Analysis of Caching and Transmitting Scalable Videos in Cache-Enabled Small Cell Networks

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Abstract—In this paper, we investigate the cache-enabled small cell networks to provide on-demand video services with differential perceptual qualities, i.e., standard definition video (SDV) and high definition video (HDV). As the extension technology of advanced video coding/H.264, scalable video coding is adopted in the considered networks and videos to be transmitted are divided into a base layer (BL) and N enhancement layers (ELs). In our proposed caching protocol, the n-th small cell base station (SBS) caches BLs and the n-th EL of the most popular videos. Depending on the distances between the typical user and SBSs in the observed cluster, the closest SBS is regarded as the serving node (SN) and the others are cooperative nodes (CNs). When SDV is required, the SN will transmit BL of the required video file to the typical user, while SN and CNs can cooperatively transmit BL and ELs to provide superior video quality if HDV is required. Based on the proposed caching and transmission protocol, we derive the expressions of the key performance indicators, i.e., local serving probability, ergodic service rate and service delay. Numerical results validate the theoretical analysis and show the superiority of our proposed scheme compared to the benchmarks.

I. Introduction

Nowadays, there is an explosive increase of mobile data traffics, which have been doubled each year due to the popularity and propagation of smart devices [1]. Meanwhile, mobile users impose strict service requirements on the next generation wireless communication networks, i.e., higher data rate, lower time delay, wider coverage and more reliable connectivity. Therefore, more advanced technologies are desired to relieve or solve these severe problems in the near future.

Though many data traffics are generated at every minute, there are many redundant contents and repeated transmissions, which have caused huge power consumptions and signaling overheads. To this end, caching is proposed as one of the enabling technologies to avoid redundant data transmissions [2]. There are various caching schemes, which can be roughly classified into two categories, namely coded caching and uncoded caching. The former refers to store different fragments of popular videos in the base stations, and the required content will be decoded if all the fragments are received [3], [4]. On the other hand, uncoded caching concentrates on store the same copies of the most popular video files [5], [6].

Small cell networks (SCNs), aiming to make better use of the available spectrum, bring small cell base stations (SBSs) closer to mobile users to improve the capacity gain [1]. Moreover, SCNs can offload data traffics from the macrocell networks [7]. Recently, many researchers have investigated various caching schemes in SCNs [4], [8]–[10]. Specifically, in [4], the authors suggest that SBSs can be grouped into disjoint clusters and multimedia subscribers can be served by a cluster of SBSs, which can significantly improve the system performance in terms of successful content delivery probability. In [8], caching is applied as a service in the virtualized mobile SCNs and different service providers are competing for the limited storage of multiple SBSs to reduce time delay caused by the transmission process of backhaul and downlink. In [9], a maximum distance separable (MDS) coded scheme is considered, which is intended to minimize the total power consumption by designing the cache placement of the coded packets. Similarly, the authors also propose an MDS coded packet placement scheme, which is intended to relieve the traffic burden of the backhaul links [10]. All the literatures mentioned above indicate that caching in SCNs will relieve the traffic load of the backhaul links and reduce service delay. However, the different viewing qualities required by users are not considered. To be more specific, the differential video perceptual requirements are ignored, which will be a resource waste if some users only request basic viewing quality.

In this paper, we consider an SCN scenario with multiple SBSs providing different video qualities to the typical user. For the ease of analysis, the typical user is located at the origin of the observed cluster [4], [11]. Based on scalable video coding (SVC), the extension technology of advanced video coding (AVC)/H.264, each video file is divided into a base layer (BL) and multiple enhancement layers (ELs). The BL can provide basic viewing quality, and the video with only BL content is defined as standard definition video (SDV). By adding ELs to the received BL, users can enjoy high definition video (HDV) with superior perceptual experiences. Based on the proposed caching and transmission protocol, we analytically derive the expressions of key performance indicators for the typical user, i.e., local serving probability, ergodic service rate and service

delay. The main contributions of this paper lie in the following aspects:

1) Under the proposed caching and transmission protocols, different perceptual qualities can be guaranteed with the cooperation of multiple SBSs in the observed cluster. Different content layers of the required videos are delivered to the typical user to provide differential perceptual experiences. Comparing to the existing schemes, the proposed caching and transmission scheme can adapt to different video quality requirements to provide flexible multimedia on-demand video services.

2) Key performance indicators, i.e., local serving probability, ergodic service rate and service delay, are derived based on the theory of stochastic geometry. From the analytical and simulation results, we can conclude the inherent relationships and tradeoffs among these indicators, which will give valuable guidance in practice.

II. SYSTEM MODEL AND PROTOCOL DESCRIPTIONS

In this section, we show the system model as well as the caching and transmission protocol of the cache-enabled SCNs.

A. System Model

Consider an SCN scenario and the SBSs are distributed independently in the area with radius r, whose locations follow the Poisson Point Process (PPP) Φ with density λ_Φ. The SBSs within the circle with radius d form a cluster $\mathcal{C}$ and the number of SBSs in this cluster is $N = |\mathcal{C}|$. For simplicity, the typical user is located at the origin of the cluster. The received power of the typical user from the n-th SBS is denoted by

$$P_n = vB_nP_th_nr_n^{-\alpha},$$

where P_t is the transmit power of the SBS and h_n is the channel power gain following exponential distribution with unit mean, i.e., $\exp(1)$. r_n is the distance between the typical user and the n-th SBS and α is the path loss exponent satisfying $\alpha \geq 2$. v is the propagation constant and B_n is the association bias. Without loss of generality, we assume that v and B_n are forced to be 1. There are two kinds of SBSs, namely serving node (SN) and cooperative node (CN). The SN provides the maximum power gain to the typical user, while other SBSs are classified as CNs. When the typical user requires SDV, only the SN will provide BL content of the requested video. Otherwise, the SN and CNs will cooperatively deliver BL and ELs to provide HDV service. We rearrange the indexes of SN and multiple CNs according to the received power strength of the typical user and they are denoted by n_i, $i = 1, 2, ..., N$, where $i = 1$ refers to the index of SN. Besides, r_i is the distance between i-th SBS and the typical user, and $\mathbf{r} = [r_1, ..., r_N]$ is defined as the distance vector.

Firstly, the signal-to-interference-plus-noise ratio (SINR) of the received BL and EL contents, i.e., SINR_{BL} and SINR_{EL}, of the typical user can be denoted as

$$\text{SINR}_{BL} = \frac{P_th_1r_1^{-\alpha}}{\sum_{n\in\Phi\setminus\text{SN}}P_th_nr_n^{-\alpha}+\sigma^2}, \tag{1}$$

and

$$\text{SINR}_{EL} = \frac{\sum_{m=2}^{N}P_th_mr_m^{-\alpha}}{\sum_{n\in\Phi\setminus\mathcal{C}}P_th_nr_n^{-\alpha}+\sigma^2}, \tag{2}$$

respectively, where σ^2 is the variance of the additive white Gaussian noise. Note that in (2), the interference comes from the SBSs outside the observed cluster. When receiving EL contents, the BL content is not the interference signal since the decoding of ELs heavily depends on the received BL content.

B. The SVC-Based Caching Protocol

Each SBS in the cache-enabled SCN is equipped with storage capacity to cache the most popular videos, whose cache size is M bits. Employing SVC, each video to be transmitted is divided into a BL and N ELs in advance. The BL can guarantee the basic viewing quality i.e., SDV, while adding ELs to the received BL will provide superior perceptual experience, i.e., HDV. Each SBS caches BLs of the most F_S popular videos and the n-th SBS caches the n-th EL of the most F_E popular videos, where the total number of the scalable video files is F in the video library. The size of the BL and the N ELs is L_B and L_E, respectively. Therefore, the number of the cached ELs in each SBS can be expressed as $F_E = \min\{F_S, \lfloor(M - F_SL_B)/(L_E/N)\rfloor\}$, where (L_E/N) denotes the size of each EL content cached in the SBS. All of the requested videos are arranged in the descending order of popularity where more popular videos are ranked with smaller indexes, and the request probability follows the Zipf's law [12]. Therefore, the probability that the video is requested by the typical user is shown as

$$p_f = f^{-\alpha}/\sum_{n=1}^{F}n^{-\alpha}, \ \ f = 1, 2, ..., F, \tag{3}$$

where f is the index of the popularity order and α is the skewness parameter. According to [13], the preference for SDV of the f-th video is denoted as

$$g(f) = (f - 1)/(F - 1). \tag{4}$$

Obviously, the preference for HDV can be expressed as $1 - g(f)$.

C. The Transmission Protocol

When the required videos cannot be obtained in the local cache, the cache miss event happens. If it happens, the SBSs will fetch BL and ELs from the video library via backhaul links. Based on caching protocol and differential video preference mentioned above, there are five transmission cases correspondingly.

Case 1: The typical user requests SDV and the video index is in the range of 1 to F_S, which can be obtained in the local cache and the typical user can be served by SN;

Case 2: The typical user requests HDV and the video index is in the range of 1 to F_E, which can be obtained in the local cache and the typical user can be served by SN and CNs;