popularity in the environment of cache enabled small cell networks. Tradeoff analysis is also presented in [8] which shows storage and bandwidth tradeoffs. The authors provided that the popularity based caching achieves lower outage probability for a given SBS density and same amount of spectrum.

However, these tradeoff-related researches has concerned little about small cell base station cooperation such as CoMP. Although there has been recent studies in caching with CoMP in small cell networks [9]-[11], none of these works had been considered hyper-densely small cell network environment. In this situation, because the coverage of many SBSs are overlapped each other, the cooperation between them is significant to enhance the throughput and the latency rather than current small cell environment.

Accordingly, in order to give a guideline for appropriate caching strategy in hyper densely small cell networks with CoMP environment, this paper compares the performance of well-known two content caching strategies: Probabilistic Randomized Caching (PRC) and Popular Content and Content Diversity based Caching (PC + CDC) [7], [11] in case of with CoMP and without CoMP in the given cache size, content popularity distribution, and SBS density. From the comparison, we analyze the influence on hit ratio, which is performance metric for throughput and latency enhancement, by CoMP according to the caching strategies and hit ratio gain by CoMP according to cache size, content popularity distribution, and SBS density. The results show that the content popularity distribution and cache size have to be considered seriously for increasing hit ratio of caching in CoMP enabled small cell networks. In addition, deploying SBSs densely by increasing SBS density and content diversity based caching shows better hit ratio gain with CoMP scenario.

The remainder of this paper is organized as follows. Section II describes the system model of hyper densely small cell networks and two caching strategies for comparing the hit ratio performance in the case of with CoMP and without CoMP are presented in Section III. In Section IV, we show the

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simulation results and analysis, and finally conclusions are drawn in Section V. In addition, we present future direction for this study.

II. System Model

A. System Topology

Consider a 3km x 3km two-dimensional space covered by only one macro base station (MBS) located at the center and SBSs are deployed with thinned homogeneous Poisson Point Process (PPP) Φ with density λ. We assume that the small cell coverage is $\leq$ 150m and if 3km x 3km space is fully covered by SBSs, SBS density 0.3 means 30% of the two-dimensional space is covered by statistically distributed SBSs as shown in Fig. 1. The number of users are 1,000 with uniformly distributed whose mobility is almost static, so average number of served users in a SBS is 10 in the case of SBS density 0.3. However, many of users could not be located in SBS's coverage area by statistical deployment of SBSs with uniformly distributed users. All users can be served by MBS and each user is associated with an SBS having highest channel quality. (We call it serving SBS.) Also, if the user is in the two or more of SBS's coverage, it is possible to receive the service from several SBSs by cooperation named CoMP.

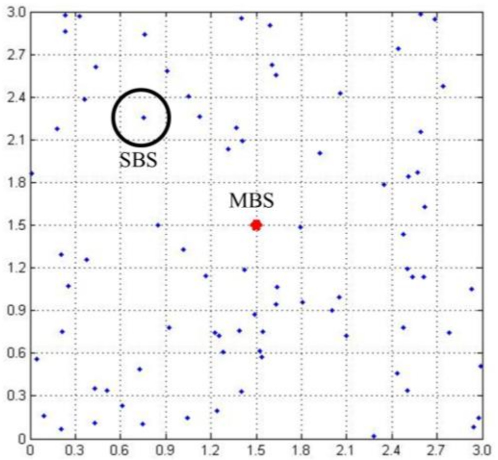

Fig. 1. Small Cell Deployment with thinned Homogeneous PPP (Density λ : 0.3).

For wireless environment, we suppose that the urban area of power law path loss with exponent $\alpha > 4$ and Rayleigh small scale fading with mean 1. The transmit power of MBS and SBS is 46dBm and 30dBm each other and we assume that the users will receive their content from the serving SBS first even if SINR of MBS is higher than that of SBS. It means the user associates with the SBS having the maximum SINR among the SBSs having SINR greater than threshold (10dB is used which is the LTE commonly accepted value for a minimum level service. [12]) preferentially. Nevertheless, if there is no SBS greater than the threshold of SINR, the user will be associated with MBS.

We consider the number of contents to be requested by the users in the system is 10,000 and its size assumes to be identical. The content popularity distribution follows Zipf's distribution shown in Equation. 1 where N is the number of contents and Zipf parameter β means skewness of popularity. As β approaches to 0, p_i will follow the uniform-like distribution while much skewed popularity distribution as β increases.

$$p_i = \frac{\frac{1}{i^\beta}}{\sum_{j=1}^{N} \frac{1}{j^\beta}}, \text{ for } i \in N \quad (1)$$

B. Small Cell Cooperation

In the system, we consider the small cell cooperation. CoMP, one of the small cell cooperation techniques, have been proposed as a prospective next generation wireless solution to alleviate inter-cell interference and increase network throughput.[13] It allows neighboring SBSs to communicate cooperatively with serving SBS. First, the serving SBS transmits Channel State Indicator-Reference Signal (CSI-RS) configuration message to the user for how to measure the channel quality of neighboring SBSs and the user replies with measured CSI such as Channel Quality Indicator (CQI), Precoding Matrix Indicator (PMI), and Rank Indicator (RI) of neighboring SBSs. Then, the serving SBS makes CoMP cooperation capable set by including oneself and performs the cooperation by choosing one or more of the SBSs among the set with various means of cooperation according to frequency, time, or spatial division. Moreover, CoMP is performed on per scheduling time basis because the cooperating SBSs share dynamic channel status of the user every scheduling time to configure the set of cooperating SBSs.

There are many types of CoMP techniques depending on how the cooperation is performed, e.g., coordinated scheduling/ beamforming (CS/CB) and joint transmission (JT).[14] CS/CB only shares CSI information between serving SBS and the neighboring SBSs for choosing best qualified SBS among CoMP cooperation capable set. It allocates different channel frequency and beam pattern to selected SBS for minimizing inter-cell interference. On the other hand, JT shares both CSI and the data for cooperatively transmitting the same data simultaneously with same channel frequency and time resources. Main purpose of JT is to enhance received signal quality while CS/CB reduces inter-cell interference. However, JT causes lots of backhaul overhead for the data sharing between cooperating SBSs while CS/CB incurs less backhaul overhead for only sharing CSI information.

In order to improve caching performance, we consider JT that use multiple SBSs to transmit the data simultaneously rather than CS/CB in the system as shown in Fig. 2. There are some advantages on JT when SBS has caching capability such that if the data to transmit to the user is in the cache of both serving SBS and neighboring SBSs included in CoMP cooperation capable set, there is no need to share the data from serving SBS to neighboring SBSs through backhaul link, thus it reduces backhaul overhead. Besides, the data can be shared directly from neighboring SBSs to the serving SBS even though the data is not hit from the cache of serving SBS, thus it reduces latency for content delivery.

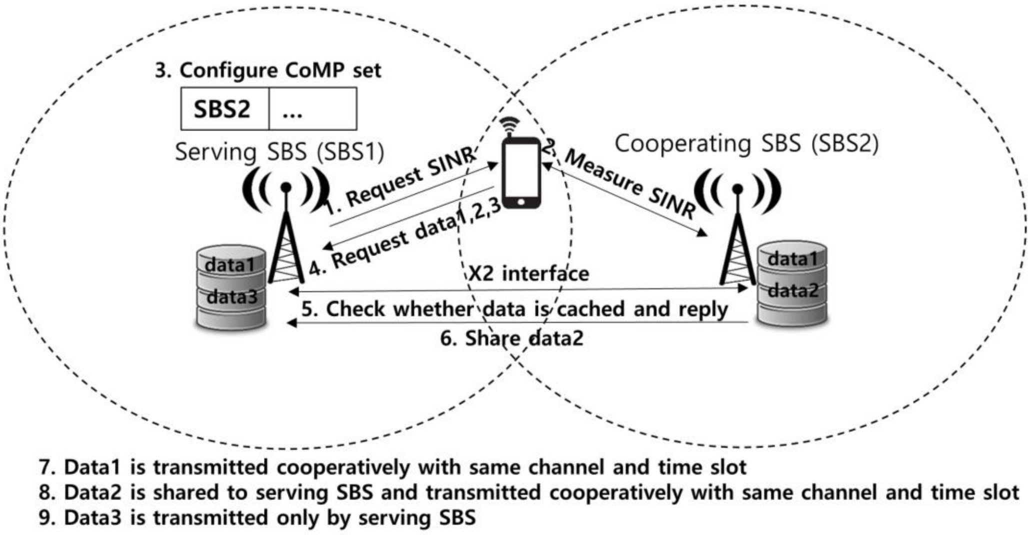

Fig. 2. Caching with CoMP scenario.

In this system, for simplicity, CoMP cooperation capable set will be determined by only the threshold of SINR, but not measured CSI signal. Then, after configuring CoMP cooperation capable set, when the user requests a specific content, only neighboring SBSs that have the content in their cache will participate in the cooperative transmission. This is in practice different from original operation of CoMP which is short time scale. In other words, it means CoMP will be performed not a schedule time basis, but on a per- user request basis.

III. Content Caching Strategies and Caching with CoMP

Due to the limited backhaul link capacity and slower changes in content popularity distribution, cache replacement occurs at off-peak period (usually at daybreak in a day) which is not frequent than the cache replacement in computing system or wired network caching.[5], [9], [11].Therefore, in this paper, content caching represents content placement and in what follows, we will use content caching and content placement interchangeably.

We consider two well-known caching strategies: Probabilistic Randomized Caching (PRC) and Popular Content and Content Diversity based Caching (PC+CDC). PRC caches each contents i randomly with probability π_i whereas PC+CDC caches most popular contents first in a certain size of cache and the remaining cache space is filled with different contents each SBS for achieving content diversity. The following sub-section describes the detail of two caching strategies.

A. Probabilistic Randomized Caching (PRC)

PRC is most simple caching strategy. Let $F = \{1,2,,\ldots,i\}$ denote the set of content to be requested by users and $\pi_i, 0 \le \pi_i \le 1$, denotes the probability to cache the contents i . Then the content is cached randomly with probability π_i until the cache storage becomes full. If we assume that the user requests content according to the content popularity distribution, π_i could be p_i in the Zipf's distribution simply.

On the other hand, by considering the other factor such as cache size or geographic characteristics of SBS, π_i would be different and could be design parameter for enhancing the caching performance.

In this paper, we merely assume that the user requests content according to the Zipf's distribution and π_i be p_i because the purpose of the paper is to compare caching performance, not to design appropriate caching strategy, in the case of with CoMP and without CoMP. Under these assumption, we compare how much gain will be obtained in CoMP-enabled caching according to the caching strategies.

B. Popular Content and Content Diversity Based Caching (PC + CDC)

PC + CDC is combinatorial caching strategy of two caching method: caching in order of popular content and caching for achieving content diversity which means each neighboring SBS should caches content to avoid duplicate caching as much as possible. Firstly, PC + CDC caches in order of most popular content for a given number of content in all of SBSs equally and then, the remaining space is filled with different contents each SBS for achieving content diversity. The most important design parameter in PC + CDC is proportion ρ of cache space between PC and CDC. In the case of Zipf's distribution, if ρ is larger than 1- ρ , it could increase content hit ratio because most of users' request are biased on a few popular contents and obtain the more chances to perform CoMP without content sharing between cooperating SBSs. However, ρ is less than 1- ρ , it would increase content diversity and also obtain the more chances to perform CoMP with content sharing, thus increasing hit ratio as well.

Furthermore, how to achieve content diversity is significant factor for enhancing the caching performance. Simple strategy to achieve content diversity is caching content with equal probability, but it is far from achieving maximum content diversity. In order for achieving maximum content diversity, it should be formulated as optimization problem and solved. Specific optimization formulation is out of scope in this paper.

In this paper, we suppose that the proportion ρ is 0.5, so that half of caching space in SBS caches most popular contents and the rest with PRC. The reason why we consider CDC as PRC is if the content popularity goes to the Zipf-like, list of file with $F^{1-\rho} = F - F^{\rho} = \{\rho \times cache\ size + 1,\ldots,i\}$ becomes less popular content and the probability to request is too small, so it seems like CDC. Furthermore, even if the content popularity goes to uniform-like, the list of file $F^{1-\rho}$ become almost equal request probability, thereby becoming CDC.

IV. Performance Evaluation

In this section we investigate the performance comparison of two aforementioned caching strategies: PRC and PC + CDC in the case of without CoMP and with CoMP according to the cache size, Zipf parameter, and SBS density. It will give a guideline to deploy the small cell network and devise appropriate caching strategies. The parameter used in the simulation is presented in Table I.

TABLE I: Simulation Parameters

System Parameters	Value
Number of contents	10,000
Number of users	1,000
Wireless bandwidth	20 MHz
Transmit power of MBS	46 dBm
Transmit power of SBS	30 dBm
SINR Threshold	10 dB
Path loss exponent	4
Cache size	[0.01, 0.1]
Zipf parameter	[0, 2]
SBS density	[0.1, 1]

User requested contents randomly according to the Zipf's distribution and we measured hit ratio, which is defined as the ratio of successful transmission of the contents from the serving SBS or cooperating SBSs over total number of requested contents. It means if the content is hit from either the serving SBS or the cooperating SBSs, not from the MBS or internet, the contents are transmitted directly by using CoMP, thus increasing hit ratio.

Fig. 3 shows hit ratio according to the varying cache size in the given Zipf parameter 1.0 and SBS density 0.3. In the figure, 0.01 of cache size means up to 1/100 of total number of contents can be cached in a SBS which is moderately reasonable because the SBS has low powered and short coverage capabilities.[7], [8] In the simulation, we measured hit ratio while increasing the cache size to 0.1. As shown in the figure, we can see the trend that the larger cache size is, the higher hit ratio is in all cases and hit ratio of caching with CoMP outperforms the hit ratio of caching without CoMP obviously. However, unusual thing is hit ratio gain of PRC with CoMP is better than that of PC + CDC about 14%. We can infer three reasons why these results came out. First reason is hit ratio degradation of PRC compared with PC + CDC without CoMP because in the case of Zipf's distribution with parameter 1.0, just caching in order of the most popular contents shows much better hit ratio than other Zipf parameter which can be verified in Fig. 3. Therefore, hit ratio gain of PRC with CoMP is improved relatively more than that of PC + CDC with CoMP. Second reason is CoMP gain of CDC is lower than expected because the less popular contents was cached by means of CDC and the number of users' requests is too small to the less popular contents. We expected that caching different content in neighboring SBSs with achieving content diversity increases hit ratio, but there is little impact on the Zipf's distribution with parameter 1.0. Finally, popular content caching in every SBS causes redundant caching in the limited cache size, so that it reduces hit ratio. Furthermore, we can observe that it has no additional effect of caching with CoMP compared with caching without CoMP as increase of cache size. If we changed proportion ρ of PC + CDC, there would be additional hit ratio improvement by CoMP.

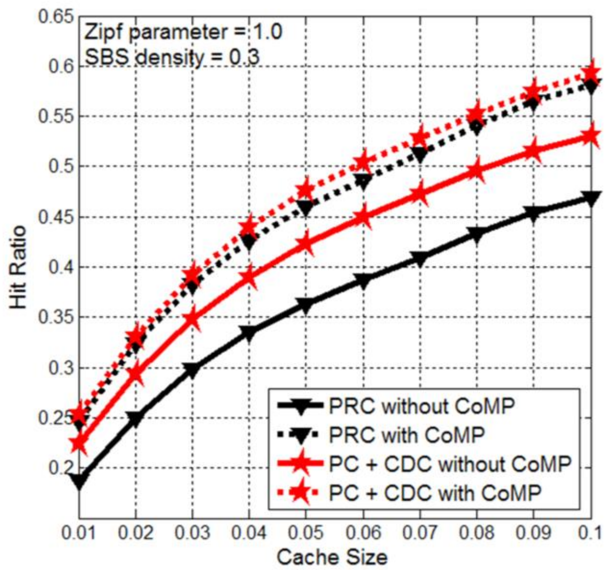

Fig. 3. Hit Ratio according to cache size in the given Zipf parameter and SBS density.

Fig. 4 shows hit ratio according to the varying Zipf parameter in the given cache size 0.05 and SBS density 0.3. As shown in the figure, both caching strategies shows very low hit ratio when the contents popularity is getting follows uniform-like distribution, whereas quite high hit ratio when approaching much skewed Zipf's distribution. Especially, when Zipf parameter is 0 which is perfectly uniform distribution and 2.0 which is too much skewed Zipf's distribution, there is no difference in hit ratio of both caching strategies without CoMP due to the similar content caching even if different caching strategies. For detailed analysis, results are divided into three parts: Zipf parameter under 0.3, from 0.3 to 1.3, and over 1.3.

Under 0.3, hit ratio of PRC with CoMP shows higher than that of PC + CDC with CoMP unlike the case without CoMP. It might indicate that if the content popularity follows uniform-like distribution, PRC strategies achieves better content diversity than PC + CDC for the reason that half of caching space have to cache the most popular contents in all

SBSs even though the popularity difference is small, thus deteriorating content diversity.

In the case of relatively general Zipf's distribution, where Zipf parameter is from 0.3 to 1.3, it shows expected results that PC + CDC with/without CoMP has better hit ratio performance than PRC with/without CoMP. In addition, decrease in Zipf parameter shows better hit ratio gain in both PC + CDC with and without CoMP compared with PRC strategy. From the analysis, we can observe that the caching with achieving content diversity helps to increase the chance to perform CoMP somewhat in Zipf's distribution.

Finally, over 1.3, there is no difference in hit ratio of both caching strategies with CoMP and also the difference is getting close in case of without CoMP. It means that both caching strategies cache popular contents similarly and even though they cache the contents differently except a few popular contents, users' content request is mostly biased to certain popular contents. However, we can obtain basic hit ratio gain when using CoMP compared with caching without CoMP.

Interesting point is change of hit ratio gain in PC + CDC with CoMP compared with PC + CDC without CoMP over Zipf parameter 1.0 which shows increase in hit ratio gain while increasing Zipf parameter. It is inferred that the more increase in Zipf parameter is, the fewer portion of content is cached as the popular contents, so that lots of caching space is cached with less popular contents achieving content diversity as increase in Ziipf parameter.

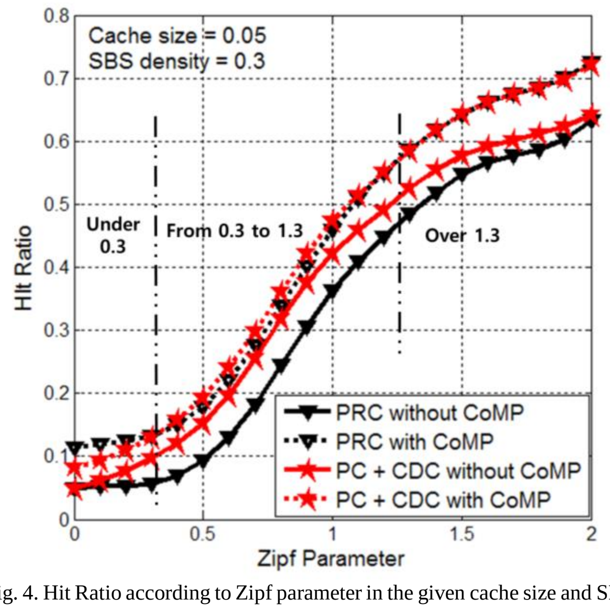

Fig. 4. Hit Ratio according to Zipf parameter in the given cache size and SBS density.

Finally, Fig. 5 represents hit ratio with varying SBS density given cache size 0.05 and Zipf parameter 1.0. In the figure, it shows effect of caching with CoMP increases as SBS density increases due to increase of cooperation opportunity in both caching strategies. Especially, PC + CDC with CoMP has more improvement of hit ratio than PRC with CoMP because the caching different contents every SBS achieving content diversity gives additional chances to cooperate in PC + CDC. However, in the case of caching without CoMP, there is fast saturation of hit ratio when SBS density is 0.3. This is the reason why there is limitation of hit ratio given cache size 0.05 and Zipf parameter 1.0 and the excessive SBS deployment causes more interference, so that it decreases hit ratio as decrease of SINR. In the other word, deploying SBSs densely improves caching performance when using CoMP to mitigate inter-cell interference and increase received signal quality, but there would be saturation or degradation due to inter-cell interference in the case of over deployed situation, especially in the case of without CoMP. Small fluctuation of the results of graph is due to different deployment by changing the value of SBS density.

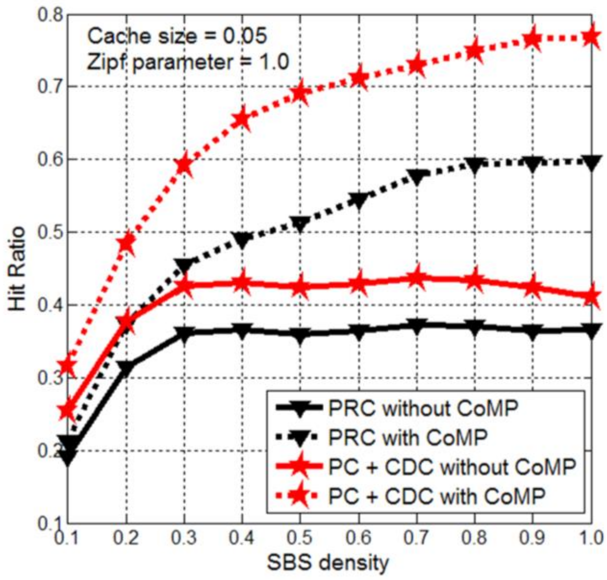

Fig. 5. Hit Ratio according to SBS density in the given cache size and Zipf parameter.

In overall, we can infer that caching with CoMP outperforms caching without CoMP in the case of hit ratio. Also, caching with CoMP can reduce the number of content sharing for CoMP, thus reducing backhaul overhead. Particularly, popular content caching in several SBS can reduce the number of content sharing for CoMP, whereas, content caching with achieving content diversity can increase the chance to cooperation by content sharing, thus increasing hit ratio. On the other hand, redundant caching interrupts hit ratio improvement due to waste of cache space in the limited cache size. Therefore, in the small cell network with CoMP environment, it has to be considered with the content popularity distribution and the limited cache size for an appropriate content placement strategy. In addition, deploying SBSs densely by increasing SBS density necessary enough and proper content diversity based caching will exhibits caching performance with CoMP scenario.

V. Conclusion

In this paper, we evaluated performance of caching strategies: Probabilistic Randomized Caching (PRC) and Popular Content and Content Diversity based Caching (PC + CDC) in the case of Coordinated Multi-Point (CoMP) enabled/disabled small cell networks environment and we analyzed hit ratio according to the cache size, content popularity distribution, and SBS density as well as hit ratio gain by CoMP according to the caching strategies. From the simulation, we obtained useful instructions to propose a decent caching algorithm in CoMP enabled small cell networks. Our analysis showed that the more caching gain can be achieved both in the case of PRC and PC + CDC with CoMP according to the given cache size, content popularity distribution, and SBS density. In particular, content popularity distribution and cache size should be considered for better caching strategy. Moreover, deploying SBS densely enough and content diversity based caching strategy is necessary to get more caching gain in CoMP enabled small cell networks.

In order for further study, we inferred a variety of perspectives about caching strategy that popular content caching in several SBS can reduce the number of content sharing for CoMP, but redundant caching degrades hit ratio improvement in the limited cache size. On the other hand, content caching with achieving content diversity can increase the chance to perform the cooperation by content sharing, but may causes considerable backhaul overhead. Therefore, it is necessary to consider such tradeoff relationship for the content caching.

In future work, we will propose a content caching algorithm of small cell networks in circumstance of more practical scenario which avoids waste of caching space by duplicated caching and achieves maximum content diversity to make full use of caching gain by CoMP.

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