A Study on D2D Caching Systems with Mobile Helpers

Soyi Kim*, Eulhyeon Go*, YoonSeok Song*, HyungJoon Cho*, Minjoong Rim* and Chung G. Kang**
*Dept. of Information and Communication Engineering, Dongguk University, Seoul, Korea
**School of Electrical Engineering, Korea University, Seoul, Korea
seh3541@naver.com, minjoong@dongguk.edu

***Abstract*—** Due to the increase of video-on-demand and streaming services, the amount of data traffic in both wired and wireless networks is increasing exponentially. In order to deal with the surge of data traffic, the wired network already utilizes caches in efficient ways. In recent years, there has been ongoing research in wireless networks to add caches to devices to reduce the burden of the radio resource. While many devices can support only small-sized caches and limited-sized batteries, some devices such as cars and buses may be able to include large caches and can provide contents to other devices via device-to-device (D2D) communications. In this paper, we discuss D2D offloading using caches on mobile devices by exploiting the mobility of the devices.

Keywords*— *Caching, D2D, Mobility, Helper, Video, Wireless

I. Introduction

Wired and wireless data traffic is increasing every single day. In particular, wireless data traffic is expected to increase due to video on demand or over the top streaming services, such as Netflix, Apple, or Alibaba services [1-3]. The amount of traffic generated by video data takes a very large part of the network. On the wired network, data traffic from video streaming in the evening, already takes up more than 50% of the total Internet traffic [1-5]. If there are a great number of user requests at a certain time, the quality of the video streaming service may be degraded or the service itself may not be feasible due to the bottleneck on the core network. In order to reduce the traffic burden on the core network, caches can be arranged to store the contents at the off-peak time and to transmit contents to the devices at the peak time.

Likewise, there can be also a bottleneck in the radio resource of a wireless network due to the surge of video data. Nowadays, it is considered to install caches in a wireless network to reduce the burden of the radio resource. For this purpose, caches can be placed at base stations (BSs) or at devices. Although BSs are suitable for carrying large-sized caches [1], there are also some advantages of including caches in devices. If users are concentrated in a specific area at a specific time, then the sum storage capacity on the devices can also increase on that area [3-6]. In addition, each device can utilize its own personal preference or mobility information using the application software installed on the device.

While many devices can support only small-sized caches and limited-sized batteries, some devices such as cars, buses, laptop computers, or fixed equipments dedicated for caching, may be able to include large caches and provide contents to other devices. In this paper, a helper equipment (HE) refers to a special device which has a large cache and can supply contents to other devices using device-to-device (D2D) communications. Other generic devices with small caches are called user equipments (UEs). A UE can receive contents at the peak time using the following three ways: self-offloading from its own cache, D2D offloading from a HE nearby the UE, and cellular communication from the BS.

There are multiple types of HEs including fixed, nomadic, and mobile HEs. In this paper, we only consider a public-transportation type of mobile HEs such as buses and taxis with large caches, while assuming that most of UEs have negligible mobility at the peak time. We assume that contents are divided into chunks of the same or similar sizes, and stored in caches at the off-peak time. While a UE can store chunks of contents based on its personal preference information generated by the installed application software, a HE can use the common preference list received from the network as well as its personal preference information.

Consider the cases in which a UE generates a request for a video content consisting of multiple chunks. While the first fraction is required immediately, the others have some time margins until they are actually consumed. Even when there is no HE having the second fraction around the UE, the UE can wait for some other HEs coming to the UE during the playing time of the first fraction. This can be viewed as the extension of the effective coverage of HEs according to the time margins of chunks. There are many works relating to the mobility of devices with caching [6-11]. While most of them exploit the mobility patterns or user trajectories of devices, this paper considers the effective coverage extension of HEs according to the time margins of chunks. In this paper, we present a caching scheme considering the mobility of HEs, and discuss the efficiency of caching according to the length of contents and the mobility of HEs. This paper is organized as follows. In Section II, we address the system model considered in this paper and calculate the offloading performance of the D2D caching system taking advantage of the mobility of HEs. The simulation results are shown in Section III and conclusions are stated in Section IV.

II. IV.Caching System with Mobile Helper

A. System Model

Fig. 1 shows a system model considered in this paper, which includes a circular cell with radius $R_{Cellular}$. We assume that the number of UEs in the cell is very large compared to the number of HEs. A HE can use D2D communication to provide chunks of video contents to UEs if they are inside the D2D coverage with radius of R_{D2D}. In this paper, we consider video contents, which are divided into chunks of the same or similar sizes, as shown in Fig. 2. Let T be the minimum time length playing one chunk. A video content with time length of $3T$ can be divided into three chunks. The first fraction is needed immediately after content request but the other fractions have some time margins before they are actually used. More specifically, the second fraction can be waited until T seconds and the delivery of the third can be postponed until $2T$ seconds. The effective D2D coverage of a HE with velocity V for the m^{th} fraction of a video content, denoted as $\eta(m)$, can be defined as the area covered by the HE at least once during the time margin $(m-1)T$, and written as follows.

$$\eta(m) = \pi R_{D2D}^{\ 2} + 2R_{D2D}(m-1)VT \tag{1}$$

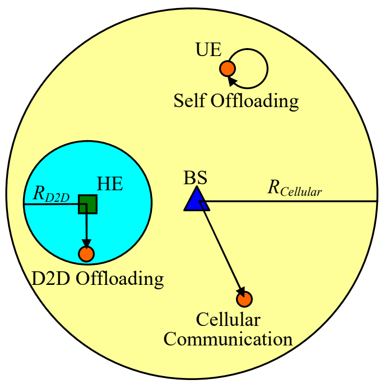

Fig. 1. System model.

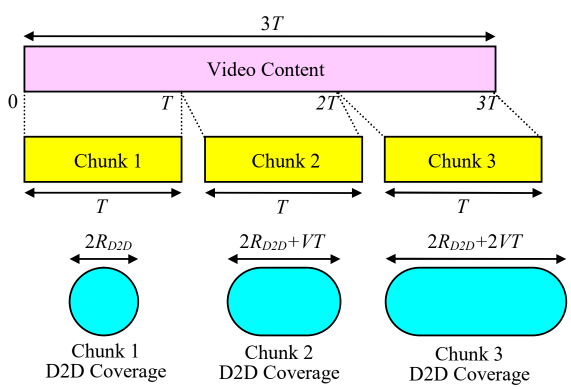

Fig. 2. Content with length 3T can be divided into 3 chunks, which correspond to different effective D2D coverages.

There are two types of preference lists of chunks available to devices: the common preference list generated by the network and the personal preference list specified for each device. We assume that the preference lists follow Zipf distributions with the Zipf parameters λ_{Common} for the common preference list and $\lambda_{Personal}$ for the personal preference lists. We also assume that chunks in the lists are sorted in the decreasing order of the preference. $P_k^{Personal}$ refers to the request probability of the k-th popular chunk for each personal preference list and P_k^{Common} refers to the request probability of the k-th popular chunk for the common preference list.

Devices can store chunks at the off-peak time using cellular communication. We assume that UEs have small-sized caches and do not provide contents to others due to the limitation of power consumption. Hence, a UE stores chunks for self offloading using its own personal preference list generated by the application software installed on the device. On the other hand, a HE has a large cache and stores chunks for other devices as well. A cache in a HE can be divided into two parts: the common cache and the personal cache. A HE can store chunks for itself to the personal cache using its own personal preference list, and store chunks for others to the common cache using the common preference list received from the network. At the peak time, a UE can receive a chunk through the following three ways. If the chunk is stored in its own personal cache, self-offloading is feasible. Otherwise, D2D offloading can be attempted. If there is a HE around the UE and the HE has the chunk in its cache, then the UE can request to the HE to receive the chunk using D2D communication. If there is no HE having the chunk around the UE, the UE needs to request the chunk to the BS.

B. Cache Hit Ratio

In this paper, we consider two hit ratios: the self-hit ratio representing the probability of success in self-offloading attempts, and the D2D hit ratio referring to the probability of success in performing D2D offloading. Let N_{UE} be the number of UEs per cell, N_{HE} be the numbers of HEs per cell, K_{Total} be the total number of chunks, $K_{UE}^{Personal}$ be the size of the personal cache in a UE, $K_{HE}^{Personal}$ be the size of the personal cache in a HE, and K_{HE}^{Common} be the size of the common cache in a HE. Assuming that a UE stores chunks in the order of the personal preference list, the self-hit ratio of a UE can be expressed as $H_{UE}^{Personal} = \sum_{k=1}^{K_{UE}^{Personal}} P_k^{Personal} \ / \ \sum_{k=1}^{K_{Total}} P_k^{Personal}$. Suppose that the m^{th} fraction of a video content is stored in N_{HE} HEs with velocity V. The probability that a UE is located at least once in the D2D coverage of a HE during $(m-1)T$ seconds can be written as

$$\rho(m) = 1 - \left\{1 - \frac{\eta(m)}{\pi R_{Cellular}^{\ 2}}\right\}^{N_{HE}} \tag{2}$$

assuming that the effective D2D coverage is included inside the cell. If $2R_{D2D} + V(m-1)T$ is greater than $2R_{Cellular}$, then the effective D2D coverage cannot be included inside a cell. The minimum number of cells overlapped with the effective D2D coverage for the m^{th} fraction of a video content can be expressed as follows.

$$N_{Cell}(m) = \left\lceil \frac{2R_{D2D} + V(m-1)T}{2R_{Cellular}} \right\rceil \tag{3}$$

Suppose that the effective coverage area is split into $N_{Cell}(m)$ pieces of the same size to be included in $N_{Cell}(m)$ cells. Then, Eq. (2) can be rewritten as follows.

$$\rho(m) = 1 - \left\{1 - \frac{\pi R_{D2D}{}^2 + 2R_{D2D}V(m-1)T}{N_{Cell}(m)\pi R_{Cellular}{}^2}\right\}^{N_{Cell}(m)N_{HE}} \quad (4)$$

Let m_k^{Common} be the fraction number of a video content for the k-th popular chunk in the common preference list. In order to take care of the extended effective coverage area, the chunks in the common preference list are sorted in the descending order of $\rho(m_k^{Common})P_k^{Common}$ $(k = 1,\cdots,K_{Total})$. Let $\widetilde{P}_k^{Common}$ be the request probability of the k-th chunk in the re-sorted list and $\widetilde{m}_k^{Common}$ be the corresponding fraction number of a video content. If HEs store K_{HE}^{Common} chunks to their common caches in the descending order of the $\widetilde{P}_k^{Common}$ values, then the D2D hit ratio for a UE can be written as follows.

$$H_{UE}^{Common} = \frac{\sum_{k=1}^{K_{HE}^{Common}} \rho(\widetilde{m}_k^{Common})\widetilde{P}_k^{Common}}{\sum_{k=1}^{K_{Total}} \widetilde{P}_k^{Common}} \quad (5)$$

C. *Offloading*

The performance indicator used in this paper is offloading, denoted as Off, defined as the ratio of the cost reduction due to self and D2D offloading compared to the cellular communication cost. Let C_{Self}, C_{D2D} and $C_{Cellular}$ be the costs or the amounts of radio resources consumed for self offloading, D2D offloading, and cellular communication, respectively, assuming $C_{Self} \le C_{D2D} \le C_{Cellular}$. Assuming that all devices request the same amount of contents and the number of UEs is very large compared to the number of HEs, the offloading can be approximated as

$$Off \approx 1 - \frac{C_{UE}}{C_{Cellular}} \quad (6)$$

where C_{UE} is the amount of radio resources for a UE with self and D2D offloading performed, expressed as follows.

$$\begin{aligned} C_{UE} &= C_{Self}H_{UE}^{Personal} + C_{D2D}(1 - H_{UE}^{Personal})H_{UE}^{Common} \\ &+ C_{Cellular}(1 - H_{UE}^{Personal})(1 - H_{UE}^{Common}) \end{aligned} \quad (7)$$

III. Simulation Results

In this section, we compute offloading for various cases assuming that a large number of UEs and a small number of HEs are uniformly distributed in a circular cell. The detailed simulation parameters are shown in Table 1. Fig. 2 shows offloading performance according to the velocity of HEs, while the time length of contents is fixed as 2 minutes. The simulation results show that as the velocity of HEs increases, the effective D2D coverage increases for chunks with large time margins and the overall offloading performance can be improved. Fig. 3 shows the offloading performance with video content lengths of 2, 3 and 4 minutes. The velocity of HEs is fixed to 15 km/h. It shows that the offloading performance can be improved when the time lengths of video contents become longer.

TABLE I. Simulation Parameters

parameters	values
Cell radius ($R_{Cellular}$)	100m
D2D coverage radius (R_{D2D})	20m
Minimum time length for one chunk (T)	60sec
Self offloading cost (c_{Self})	0.1
D2D offloading cost (c_{D2D})	0.4
Cellular transmission cost ($c_{Cellular}$)	1
Zipf parameter for personal preference list ($\lambda_{Personal}$)	1.0
Zipf parameter for common preference list (λ_{Common})	0.5
Size of common cache on a HE (K_{HE}^{Common})	100
Size of personal cache on a UE (K_{UE}^{Common})	10

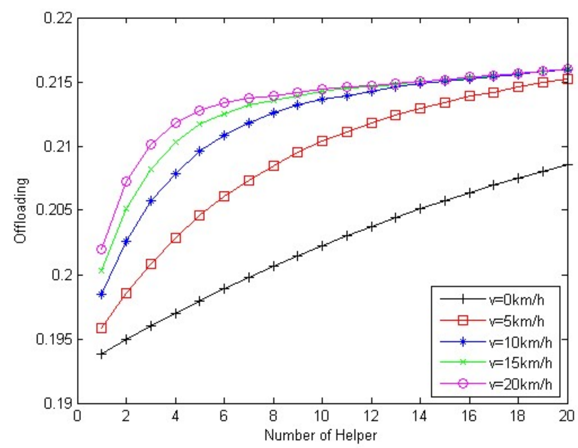

Fig. 3. Offloading performance according to the mobility of HEs

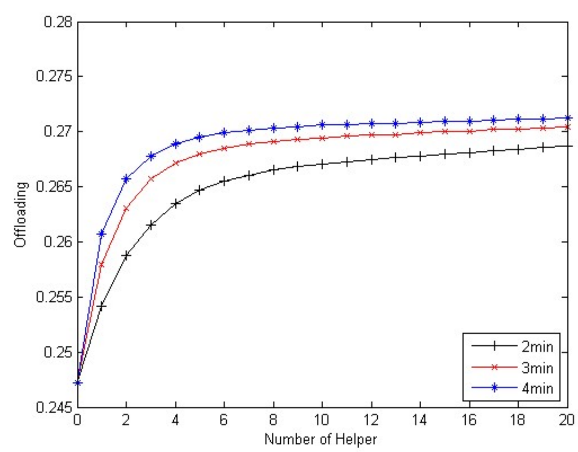

Fig. 4. Offloading performance according to the content length.

IV. CONCLUSION

In this paper, we have discussed offloading performance when mobile HEs support content requests from UEs using D2D communications. When a video content can be segmented into multiple chunks, many of chunks have some time margins before they are actually used. For chunks with sufficient time margins, the mobility of HEs can increase the effective D2D coverage and the D2D offloading performance can be improved especially when the D2D offloading cost is small compared to the cellular communication cost. The analysis and simulation results show that the offloading performance can be improved with high velocity of HEs and long time length of contents. However, in the real system, there can be some performance degradation in D2D communication with high velocity of HEs. In addition, mobile HEs such as cars and buses will not be distributed uniformly in the real world and it is required to model the system with more realistic assumptions.

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