Caching at the Wireless Edge: Design Aspects, Challenges and Future Directions

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Abstract

Caching at the wireless edge is a promising way of boosting spectral efficiency and reducing energy consumption of wireless systems. These improvements are rooted in the fact that popular contents are reused, asynchronously, by many users. In this article, we first introduce methods to predict the popularity distributions and user preferences, and the impact of erroneous information. We then discuss the two aspects of caching systems, namely content placement and delivery. We expound the key differences between wired and wireless caching, and outline the differences in the system arising from where the caching takes place, e.g., at base stations, or on the wireless devices themselves. Special attention is paid to the essential limitations in wireless caching, and possible tradeoffs between spectral efficiency, energy efficiency and cache size.

I. Introduction

The main trend of improving spectral efficiency (SE) for 5th generation (5G) cellular networks is an enhanced exploitation of spatial resources. By reducing the distance between base stations (BSs) and users, order-of-magnitude increase in network throughput can be expected. However, the effectiveness of this approach relies on high-speed backhaul connectivity to every single BS, whose capacity must exceed the aggregated data rate of all its served users, which often is not practical for the reason of cost.

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This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 61120106002 and National Basic Research Program of China (973 Program) under Grant 2012CB316003. The work of D. Liu was supported by the Academic Excellence Foundation of BUAA for PhD Students. The work of A. F. Molisch was supported by the National Science Foundation.

An alternative approach to improving SE is to reduce the unnecessary traffic load by rethinking the characteristics of the traffic itself and coming back to the most basic questions. Should all the data be conveyed right after they are generated or even requested?

The major driver of the exponential traffic growth in today's wireless networks is mobile Internet, which inherits a large portion of traffic from the wired Internet. The majority of such traffic is content delivery, which is non-real-time in nature. In fact, it has been reported that video on demand (VoD), a major class of content dissemination traffic, will generate more than 69% of mobile data traffic by the end of 2019. Different from conventional communications, the content generation of this traffic is usually decoupled from the content delivery, both in terms of source-destination and the time instance of generation-request.

Another key feature of the content delivery traffic is that a few popular contents account for most of the traffic load, and are requested by many users at different times. With predicted content popularity endowed by big data analytics, it is advantageous to cache popular contents *locally* before the requests truly arrive, directly at the wireless edge, e.g., at BSs or even end user devices [1], [2]. This is all the more attractive as trend on the rapid growth of storage capacity of devices enables such caching at a relatively low cost.

Caching in the wired Internet is well established and has shown to reduce latency and energy consumption. Similar benefits can be achieved by caching at the wireless edge, which can improve both SE and energy efficiency (EE) by precaching at users or further enabling device-to-device (D2D) communications, and by caching at small BSs (SBSs) to eliminate the backhaul bottleneck, possibly with a higher gain. This is because content is available *locally*, instead of requiring redundant traverse across backhaul links (not to mention transport across the Internet and mobile core network). However, the limitations of wireless networks need to be taken into account.

While the potential of local caching has been revealed by several recent investigations [1]–[5], the current article provides an overview of the state-of-the-art challenges and possible solutions of caching at the wireless edge, which differs from [6] that focused on caching at mobile core networks. To identify what is unique in wireless caching, we address the similarity and emphasize the difference between local caching in wired and wireless edge.

For both wired and wireless networks, caching consists of two closely-coupled problems: content placement and content delivery. The content placement problem includes determining the size and location of each cache, selecting which content from a library to place at which nodes, and how to download the content to these cache nodes. The content delivery problem is

how to convey a content to a user that requests it.

Since local caching aims to improve the quality of experience (QoE) of users or improve network performance without compromising QoE, the benefits and the solutions of caching highly depend on the traffic characteristics, e.g., the users' demand profile and quality requirement. Therefore, we first introduce *content popularity* and *user preference*, and discuss the QoE metrics of two representative types of content delivery traffic and the resulting challenge. Then, we address the differences in content placement and content delivery in wireless and wired networks. Next, we compare the SE and EE gains from caching at wireless and wired edge, and illustrate the fundamental tradeoffs and design aspects of caching at the wireless edge by simulation for two example systems. Finally, concluding remarks are provided.

II. KEY FEATURES OF CONTENT DELIVERY TRAFFIC

A. Content Popularity and User Preference

Using big data analytics, the statistical patterns of content requests, both in aggregate form, and on a per-user basis, can be predicted and play a key role in the design of caching.

1) Content popularity: By popularity we mean the ratio of the number of requests for a particular content to the total number of requests from users – usually obtained for a certain region during a given period of time. It has been reported that the popularity of content follows a Zipf distribution, a sort of power law distribution [7], which can be characterized by the content catalog size N_f and a skewness parameter β . In general, the content popularity distribution changes at a much slower speed than the traffic variation of cellular networks. Consequently, it is usually approximated as constant over long time (e.g., one week for movies, and two or three hours for news [1]). Another important fact is that global popularity in a large region (say in a city or even a country) is often different from local popularity in a small region (say in a campus) [8].

Popularity prediction is an active research field recently, as it is beneficial to many applications such as network dimensioning and on-line marketing. Many prediction methods have been proposed, e.g., cumulative views statistics based on the popularity correlation over time [7]. A special difficulty in wireless networks is the fine spatial granularity at which content popularity often needs to be known. Specifically, predicting the content popularity in the coverage of a BS is challenging because the users associated with a BS is dynamic and the number of cumulative requests is limited during the lifetime of popular content.

2) User preference: The user preference profile comprises the probability that each content is requested by a specific user during a certain period, and differs among individuals. This comes from the fact that a user usually has strong preference toward specific content categories [8].

The preference of a user can be predicted by machine learning (say collaborative filtering) based on the historical content requests of the user and the similarity among users [9]. This has been extensively studied in recommendation systems and is a hot topic nowadays for more general applications.

3) Prediction uncertainty: The prediction accuracy of the content popularity and user preference affects the performance of proactive caching. Specifically, the erroneous information reduces the probability of finding the requested files in the cache, called *cache-hit probability*, a metric usually used to reflect caching performance. As a result, it reduces the performance gain from caching and introduces extra cost, e.g., the energy consumed at backhaul and BS for improper content placement.

B. VoD and File Downloading

Content delivery traffic includes file downloading (e.g., software or data library update, music or video download) and video streaming. For file downloading, the content is consumed after the complete file has been delivered, where download time is often used as a metric to reflect the QoE. For video streaming, the user starts to play the video immediately after sending the request, where low initial delay, requested video quality, and few stalls during playback should be guaranteed.

Dynamic adaptive streaming over HTTP is common to reduce stalling under varying network congestion by providing various quality levels of videos in content server. Caching at the wireless edge to support video streaming service is more challenging. Multiple versions of a video with different quality levels need to be cached by either storing differently compressed versions of the same video, or by using difference encoding such that a better quality video can be reconstructed from the lower quality video plus an enhancement layer. Moreover, a mobile user may retrieve only a partial segment of a video from a BS according to the video playback process and the moving speed. With limited cache size, caching each complete video at every BS allows only a smaller number of distinct videos to be stored, while caching partial video may cause the cached part to be useless for catching up with the playback process.

III. CONTENT PLACEMENT: DIFFERENCE BETWEEN CACHING IN WIRELESS AND WIRED EDGE

In this section, we address the possible benefits, tradeoffs, and research issues of content placement at the wireless edge, by highlighting the difference with that at the wired edge, which comes from the architecture of wireless networks, nature of wireless channels, and user mobility.

A. Caching at BSs or Users: Benefits and Tradeoffs

In wireless networks, caches can be installed in macro BSs (MBSs), SBSs (say, pico or femto BSs), relays, or at users devices, see Fig. 1.

1) Caching at BSs: Compared with caching at evolved packet core (EPC) or at higher level, caching at existing MBSs and SBSs essentially plays the role of replacing backhaul links, and hence alleviates the backhaul congestion. Moreover, a new type of SBSs without any backhaul connections, called *helpers* [1], enable flexible and cost-effective deployment to deliver popular contents.

Because increasing cache size can increase the cache-hit probability, and hence lower the required backhaul capacity, there is a tradeoff between cache size and backhaul capacity. When the backhaul capacity is a bottleneck, increasing cache size is able to increase throughput. This translates to a tradeoff between the cache size and the network SE.

Since caching at the BSs can reduce the traffic in backhaul, mobile core network and wired Internet, it can also improve the EE of the network, if power efficient cache hardware such as high-speed solid state disk is used.

As an important difference to wired networks, the performance gain of caching at the wireless edge highly depends on the inter-cell interference (ICI) level. In one example, the maximal EE gain of caching over not caching will be 575% if the ICI can be completely removed and 250% without any ICI coordination [5]. When further considering overlapped coverage of densely deployed SBSs or heterogeneous networks and user mobility, the performance of caching in the wireless edge are yet to be fully exploited.

2) Caching at users: Precaching contents at user terminals such as smartphones, tablets and laptops has long been applied as a technique to improve QoE [10]. Recently, it is also proposed to offload wireless traffic.

With known content popularity, a BS can push the popular contents to all users via broad-cast [11]. With known user preference, the BS can pre-download favorite contents to some

users via unicast. According to whether the contents are placed to a user via unicast [10] or broadcast [11], in this article we classify *precaching* into *prefetching* and *pushing*.

When a user requests a content already cached at its local storage, the content can be retrieved from the cache (referred as self-serve as in Fig. 1), with zero delay and without generating interference to other users. Otherwise, the content can be conveyed to the user via unicast. In this way, precaching can improve QoE of all users either directly or indirectly, and improve wireless throughput by offloading.

In practice, a user may not be willing to contribute a large portion of its storage space for caching files. Then, pushing according to content popularity in a cell may not yield high cache hit probability, p_h . For instance, when the content popularity is Zipf distributed with $N_f = 1000$ and $\beta = 0.8$, and 10 files can be pushed to a user, $p_h = (\sum_{i=1}^{10} i^{-0.8})/(\sum_{i=1}^{N_f} i^{-0.8}) = 23\%$. How to motivate users to cache more contents deserves investigation.

By further exploiting D2D communications, some users can share their cached contents to help improve the QoE of other users in proximity and offload the traffic [1]. If the requested file is not cached at the local storage but cached at a nearby user, a D2D link can be established to deliver the content.

Recent results have demonstrated pronounced performance gain brought by cache-enabled D2D communications. Under many parameter settings, cache-enabled D2D provides a network throughput that increases linearly with the number of users (or, equivalently, a per-user throughput independent of the number of users) [4]. This makes this technology one of the most promising methods for achieving order-of-magnitude improvements in SE. Besides, a tradeoff between throughput and outage is possible in cache-enabled D2D networks [4].

However, a high offloading ratio comes at the cost of the energy consumed at users, especially those acting as D2D transmitters. This may lead to a tradeoff between the offloading ratio and the energy consumption.

B. Caching Policy in Wireless Edge: Unique Features

Similar to caching in the wired networks, appropriate caching policy in wireless networks is critical for achieving the potential gain.

Caching policy can be either *reactive* or *proactive*. A *reactive* caching policy determines whether to cache a particular content after it has been requested according to certain replacement algorithms [8]. A *proactive* caching policy determines which contents should be cached at each

node before they are requested based on the predicted users demand profile [1], [2], [8]. For proactive caching, the decision to cache among multiple nodes can be jointly optimized, and hence the caching gain is high with perfect prediction. With prediction errors, however, the cachehit probability will reduce, and proactive caching may perform worse than reactive caching [12].

1) Caching at BSs: Because the coverage of a BS is much smaller than an EPC or server and the connectivity between BS and user is with high uncertainty, caching policy design at BSs is more challenging.

Low cache-hit probability: The size of cache and the number of requests at each BS are much smaller than those in the core network or Internet. As a result, the reactive caching policies designed for Internet are not effective for caching at the BSs [8]. Designing proactive caching policy for each BS independently, e.g., each BS caching the most popular contents, may result in insufficient utilization of caches.

One way to cope with this problem is to enable BSs to share the cached contents through a backhaul link, i.e., *cooperative caching* [6], [12]. If the requested content is not in the cache of the local BS, by retrieving the requested content from the caches of adjacent BSs instead of from the server, the delivery cost and latency can be reduced, and the overall cache-hit probability can be improved. Such an approach is more likely to be viable for MBSs that have high-capacity fiber connection to share data, but is hard to implement for SBSs.

Due to the openness of wireless channels, the coverage of the SBSs are often overlapped. This indicates that a user is able to fetch contents from multiple caches and hence the equivalent cache size seen from the user is increased. Based on this observation, caching policies for adjacent BSs can be jointly optimized to increase the cache-hit probability without data sharing over backhaul links, which is referred to as *distributed caching* [1].

Topology uncertainty: Different from the wired networks with fixed and known node topology, in wireless networks it will not be known *a priori* which user will connect to which BS, due to the undetermined user locations.

One way to deal with this problem is to employ a probabilistic caching policy [13], rather than the deterministic caching policy used in wired networks. To reflect the uncertainty, this approach treats the user locations as spatial random process, and then optimizes the probability of each content being cached at each BS.

A further complication arises when a user is moving from one cell to another during the duration of content delivery. If the user mobility pattern can be predicted, the caching decision

can be optimized [14]. Otherwise, a less-than-ideal alternative is to model the user movement as Markov chain with predictable probability transfer matrix.

Fading and interference: In most of the current literature, the caching policy optimization fails to take into account channel fading and interference, which are essential to wireless networks. Consequently, the optimized policy may not perform well in practice. For example, distributed caching can increase cache-hit probability, which however may not improve SE and EE when path loss and ICI are considered [5]. Specifically, when the nearest BS of a user does not cache the requested content of the user but the second nearest BS does, the signal power from the second nearest BS is lower due to path loss. Even worse, the nearest BS is possibly generating a strong interference towards the user.

2) Caching at users: The content placement at users in wireless networks differs from that in wired networks in both caching policy and the way to download contents. For precaching, the difference comes from fading and interference. For cache-enabled D2D, the difference comes from all mentioned aspects in wireless networks as in caching at the BSs.

Precaching: Traditional prefetching is implemented by over-the-top operators for the users who have installed applications (APPs) [10]. Since the caching decision is made according to the predicted preference of a user and aims to improve QoE, the contents are naturally predownloaded to each user via unicast when the channel is in good condition. This may generate interference to other on-going transmission.

When prefetching is implemented by a mobile operator who has knowledge of the congestion status of BSs and the channel conditions of users, the degradation of the network performance can be minimized by designing sophisticated scheduling. Given that the predownloading via unicast consumes the energy at both BS and user and may cause interference to other users, accurately predicting the contents that a user will request and the time instance when the user will initiate the request are important to guarantee that the advantages succeed the harms brought by prefetching.

Considering that content popularity usually changes slowly, the most popular contents can be pushed by broadcast at off-peak time, which causes negligible or even no performance degradation to the network. For the contents (e.g., news) that update fast, a part of the network

¹Cache-hit probability can reflect the cache utilization efficiency, but does not necessarily reflect wireless resource utilization efficiency. This is an example of how content placement and content delivery are strongly entwined.

bandwidth can be reserved for broadcasting to dynamically push the popular files to users [11]; on the downside this may degrade the performance of the network during peak time.

Cache-enabled D2D: Different from prefetching where the way to select contents for predownloading is "selfish", the principle of designing caching policy for D2D communications is to help other users. Due to the user mobility, devices that will be in range of each other when a transmission request occurs are dynamic, which makes probabilistic caching more appropriate. For a given popularity distribution, the caching distribution that maximizes the offloading ratio takes on a form similar to water-filling [4].

With the probabilistic caching policy, the contents can be downloaded to users by a combination of multicast and unicast. To saves wireless resources, the BS can transmit content to a user only when first requested, while the other users "overhear" and cache content they find suitable; the gain of this approach is still unknown.

IV. CONTENT DELIVERY: IMPACT OF CACHING ON WIRELESS TRANSMISSION

To exploit the cache resource and traffic characteristics, some transmit strategies (essentially cross-layer) need to be re-designed. Since caching at the BSs can replace backhaul and reduce latency while caching at the users can even offload wireless traffic, new criteria emerge for optimization, e.g., minimizing backhaul traffic or end-to-end delay, and maximizing offloading ratio.

A. User Association

In heterogeneous networks with overlapped coverage of different BSs, caching may change the way of user association. To reduce end-to-end delay, or balance the traffic load in backhaul links, users are not always associated with the nearest BS. Instead, associating the users with the BSs that cache the requested contents may be more beneficial. In this case, the closest BS to the user may generate interference stronger than the desired signal. Such a problem has been identified and studied in the literature.

B. Coordinated Multi-Point Transmission (CoMP-JT)

CoMP-JT is hard to implement in traditional networks due to the high capacity backhaul required for exchanging data among BSs. Caching at SBSs makes CoMP-JT a possible cost-effective way to alleviate ICI, another limiting factor on wireless transmission capacity of small

cell networks. If the requested contents for the users are cached at several adjacent BSs, the BSs can serve the users with CoMP-JT by only exchanging channel information [15]. For helpers that completely lack backhaul, channel information needs to be shared with the assistance of the user device, or non-coherent CoMP-JT can be employed to avoid ICI and enhance the signal (but without any multiplexing gain).

Considering the limited cache size at SBSs and the dynamic nature of users' requests, cache-enabled CoMP-JT can only operate opportunistically. To enjoy the gain from CoMP, the probability that the content desired by a user can be found in local caches of multiple adjacent BSs should be increased. A simple way to do this is caching popular contents in every SBS, which however inevitably reduces the overall cache-hit probability. To maximize SE of the cache-enabled CoMP-JT with given cache size, the caching policy needs to be carefully designed. Because not all users in each cell can be jointly served by adjacent SBSs with the requested contents locally cached, the SBSs not using CoMP-JT will generate interference to the CoMP users, which will limit the overall throughput gain.

C. Multicast

Multicast is a mechanism to exploit content popularity for reducing duplicated transmission, with which a BS can serve multiple users requesting identical contents if they send the requests at the same time that happens for live video events.

The requests of users for content delivery are highly asynchronous. For file downloading that is delay tolerant, this is not a big issue, where traditional multicast technology can be used to let the users wait for each other before starting transmission. For VoD streaming that has the particular QoE provision, this results in a large initial delay, which degrades the user perceived QoE. Although schemes such as harmonic broadcasting partly overcomes this problem, they do not provide maximal SE. This dilemma can be solved by jointly optimizing the content placement and content delivery. In [3], an ingenious coded-multicast strategy was proposed, which precaches partial contents possibly requested by all the users with a carefully designed network coding. Then, during the content delivery phase, different requests can be satisfied with a single multicast transmission. Despite the theoretical beauty and importance of this strategy, practical challenges remain, since the coding complexity grows exponentially and the download delay for each user increases with the number of users.

D. Device-to-Device communications

Traditional D2D communications can only offload peer-to-peer (P2P) traffic between source and destination in proximity at the time they wish to communicate. Cache-enabled D2D creates new opportunities to offload client/server traffic [1].

Nonetheless, different from wired P2P networks, in D2D transmission there is not only a question of which users in vicinity are willing for help, but also the willingness of the users might change with time, and specifically with the state of their battery. Consequently, incentivizing users to act as helpers is an important issue. To justify the feasibility of cache-enabled D2D communications, the energy consumed by D2D transmitters needs to be evaluated, and the caching policy needs to be jointly optimized with communication protocol to balance the throughput gain and the energy cost. For readers' convenience, the key points of sections III and IV are summarized in Table I.

V. SIMULATION RESULTS

To illustrate the design aspects in content placement and delivery, the performance difference between caching in wired and wireless edge, and quantitative results for some tradeoffs, we consider two representative systems. The simulation parameters are summarized in Table II.

To compare the SE and EE gains of caching at wireless and wired edge over not caching, and show the SE/EE-cache size tradeoff, we consider a small cell network. Caches are either deployed at SBSs or the edge router as shown in Fig. 1. Each cache node caches the most popular files until it is full.

It is shown from Fig. 2 that both SE and EE benefit more from caching at the wireless edge than at the wired edge. Specifically, the maximal SE gains are about 200% and 900% for wired and wireless edge caching, and the maximal EE gain are 200% and 500%, respectively. This is because compared with caching at the wired edge that can only relieve congestion in the mobile core network and Internet, caching at BSs can also relieve backhaul congestion, though the cache hit probability is lower. As the total cache size increases, SE increases for both wireless edge and wired edge caching. In both cases SE saturates, though the saturation point occurs at higher total cache size for wireless edge caching, since popular files need to be stored at multiple locations. EE generally also increases with total cache size, though EE first increases and then decreases for the case of very large library size (and thus large number of unpopular files), since the caches consume circuit power and caching rarely used files requires more energy than it saves [5].

To illustrate the design aspects except the cache size, we consider a cache-enabled D2D network, where each user sends N_r requests sequentially in a period, and only the users within a collaboration distance r_c can establish D2D links. We also show the tradeoff between *offloading ratio*, the amount of data conveyed by D2D divided by the total amount of data transmitted in the cell, and *energy consumption*, which is the total transmit and circuit power consumed at each D2D transmitter averaged over channel fading, user location and file request. We consider *optimal caching* proposed in [4], *uniform caching* where each user caches files with identical probability, and *popularity caching* where each user caches a file with probability equal to the file popularity. We consider maximal transmit power (with legend " $P_{\rm max}$ ") and optimal transmit power (with legend " P^* ") at each D2D transmitter, where P^* is obtained numerically by maximizing the offloading ratio.

It is shown from Fig. 3 that optimizing the caching policy can improve the offloading ratio and reduce the energy consumption, while optimizing the collaboration distance r_c and transmit power are more critical. Furthermore, there is a tradeoff between the offloading ratio and the energy consumption when r_c is small, as we mentioned in Section III-A-2.

VI. CONCLUSION REMARKS

Caching at the wireless edge can significantly improve SE and EE of wireless networks compared with caching at the wired edge. The gain comes from saving bandwidth and energy both for getting the files from the servers to the wireless infrastructure, as well as for the transmission from wireless infrastructure to users. To exploit the full potential of wireless edge caching, the unique limitations in wireless networks due to architecture and channel, such as topology, interference, users' mobility and limited battery must be considered for both content placement and delivery, and accurate predictions of popularity distributions and user preferences are critical.

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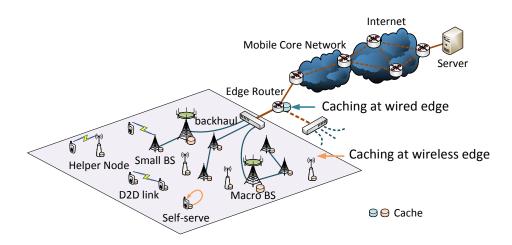


Fig. 1. Local caching and content delivery at wireless edge.

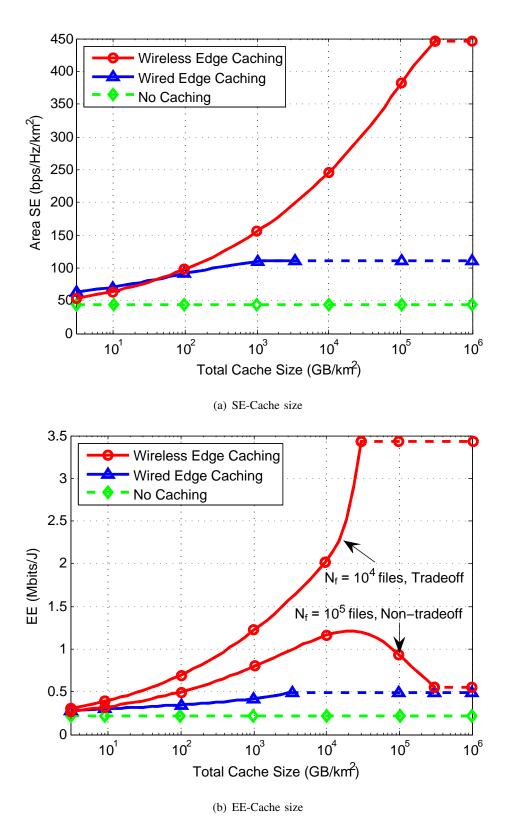


Fig. 2. SE and EE comparison between caching at wireless and wired edge. The solid curves end when all the files have been cached at each cache node.

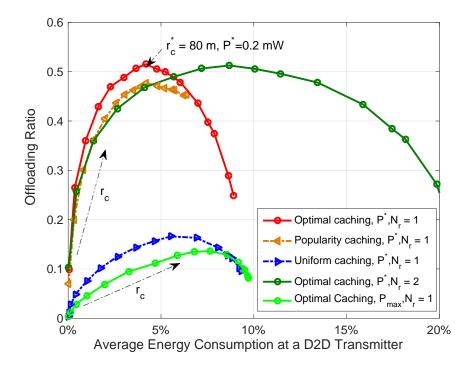


Fig. 3. Offloading ratio and energy consumption. Each curve starts from $r_c = 10$ m and ends at $r_c = 400$ m, and r_c^* is the optimal collaboration distance that maximizes the offloading ratio.

 $\label{table I} \mbox{TABLE I}$ Tradeoffs, features and impacts of caching in wireless networks

		Caching at users		
	Caching at BSs	Cache-enabled D2D	Precaching	
	SE and cache size			
Tradeoffs	EE and cache size	Offloading gain and energy cost		
	Backhaul capacity and cache size	Throughput and outage	/	
Features in content placement	Small cache size and number of requests		Small cache size	
	Uncertainty in topology		/	
	Openness of wireless channel: a) overlapped coverage		b) multicast/broadcast	
	Fading and interference			
	/	Limited battery capacity		
Impacts on wireless transmission	Optimization criteria: delay, backhaul traffic, offloading ratio	User incentive to act as helpers	/	
	Transmission strategies: user association, CoMP-JT, multicast	Balancing offloading and energy		

TABLE II
SIMULATION PARAMETERS

Systems	Caching in SBSs	Cache-enabled D2D	
File catalogue size, N_f	10^{5}	10^{3}	
File size	30 MB		
Zipf distribution skewness parameter, β	0.8		
Wireless transmission bandwidth	20 MHz (without interference coordination)		
Transmit power of SBS or user	200 mW		
Other power consumption parameters	See [5] and its reference [9]	Circuit power, 100 mW	
Considered region	1 km×1 km	0.5 km×0.5 km	
Number of SBSs (each with four antennas)	100 (uniform-located)	1	
Number of single-antenna users	300 (uniform-located)	2500 (uniform-located)	
Capacity of backhaul	30 Mbps (microwave)	1	
Transport bandwidth of wired network	1 Gbps	1	
Maximal energy allowed for transmitting one file	/	10% fraction of user battery capacity (1800 mAh)	