An Economic Vision of Caching Issues in Content Delivery Networks: Opportunities and Challenges

Yuming Zhang, Bohao Feng, Wei Quan, Hongke Zhang

School of Electronic and Information Engineering, Beijing Jiaotong University, China
yumingzhang@bjtu.edu.cn, bhfeng@bjtu.edu.cn, weiquan@bjtu.edu.cn, hkzhang@bjtu.edu.cn

Abstract

Content delivery network is an indispensable part of today's value chain of content delivery. In the 4G era, telco companies operate CDN only for their own use. With the development of 5G, they have envisioned to re-architect CDN based on emerging technologies such as SDN and NFV to provide flexible and high-performance CDN service to multiple third parties. The unique features of the new proposed architecture have attracted plenty of effort on several research aspects. Yet, there is still no literature to characterize the unique features of telco CDN and survey the existing publications. In this paper, we first give an overview of telco CDN in the 5G cloudified network architecture. Then, compared with traditional CDN, the unique features of telco CDN are illustrated. Next, we give a survey of existing work that addresses the new-arising problems in the development and operation of telco CDN. In addition, to aid the adopter's decision-making when choosing CDN service, we conduct an economic case study to assess the cost that an adopter has to pay in telco CDN in comparison with that in traditional CDN.

Keywords: CDN, vCDN, Cache management, Pricing

1 Introduction

Content delivery networks (CDNs) are overlay networks that consist of massive distributed surrogate servers in different strategic locations [1]. Through employing CDN services (e.g., web acceleration, video on demand service), the OTT (over-the-top) companies could provide premium quality of service (QoS) to their users without having to build their own data centers, reducing their capital expenditure (CAPEX). In the past two decades, with the persistent growth of Internet users and the rapid development of the mobile network, CDN has become an indispensable role in the content delivery value chain. In this trend, large-scale worldwide CDN companies (e.g., Akamai, Limelight, Wangsu) have been growing in size and profit [2]. With the prosperity of video services and the emergence of new applications such as 8K HD live and VR games, CDN traffic will continue to grow at high growth rate. According to the Cisco Visual Networking Index [3], CDN will carry 71% of Internet traffic by 2021 globally, up from 52% in 2016. The huge profit brought by the continuous growth of CDN business has attracted many companies to step into the CDN market. The CDNs that are operated by these companies are classified into two types as follows.

The first type is cloud CDNs that are operated by large OTTs (e.g., Amazon CloudFront, Alibaba CDN). In earlier years, these companies started deploying data centers for their own use. Then as the scale of the data centers becomes large enough, they find that the redundant cloud resources could be utilized to provide CDN service (and other cloud services) to third parties. With the advantages of low prices and multiple value-added cloud services, cloud CDN providers gradually occupy more and more market shares. For example, Alibaba has become the largest CDN provider in China and ranked third in the global Cloud market, carrying one-third of the domestic Internet traffic and accelerating 70% of the domestic content [4].

The second type is telco CDNs that are operated by telecommunication companies/mobile network operators (MNOs) (e.g., AT& T, China Unicom). It has been realized that MNOs could hardly make sustainable profits by acting only as dumb pipes for OTTs. In addition, MNOs do have the unique advantages to be potential CDN providers because they own the end-to-end underlying network status, which is important in CDN optimization and always be confidential to other CDN providers. Limited by their own scant cloud resources, MNOs failed to gain significant market share in the 4G era. With the development of 5G network, MNOs have envisioned to deploy thousands of data centers at the network edge [5], making themselves more competitive in the CDN market in the upcoming 5G era.

As to cloud CDN, it has matured in deployment and business model, and there have been several surveys focus on its important research dimensions [6-7]. However, for telco CDN that is evolving with the evolution of the MNOs' network architecture, there is still no related work to summarize its research

*Corresponding Author: Bohao Feng; E-mail: bhfeng@bjtu.edu.cn
DOI: 10.53106/160792642021122207003

dimensions and look forward to the future directions. In this paper, we conduct a survey of the recent advances in telco CDN. Moreover, combining the architecture and technical features of telco CDN, we present an economic case study that analyzes the cost of third parties when adopting the telco CDN service, compared with the cost under Alibaba CDN.

We believe that our work is meaningful for two reasons. First, coordinating deeply with the underlying cloudified network, telco CDN faces new challenges in the perspective of implementation, resource allocation, caching management, etc. As the deployment of 5G is still in its infancy, more efforts are needed in the near future to bring out reliable and high performance CDN service in 5G environment. Therefore, it is essential to summarize the existing work and shed light on future directions. Second, for adopters of telco CDN service, cost is an important factor in decision making of service deployment.

The remainder of this article is structured as follows. Section 2 demonstrates the general architecture of Telco CDN. Section 3 presents existing work on different fields of telco CDN. In Section 4, we conduct an economic case study to analyze the cost of a third party when adopting telco CDN service. Finally, Section 5 concludes this paper.

2 Overview of Telco CDN

Though MNOs also provide CDN service in 4G era, they lack competitiveness due to limited service capacity constrained by the cumbersome network architecture and scarce distribution of cloud sites [8]. With the advancement of 5G networks, the deployment flexibility of network is increased by SDN [9] and NFV [10] and massive distributed edge data centers are deployed. Therefore, MNOs have the capability to provide premium CDN service to third parties (i.e., OTTs). Moreover, besides the basic CDN functions (i.e., content caching and web acceleration), new functions such as data mining could be integrated into the CDN service chain, enabled by new features of 5G network (i.e., multi-access edge computing, MEC, [11-12]). Therefore, telco CDN is envisioned to bring new business opportunity for MNOs in the upcoming 5G era, attracting more and more attention from both academia and industry.

With reference to the 5G CDN architecture of China Unicom [13], in Figure 1 we present a general telco CDN architecture that overlays a cloudified 5G MNO's network. As shown, there are massive data centers sitting in metropolitan network and backbone network of the MNO, enabling the service capability of edge CDN, whose workflow is same as that of traditional CDN. Moreover, fog nodes (i.e., home gateways, user devices) and data centers in radio access network enable the service capability of fog CDN, which is built upon the technologies of peer to peer networks [14].

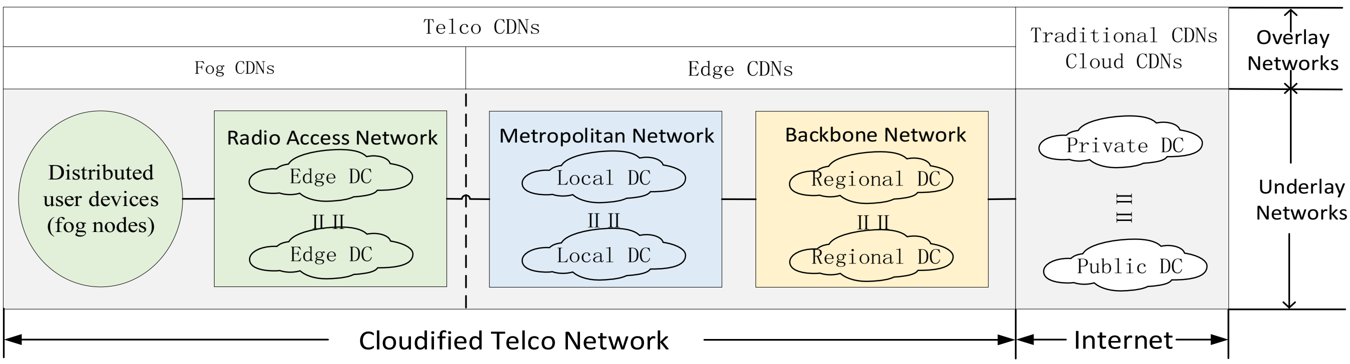

Figure 1. Overview of telco CDN in 5G era, compared with traditional CDN, cloud CDN

For better understanding of the unique features of telco CDN, the differences between telco CDN and traditional CDN are elaborated from three aspects as follows.

(1) Architecture of both overlay and underlay. Traditional CDN providers run their business base on the data centers they own in the Internet or the PoP-level infrastructure they lease from MNOs. In other words, the overlay networks (CDNs) and the underlay networks are operated by traditional CDN providers and ISPs/MNOs, respectively. In comparison, in the upcoming 5G era, an MNO owns the cloudified underlay infrastructure which is based on SDN and NFV, enabling efficient and on-demand telco CDN service (Section 3.1, 3.2). Moreover, based on the ownership of both overlay and underlay, the MNO may employ different business models to operate its telco CDN business (Section 3.2).

(2) CDN optimizing strategy. Traditional CDNs make optimization decisions (i.e., request redirection) base on their observation of the network status through probing techniques. However, it is hard for them to track the dynamic changes of network status in time in case of unexpected traffic bursts, then they could only adjust their strategies passively, which may lead to inevitable performance degradation. In comparison, an

MNO has a comprehensive view and control of its underlying network, which could be combined into the content delivery optimization to make decisions with higher efficiency [8]. Moreover, with the deployment of hierarchical edge data centers distributed in access networks, telco CDN is enabled to provide guaranteed delay even for delay-sensitive applications [15].

(3) Value-added services. Besides the basic service such as content caching and web acceleration, CDN operators also provide value-added services to satisfy different customized requirements. Thanks to the booming development of software-as-a-service (SaaS), common value-added services such as video transcoding and video analysis have been supported in traditional CDNs. Yet in telco CDN, many unique value-added services could be provided based on new features of the underlying architecture. For example, network information (e.g., cell load, user mobility) provided by the underlay network could be utilized to analyze user preference in different areas, enabling local advertising service which helps improving user experience and increasing third parties' revenues.

3 Existing Work on Telco CDN

In this section we review the existing work that address the new-arising problems in telco CDN.

3.1 Design Principles and Architecture

Together with the complete knowledge of the network they maintain, network operators have the potential to provide cost effective and high qualified CDN service. However, to build up CDN over the evolving underlying architecture, many challenges should be addressed as discussed in [16].

First, telco CDN has to meet the need of growing user traffic and evolutional user expectation. Besides video traffic, the consumption of customized contents and user generate contents is also increasing rapidly. Moreover, both fix and mobile users have higher QoE requirements and extended mobility requirements, which cannot be well satisfied in current content delivery system.

Second, telco CDN has to embrace the evolution of the content delivery ecosystem. On the one hand, great amount of traffic generated by the emerging IoT systems needed to be handled properly. The traffic is highly distributed and with high diversity, raising critical requirements on the position and delay performance of the CDN sites. On the other hand, the underlying infrastructure is re-architected by new technologies such as could computing, SDN, NFV, ICN. In this context, building up CDN to provide on demand and SLA-based service is challenging.

Third, telco CDN has to deal with the business and technological issues among different stakeholders that are raised by the former two challenges. Specially, how to effectively allocate the resource to the CDN users? How to price the allocated resource properly? How to federate with other telco CDNs in a win-win manner? What would the strategy be when a telco CDN want to oursource its missing capabilities to third parties?

Except for the above mentioned challenges, the basic functionalities of telco CDN have to accommodate its unique features. [17] outlines the design goals of telco CDN which are listed below

- Network-tailored cache placement
- Flexible content outsourcing
- Balanced replica placement
- Network-aware request routing

Besides the potential solutions that are presented in [17], many existing researches are conducted in last few years to address the challenges and satisfy the design goals. We focus the architecture design and implementation in this subsection, other existing work is discussed in the subsequent subsections. In summary, existing work raise the concept of CDN as a service in the implementation of telco CDN [18-20]. Compared with traditional CDN, the CDNaaS architecture is NFV-based and designed with new APIs and modules to enable on-demand customization of various CDN service types.

It has been realized for many years that being only dumb pipes is hard for MNOs to obtain sustainable revenue growth, and providing CDN service is a promising method that brings a new source of income. Early works have discussed the design principles of telco CDN and conducted a qualitative analysis of its profitability.

In [17], Spagna et al. outline the design goals, general architecture and design principles of a highly distributed mobile network-owned CDN. Specially, they analyze the centralized nature of the mobile carrier network and point out the importance of cache server placement, which determines the CAPEX, OPEX of the MNO and affects the performance of CDN service. In addition, a key observation is that the trade-off between network cost and cache cost should be parameterized when formulating the content placement problem.

Ibrahim et al. point out the potential new roles of telcos in the future content delivery ecosystem [16]. Three business models that telcos may adopt to involve in the content delivery value chain are proposed, namely, telco-CP model, telco-CDN provider model and telco-users model. Nevertheless, to support the new business models, the evolution of the control plane of traditional MNO network is essential and complex [16].

With the development of 5G, many promising network technologies are employed, which enable MNOs to provide on-demand telco CDN service cost-efficiently. Thus, the architecture design and implementation of NFV-based telco CDN systems have attracted much attention [18-20]. Frangoudis et al. design and implement a CDN-as-a-service architecture following the NFV-MANO spirit [18-19]. Built upon Openstack, the architecture receives the deploy requests of third parties through the northbound API, executes the VNF placement algorithm and translates the allocation results to the configuration of the VMs in the infrastructure layer, finally a virtual CDN (vCDN) starts running. Moreover, it introduces the concept of service plugin that enables combination of specific components for every vCDN type, therefore different flavored vCDN service could be supported on demand, enabling the business models that are discussed in [16].

In [20], Khedher et al. propose a similar vCDN architecture, which is also based on the MANO framework. Specially, they give details about the virtual functions in an instantiation of vCDN and demonstrate different deployment scenarios at different positions in an MNO's network.

3.2 Economic Related and Federation

(1) Profitability and impact: Given cloudified and virtualized architecture of telco CDN, different business models could be employed [21]. Before launching the business, it is essential for an MNO to choose the most appropriate business model(s) by economically analyzing the corresponding pros and cons.

Herbaut et al. propose a CDN-as-a-VNF model in their ISP NFV platform [21]. Further they quantitatively analyze the model's optimality conditions, comparing with other collaboration strategies, including uncollaborative scenario, managed CDN, licensed CDN, telco CDN. [22] is the first work that explores whether it is profitable for an ISP to introduce CDN service.

Maillé et al. study the impact of vertical integration of ISP and CDN on the competition of ISPs [23]. Through game theoretic analysis, they obtain counterintuitive observations: an ISP may prefer collaborating with an independent CDN over controlling its own CDN, yet end users prefer the vertical integration.

(2) Federation and impact: Lee et al. study the impact of alliance of telco CDNs on the CDN market competition [24]. Through a non-cooperative game analysis between CDNs and CPs, they conclude that poor operational efficiency of telco CDNs may lead to cutthroat price competition in CDN market. In contrast, sufficient merits provided by telco CDNs help reducing the competition and contribute to the growth of total market revenue. In [25], the authors further discuss the type of the telco CDN's federation, namely, partial federation and full federation, and analyze their incentive conditions followed by numerically comparing different revenue sharing policies.

(3) Pricing for Edge Caching and Optimal Cache Renting: Different from large capacity cloud cache servers sit in data centers, edge storages, having limited capacity, are deployed in highly distributed small-scale data centers or even in BSs. Therefore, for a telco CDN, the owner of cache infrastructure, it is important to design proper and robust pricing mechanism to efficiently allocate the edge cache and thus help offload more traffic [26-29]. And for a content provider (CP), it is important to rent proper amount of edge cache to maximize its own utility [30-31]. We summarize the aforementioned works in Table 1.

Table 1. Summarization of existing work on cache pricing and renting

Ref	Scenario	Algorithm	Description
[26]	Genaral edge network	Double Auction	Conduct social welfare maximization. Propose a region-based demand cover mechansim, achieving 74-91% of the maximum social welfare.
[27]	Small-cell Network	Sequential Auction	Conduct social welfare maximization that considers collaborative caching, improve 20-70% of social welfare than the VCG mechanism.
[28]	Small-cell Network	Stackelberg Game	Define satisfaction funtion to quantify CPs' revenue. MNO and CPs could all achieve a utility that is up to 50% higher than that in the arbitrarily trading case.
[29]	Small-cell Network	Stackelberg Game	Derive backhaul cost reduction of MNO and revenue gains of CPs. Investigate both non-uniform and uniform pricing schemes and the corresponding relationship with the impact factors, i.e., BS cache size and content popularity.
[30]	Small-cell Network	Optimization decomposed by Lyapunov technique	Given cache prices, CP maximizes the benefit in average download delay with budget constraint. Solve two SBS coverage cases separately.
[31]	Small-cell Network	Optimization with generalized Benders decomposition	Given cache prices, CP solves the master problem in pre-fetching phase, MNO solves the salve problem in the delivery phase

3.3 Resource Allocation

As shown in Figure 1, the deployment of edge CDN is based on large number of edge cloud infrastructures (e.g., data centers). Specially, the function modules of telco CDN are realized as different VNFs [10], allocated by an orchestrator.

Although there have been many previous works on resource allocation in cloud CDN [6, 32], the characteristics of edge cloud and the envisioned new features of telco CDN bring new challenges. First, the geographic diversity and limited capacity of the edge clouds make the resource allocation problem more complex [33]. Second, it is envisioned that telco CDN users could submit various types of deployment requirements. For example, the location of a VM, the desired response time [34], target QoE level of the covered area [35]. The customized requirements make the algorithm design, which has to be conducted in an online manner, more challenging.

(1) QoE aware virtual computation/storage allocation: Based on the basic architecture designed and implemented in [19], Yala et al. explore the quantity relationship between the server load and the QoE, then they design a QoE-aware resource allocation algorithm to determine the optimal number of vCPUs to deploy in every region [35]. Given the provisioned number of vCPUs, the authors further explore how to efficiently initiate VMs with proper quantity of vCPUs in the physical infrastructure while the trade-off between service availability and the physical cost is achieved [36]. [37] jointly optimize the placement and routing of the content objects and the vCDN resource allocation while satisfying the requirements of all the players, namely, the owner of the telco CDN (the MNO), the customers of the telco CDN and the end users.

(2) SLA-based vCDN embedding: Different from the QoE aware resource allocation approach in [35] where QoE is quantified through measurement study, Herbaut et al. propose a virtual network embedding approach whose constraints naturally capture the capacity and service delay requirements described in the SLA negotiation [38-39]. Moreover, they design a heuristic algorithm to reduce the embedding time and analyze the embedding cost through implementation on a SDN testbed [40].

(3) On-demand vCDN migration: In order to determine the vCDN migration strategy, Ibn-Khedher et al. formulate an optimization that minimizes the migration cost with the constraints related to vCDN component size, physical server capacity and network capacity [41]. Then a dynamic plugin is designed in [42] to select the optimal migration layer(s) in the hierarchical physical architecture of a telco CDN. Furthermore, the same authors design a heuristic algorithm in [43] to make the migration process better adaptive to a larger network scale. Through simulations over different topologies, they analyze the migration cost, migration time and scalability issues. In [44], the authors give a comprehensive analysis of the impact factors of the proposed migration algorithm and compare it with different related work.

(4) Video-specific optimization: Since video traffic has dominated the CDN bandwidth consumption and always leads to traffic bursts, QoS/QoE and resource efficiency of video delivery have become the most concerned issues of resource allocation in telco CDN network. Zhou et al. focus on overlay construction and bandwidth allocation for multiple live video channels [45]. They construct one overlay for every channel and formulate two different optimizations to delivery as many important channels as possible while minimizing the total bandwidth consumption. In [46], Calvigioni et al. focus on QoE-aware routing for HTTP based adaptive streaming sessions in overlay of ISP networks. Specially, based on the QoE reference model in an ITU-T standard, they propose a QoS-QoE model that quantifies QoE as a function of a set of QoS parameters.

3.4 Cache Management

Cache placement and user request redirection are also key components of a telco CDN system. However, telco CDN leads several new research directions of cache management as follows.

(1) Resource-constrained edge caching: Compared with the high-capacity cloud resources in traditional CDN, resources (i.e., cache, computation) in telco CDN are more constrained because the caching nodes sit in distributed BSs or small scaled edge data centers [47]. In [48], Liu et al. demonstrate that the limited user popularity and storage capacity per BS in mobile CDN may lead to low hit ratio compared with traditional CDN. Vleeschauwer et al. argue that in telco CDN with highly distributed caches, the LRU strategy which is widely used in traditional CDN may be not efficient enough [49]. In [50], the authors discuss the optimal condition (in terms of bandwidth saving) when designing content placement strategy in cache size limited cellular network.

(2) Multi-tier collaborative caching: As envisioned in [51], caching in telco network could be conducted at multiple layers, i.e., EPC, RAN, D2D (also shown in Figure 1). The resource of a single caching node becomes more and more limited as the distance between users and the caching node becomes shorter, leading to moderate caching performance. To push the infrastructure capacity and caching performance to the limit, a number of schemes that focus on inter-layer and intra-layer collaborative caching have been proposed. [52-53] explore two-tier (macro, micro) and three-tier (macro, micro, pico) BS-level collaborative caching, respectively. Especially, the authors of [52] formulate the caching placement problem by directly minimizing the summation of delivery cost and delay cost. In comparison, the authors of [53] decompose the complex multi-tier caching problem into three subproblems to achieve low complexity. Furthermore, they study the D2D aided hierarchical mobile caching problem in [54]. In addition, Tran et al. [55] argue that pure BS-level collaborative caching that leverages

capacity-limited interconnection between BSs cannot satisfy the explosive content demands. They employ cloud processing unit in BS-level edge caching and achieve better performance in terms of cache hit ratio, content access delay and backhaul traffic load. In [56], a comprehensive caching framework including router-level, BS-level, D2D-level is considered. The authors formulate the caching problems by formulating inter-tier problem and intra-tier problem, respectively.

(3) Joint optimization of caching and traffic engineering: While it has been proved that edge caching in telco CDN helps reduce traffic burden [48, 51], some existing work focus on exploring whether traffic engineering could help promote the cache performance. Sharma et al. raise the concern for traffic management from the perspective of network when designing the content distribution strategy of a telco CDN [57]. They analyze the performance of joint optimization of content placement and traffic routing. Unexpectedly, their conclusion is that the existing disjoint approach is good enough. However, with more realistic settings, Li et al. prove that the joint approach they propose could achieve higher hit ratio and better traffic management results [8].

(4) Caching for emerging applications: Emerging applications such as cloud gaming, AR have raised stringent latency requirements to the content delivery process [58]. Deployed deeply into access network, telco CDN has a natural advantage to support delay-sensitive applications, even could provide delay guarantee. [15] is the first research focusing on the problem of distributing delay-sensitive contents in the context of telco CDN. Then in [59] where a more generalized scenario is considered, they focus on congestion and unbalanced traffic loads caused by previous cache management approaches. By solving a Lyapunov optimization, the problems are addressed and the transmission cost is minimized.

(5) Caching with dynamic content popularity: As the cache sites in telco CDN are more distributed and capacity-limited than those in traditional CDN, the content popularity at different sites may be temporal and spatial different. Except for [60] that exploits location differentiation of popularity in edge caching, most existing work focus on handling time-varying content popularity. Claeys et al. propose a hybrid cache management approach that consists of both proactive content push strategy and reactive caching strategy, thus they achieve high efficiency in caching contents with perfectly-predicted popularity and unexpected popularity, respectively [61]. Similarly, to achieve high caching efficiency in case that the content popularity change frequently, Nakajima et al. propose a hybrid caching approach based on modified LFU and LRU by adding color tags to cache servers and contents [62-63].

Recently, machine learning has become a good choice for predicting content popularity. In [64], Tanzil et al. utilize the extreme learning machine (ELM) to predict the content popularity and design a content and network aware cache scheme which achieves efficient cache deployment and content placement. In [14], neural network is utilized to predict the content popularity and the P2P node capacity to solve the seed scarcity problem in the CDN-P2P VoD system. In [65], ISP is enabled to directly leverage the public available results from the current recommendation system to promote the cache performance. In addition, given known/perfectly-predicted content popularity, precaching contents at the user devices has raised more and more attention, especially since wireless offloading is proposed [47, 66-67].

4 Cost Analysis of Adopting Telco CDN Service: An Economic Case Study

It has been demonstrated in the previous sections that the motivation of an MNO to launch CDN service is to increase its revenue. Thus, it is important to attract as many customers as possible, providing them with premium service and reasonable prices. Existing works listed in the previous section contribute to the realization of the overall technical architecture of telco CDN, satisfying multiple service requirements of customers. Nevertheless, besides service quality, cost is another significant factor that affects the customers' decision on whether to adopt a telco CDN service. To the best of our knowledge, there is still no relevant work pays attention to the cost of adopting a telco CDN service, which we focus on in this section. We conduct an economic case study that helps customers make adoption decision and provides MNOs with insights on pricing of telco CDN, considering its technical features.

4.1 Cost Structure of VoD CDN Service

Considering that CDN has been indispensable in the video delivery chain, we take video on demand (VoD) CDN service as example in this economic study. We assume that a telco CDN employs the same pricing model as cloud CDN. Then, we demonstrate the cost structure when a content provider adopts VoD CDN service.

Figure 2 gives a general CDN service model and shows the billing-related CDN nodes, namely, the edge caches and the source library. Edge caches, with relatively limited capacity, cache/replace contents requested by end users dynamically according to certain cache management strategies (Section 3.4), generating cache cost, denoted by C_{cache}. The source library caches all contents uploaded by the content provider. We assume the source library is realized by employing the MNO's cloud cache service, further we assume that the prices of caching in cloud CDN and telco CDN are the same. Moreover, edge caching is a potential cost-saving design to supplement, not replace, traditional cloud caching. Therefore, the cost of cloud caching is not accounted in the cost-saving we concerned.

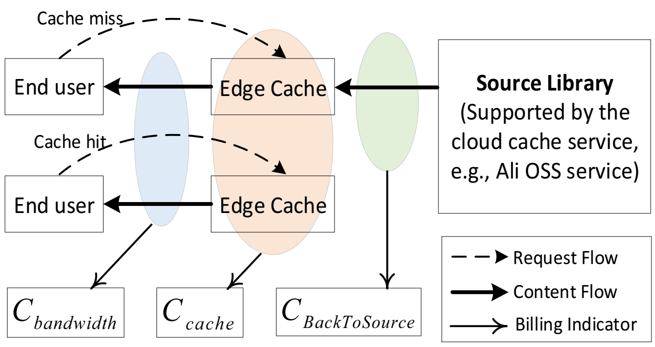

Figure 2. General VoD CDN service model, indicating the billing items

As shown in Figure 2, when there is a cache hit upon a user request, only a certain edge server generates downstream traffic, which is billed based on daily peak- bandwidth, generating bandwidth cost donated by $C_{Bandwidth}$. Yet when a cache miss happens, the request is further directed to the source library to fetch the content, which is then cached in the edge cache and sent to the user, thus both the edge server and the source library generate downstream traffic, where the latter part is billed based on the usage amount, generating cost denoted by $C_{BackToSource}$.

To sum up, the total cost of VoD service, denoted by C , is expressed as Eq. (1). To be intuitive, we list the prices of different billing items in Alibaba VoD CDN service in Table 2, which will be used as the baseline price strategy in latter analysis.

Table 2. Price of billing items in Alibaba VoD CDN service (China Mainland)

Billing Item	Price
Cache (U/GB/Month) [68]	0-50GB, free; >50GB, 0.148
Bandwidth*(U/Mbps/Day) [68]	0-500 Mbps, 0.6; 500 Mbps - 5Gbps, 0.58; 5Gbps - 20Gbps, 0.56; >20Gbps, 0.54
Back to Source Traffic (U/GB) [69]	0.15

$$C = C_{cache} + C_{Bandwidth} + C_{BackToSource} \quad \textbf{(1)}$$

Note that in practice, the above mentioned VoD service is always combined with some value-added services, such as transcoding, overlay advertising, etc. However, new features of telco networks may introduce new value-added services with new pricing models, thus this part of cost is not considered in this work.

4.2 Simulation Scenario and Parameters

We consider a scenario where a cloud CDN and a telco CDN both have CDN infrastructures covering a region that serve 2000 users. Assume that in the region, the cloud CDN only has one cache site that sits in a private data center. On the other hand, the telco CDN has one root cache site and N local cache sites that sit in one regional data center and N local data centers that are connected to the regional data center, respectively. The capacity of every cache site is set as a certain percentage, γ , of volume of the total contents.

Request Arrival and Content Characteristics. We use parameters shown in Table 3 to generate the CDN traffic. A is the average of the total number that a user sends VoD requests in a day. There are 100000 videos in total with popularity following Zipf distribution with the Zipf parameter $\alpha = 1$. s is the average size of a video. h_i is the ratio of the number of the VoD requests in the $i-th$ hour in a day to the total number of requests in the day [70]. Assume the VoD requests arrive according to Poisson process with the intensity in the $i-th$ hour $\lambda_i = A \cdot h_i / 60$.

Table 3. Parameters for generating CDN traffic

Parameter	Value
U	2000
A	200
C	100000
s (MB)	50
α	1
[h1… h24] (%)	[3.87, 4.14, 4.42, 4.70, 4.97, 4.97, 4.70, 5.52, 5.80, 6.35, 6.91, 7.18, 7.18, 6.63, 5.52, 3.87, 2.49, 1.38, 0.83, 0.55, 0.83, 1.38, 2.49, 3.31]
γ	0.1～0.18

Cache Strategy. In simulation, LRU, which is widely adopted in commercial CDN [7], is employed as the content replacement strategy of the cloud CDN. Besides LRU, MLRU [49] is also employed as a possible adopted strategy of the telco CDN. Specially, the jump ratio is set to 0.2, which means that the ranking of the most recently requested content will increase by 20 percent of the cache capacity. In addition, considering that collaboration is always needed in edge caching [27, 53], every local site of the telco CDN is enabled to be collaborative with its nearest neighbor site. Therefore, according to the cache strategy (LRU/MLRU) and collaboration strategy, there are four cases of telco CDN to be observed.

Observed Metric. Assume that a content provider adopts the CDN service of either the cloud CDN or the telco CDN to cover the user demand. We observe the one-day cost that a content provider should pay to the cloud CDN/ telco CDN to satisfy the user demand in the covered region. With the ownership of large amount of edge cloud resources, the telco CDN could set the prices of the billing items lower than those of the cloud CDN. Here we assume that the telco CDN set prices according to Table 2 to be competitive, leaving its own pricing issues for future work.

4.3 Cost Analysis When Two-tier Caching and Competitive Pricing Are Employed

Figure 3, Figure 4 and Figure 5 respectively show the cost in cloud CDN and different cases of telco CDN when $N = 2$, $N = 4$ and $N = 8$. We observe that telco CDN indeed help the adopter save cost. In addition, as the cache ratio increases, the total cost decreases in all the cases in the three figures. This is because when the cache ratio is larger, more contents could be cached locally and less requests redirected to the source library, bringing lower than $C_{Bandwidth} + C_{BackToSource}$, which dominates the total cost. Specially, in the telco CDN, collaboration and MLRU strategies always bringing more cost saving. In summary, the additional cache costs help save more bandwidth cost, giving telco CDN the unique advantage among CDN markets.

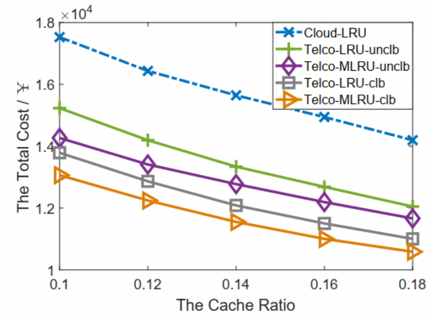

Figure 3. The total cost when N=2 in telco CDN

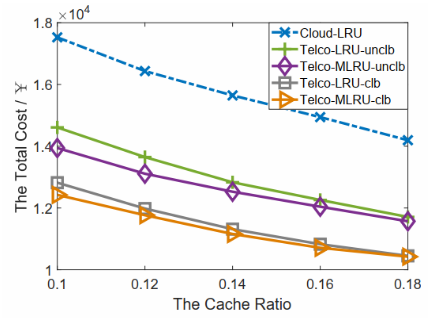

Figure 4. The total cost when N=4 in telco CDN

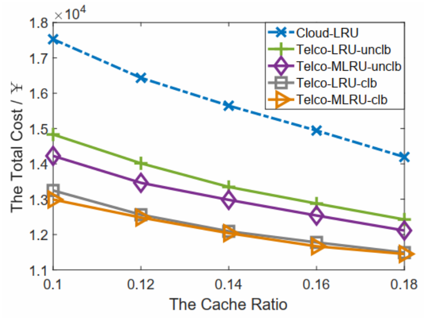

Figure 5. The total cost when N=8 in telco CDN

4.4 Discussions on Dynamic Bandwidth Pricing

In telco CDN where the bandwidth resources are more distributed, it is essential to spread the traffic properly to different sites while achieving acceptable/guaranteed user experience and resource utilization. Yet, in the current VoD service model, the bandwidth pricing function is fixed and independent from the traffic engineering method. Thus it is not efficient enough as a tool to adjust flexible demands and help improve social welfare [71]. We plan to combine dynamic bandwidth pricing with request routing and/or traffic engineering in future work to explore the benefits that dynamic pricing may bring.

5 Open Directions

To form large-scale hierarchical telco CDN in 5G era, continuous deployment is required through several different phases, during which several urgent aspects should be focused on in the near future [72]. First, to ensure the reliability and scalability of fog CDN, the drawbacks of existing p2p technologies need to be addressed [73]. Second, the integration of MEC and telco CDN is promising to promoting QOE [74]. Third, the security issues faced by telco CDN are more complicated, considering the new security problems brought by underlay infrastructures and the security requirements of emerging services [75].

6 Conclusion

With the development of 5G, telco CDN is envisioned to be part of infrastructure of an MNO's 5G network. Different from traditional CDN and cloud CDN, telco CDN cloud be built based on an MNO's own network infrastructure, namely, the continuum from the backbone network to radio access network, forming a hierarchical CDN architecture from the cloud-level to the fog-level. In this paper we survey recent publications that focus on the above research dimensions. In addition, considering that it is always important for a CDN customer to spend the least while its users' demand is satisfied, we conduct an economic case study to compare the payment of an adopter when employing either telco CDN or cloud CDN. Results show that even price the same as cloud CDN, telco CDN could still help the adopter save money to different extent when topology of the telco CDN's underlay is different.

Acknowledgments

This work is partially supported by the Fundamental Research Funds for the Central Universities under Grant No. 2020JBM013, and National Natural Science Foundation of China under Grant No. 61802014.

References

[1] G. Pallis, A. Vakali, Insight and Perspectives for Content Delivery Networks, *Communications of the ACM*, Vol. 49, No. 1, pp. 101-106, January, 2006.

[2] A.-M. K. Pathan, R. Buyya, A Taxonomy and Survey of Content Delivery Networks, pp. 1-44, 2007.

[3] Cisco, Cisco Visual Networking Index: Forecast and Methodology 2016-2021, 2017.

[4] Gartner, Market Guide for CDN Services, ID: G00343230, January, 2018.

[5] China Unicom, White Paper for China Unicom's Edge-Cloud, February, 2018.

[6] M. Wang, P. P. Jayaraman, R. Ranjan, K. Mitra, M. Zhang, E. Li, S. Khan, M. Pathan, D. Georgeakopoulos, An Overview of Cloud Based Content Delivery Networks: Research Dimensions and State-of-the-art, in: A. Hameurlain, J. Kung, R. Wagner, S. Sakr, L. Wang, A. Zomaya (Eds.), *Transactions on Large-Scale Data-and Knowledge-Centered Systems XX*, Springer, 2015, pp. 131-158.

[7] M. A. Salahuddin, J. Sahoo, R. Glitho, H. Elbiaze, W. Ajib, A Survey on Content Placement Algorithms for Cloud-Based Content Delivery Networks, *IEEE Access*, Vol. 6, pp. 91-114, September, 2017.

[8] Z. Li, G. Simon, In a Telco-CDN, Pushing Content Makes Sense, *IEEE Transactions on Network and Service Management*, Vol. 10, No. 3, pp. 300-311, September, 2013.

[9] H. Farhady, H. Lee, A. Nakao, Software-Defined Networking: A Survey, *Computer Networks*, Vol. 81, pp. 79-95, April, 2015.

[10] B. Yi, X. Wang, K. Li, S. K. Das, M. Huang, A Comprehensive Survey of Network Function Virtualization, *Computer Networks*, Vol. 133, pp. 212-262, March, 2018.

[11] MEC, *Mobile Edge Computing (MEC); Framework and Reference Architecture*, Tech. Rep. ETSI GS MEC 003, March, 2016.

[12] X. Chen, C. Xu, M. Wang, Z. Wu, L. Zhong, L. A. Grieco, Augmented Queue-based Transmission and Transcoding Optimization for Livecast Services Based on Cloud-Edge-Crowd Integration, *IEEE Transactions on Circuits and Systems for Video Technology*, Early Access, pp. 1-15, December, 2020.

[13] China Unicom, *The New CDN Network Architecture of China Unicom*, April, 2018.

[14] Y. Zhang, C. Gao, Y. Guo, K. Bian, X. Jin, Z. Yang, L. Song, J. Cheng, H. Tuo, X. Li, Proactive Video Push for Optimizing Bandwidth Consumption in Hybrid CDN-P2P VoD Systems, *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*, Honolulu, HI, USA, 2018, pp. 2555-2563.

[15] J. Liu, Q. Yang, G. Simon, Delay Oriented Content Placement and Request Redirection for Mobile-CDN, *2017 IEEE 42nd Conference on Local Computer Networks (LCN)*, Singapore, 2017, pp. 498-501.

[16] G. Ibrahim, Y. Chadli, D. Kofman, A. Ansiaux, Toward A New Telco Role in Future Content Distribution Services, *Intelligence in Next Generation Networks (ICIN)*, Berlin, Germany, 2012, pp. 22-29.

[17] S. Spagna, M. Liebsch, R. Baldessari, S. Niccolini, S. Schmid, R. Garroppo, K. Ozawa, J. Awano, Design Principles of An Operator-Owned Highly Distributed Content Delivery Network, *IEEE Communications Magazine*, Vol. 51, No. 4, pp. 132-140, April, 2013.

[18] P. A. Frangoudis, L. Yala, A. Ksentini, T. Taleb, An Architecture for On-Demand Service Deployment Over A Telco CDN, *2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia, 2016, pp. 1-6.

[19] P. A. Frangoudis, L. Yala, A. Ksentini, CDN-As-a-Service Provision Over A Telecom Operator's Cloud, *IEEE Transactions on Network and Service Management*, Vol. 14, No. 3, pp. 702-716, September, 2017.

[20] H. Khedher, E. Abd-Elrahman, H. Afifi, M. Marot, Optimal and Cost Efficient Algorithm for Virtual CDN Orchestration, *2017 IEEE 42nd Conference on Local Computer Networks (LCN)*, Singapore, 2017, pp. 61-69.

[21] N. Herbaut, D. Negru, Y. Chen, P. A. Frangoudis, A. Ksentini, Content Delivery Networks as a Virtual Network Function: A Win-Win ISP-CDN Collaboration, *2016 IEEE Global Communications Conference (GLOBECOM)*, Washington, DC, USA, 2016, pp. 1-6.

[22] D. Lee, J. Mo, J. Park, ISP vs. ISP+ CDN: Can ISPs in Duopoly Profit by Introducing CDN Services?, *ACM SIGMETRICS Performance Evaluation Review*, Vol. 40, No. 2, pp. 46-48, September, 2012.

[23] P. Maillé, G. Simon, B. Tuffin, Vertical Integration of CDN and Network Operator: Model and Analysis, *2016 IEEE 24th International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS)*, London, UK, 2016, pp. 189-195.

[24] H. Lee, D. Lee, Y. Yi, On the Economic Impact of Telco CDNs and Their Alliance on the CDN Market, *2014 IEEE International Conference on Communications (ICC)*, Sydney, NSW, Australia, 2014, pp. 2950-2955.

[25] H. Lee, L. Duan, Y. Yi, On the Competition of CDN Companies: Impact of New Telco-CDNs' Federation, *2016 14th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, Tempe, AZ, USA, 2016, pp. 1-8.

[26] Y. Zhong, K. Xu, X. Li, H. Su, Q. Xiao, ESTRA: Incentivizing Storage Trading for Edge Caching in Mobile Content Delivery, *2015 IEEE Global Communications Conference (GLOBECOM)*, San Diego, CA, USA, 2015, pp. 1-6.

[27] Q. Ding, H. Pang, L. Sun, SAM: Cache Space Allocation in Collaborative Edge-Caching Network, *2017 IEEE International Conference on Communications (ICC)*, Paris, France, 2017, pp. 1-6.

[28] F. Shen, K. Hamidouche, E. Bastug, M. Debbah, A Stackelberg Game for Incentive Proactive Caching Mechanisms in Wireless Networks, *2016 IEEE Global Communications Conference (GLOBECOM)*, Washington, DC, USA, 2016, pp.

1-6.

[29] J. Li, H. Chen, Y. Chen, Z. Lin, B. Vucetic, L. Hanzo, Pricing and Resource Allocation via Game Theory for a Small-Cell Video Caching System, *IEEE Journal on Selected Areas in Communications*, Vol. 34, No. 8, pp. 2115-2129, August, 2016.

[30] J. Kwak, G. Paschos, G. Iosifidis, Dynamic Cache Rental and Content Caching in Elastic Wireless CDNs, *2018 16th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, Shanghai, China, 2018, pp. 1-8.

[31] J. Krolikowski, A. Giovanidis, M. Di Renzo, A Decomposition Framework for Optimal Edge-Cache Leasing, *IEEE Journal on Selected Areas in Communications*, Vol. 36, No. 6, pp. 1345-1359, June, 2018.

[32] B. Jennings, R. Stadler, Resource Management in Clouds: Survey and Research Challenges, *Journal of Network and Systems Management*, Vol. 23, No. 3, pp. 567-619, July, 2015.

[33] F. Hao, M. Kodialam, T. V. Lakshman, S. Mukherjee, Online Allocation of Virtual Machines in a Distributed Cloud, *IEEE/ACM Transactions on Networking*, Vol. 25, No. 1, pp. 238-249, February, 2017.

[34] P. Smet, B. Dhoedt, P. Simoens, Docker Layer Placement for On-Demand Provisioning of Services on Edge Clouds, *IEEE Transactions on Network and Service Management*, Vol. 15, No. 3, pp. 1161-1174, September, 2018.

[35] L. Yala, P. A. Frangoudis, A. Ksentini, QoE-Aware Computing Resource Allocation for CDN-as-a-Service Provision, *2016 IEEE Global Communications Conference (GLOBECOM)*, Washington, DC, USA, 2016, pp. 1-6.

[36] L. Yala, P. A. Frangoudis, G. Lucarelli, A. Ksentini, Balancing between Cost and Availability for CDNaaS Resource Placement, *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Singapore, 2017, pp. 1-7.

[37] J. Llorca, C. Sterle, A. M. Tulino, N. Choi, A. Sforza, A. E. Amideo, Joint Content-Resource Allocation in Software Defined Virtual CDNs, *2015 IEEE International Conference on Communication Workshop (ICCW)*, London, UK, 2015, pp. 1839-1844.

[38] N. Herbaut, D. Negru, D. Magoni, P. A. Frangoudis, Deploying a Content Delivery Service Function Chain on an SDN-NFV Operator Infrastructure, *2016 International Conference on Telecommunications and Multimedia (TEMU)*, Heraklion, Greece, 2016, pp. 1-7.

[39] N. Herbaut, D. Négru, D. Dietrich, P. Papadimitriou, Dynamic Deployment and Optimization of Virtual Content Delivery Networks, *IEEE MultiMedia*, Vol. 24, No. 3, pp. 28-37, July-September, 2017.

[40] N. Herbaut, D. Negru, D. Dietrich, P. Papadimitriou, Service Chain Modeling and Embedding for NFV-based Content Delivery, *2017 IEEE International Conference on Communications (ICC)*, Paris, France, 2017, pp. 1-7.

[41] H. Ibn-Khedher, E. Abd-Elrahman, H. Afifi, OMAC: Optimal Migration Algorithm for Virtual CDN, *2016 23rd International Conference on Telecommunications (ICT)*, Thessaloniki, Greece, 2016, pp. 1-6.

[42] H. Ibn-Khedher, E. Abd-Elrahman, Cdnaas framework: Topsis as Multi-Criteria Decision Making for VCDN Migration, *Procedia Computer Science*, Vol. 110, pp. 274-281, 2017.

[43] H. Ibn-Khedher, M. Hadji, E. Abd-Elrahman, H. Afifi, A. E. Kamal, Scalable and Cost Efficient Algorithms for Virtual CDN Migration, *2016 IEEE 41st Conference on Local Computer Networks (LCN)*, Dubai, United Arab Emirates, 2016, pp. 112-120.

[44] H. Ibn-Khedher, E. Abd-Elrahman, A. E. Kamal, H. Afifi, OPAC: An Optimal Placement Algorithm for Virtual CDN, *Computer Networks*, Vol. 120, pp. 12-27, June, 2017.

[45] F. Zhou, J. Liu, G. Simon, R. Boutaba, Joint Optimization for the Delivery of Multiple Video Channels in Telco-CDNs, *IEEE Transactions on Network and Service Management*, Vol. 12, No. 1, pp. 87-100, March, 2015.

[46] G. Calvigioni, R. Aparicio-Pardo, L. Sassatelli, J. Leguay, P. Medagliani, S. Paris, Quality of Experience-based Routing of Video Traffic for Overlay and ISP Networks, *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*, Honolulu, HI, USA, 2018, pp. 935-943.

[47] D. Liu, B. Chen, C. Yang, A. F. Molisch, Caching at the Wireless Edge: Design Aspects, Challenges, and Future Directions, *IEEE Communications Magazine*, Vol. 54, No. 9, pp. 22-28, September, 2016.

[48] J. Liu, Q. Yang, G. Simon, Optimal and Practical Algorithms for Implementing Wireless CDN Based on Base Stations, *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, Nanjing, China, 2016, pp. 1-5.

[49] D. De Vleeschauwer, D. C. Robinson, Optimum Caching Strategies for a Telco CDN, *Bell Labs Technical Journal*, Vol. 16, No. 2, pp. 115-132, September, 2011.

[50] Z. Naor, S. K. Das, M. Raj, Content Placement for Video-on-Demand Services over Cellular Networks, *Wireless Personal Communications*, Vol. 98, No. 1, pp. 467-486, January, 2018.

[51] X. Wang, M. Chen, T. Taleb, A. Ksentini, V. C. M. Leung, Cache in the Air: Exploiting Content Caching and Delivery Techniques for 5G Systems, *IEEE Communications Magazine*, Vol. 52, No. 2, pp. 131-139, February, 2014.

[52] J. Sung, M. Kim, K. Lim, J. K. Rhee, Efficient Cache Placement Strategy in Two-Tier Wireless Content Delivery Network, *IEEE Transactions on Multimedia*, Vol. 18, No. 6, pp. 1163-1174, June, 2016.

[53] X. Li, X. Wang, K. Li, Z. Han, V. C. M. Leung, Collaborative Multi-Tier Caching in Heterogeneous Networks: Modeling, Analysis, and Design, *IEEE Transactions on Wireless Communications*, Vol. 16, No. 10, pp. 6926-6939, October, 2017.

[54] X. Li, X. Wang, P. Wan, Z. Han, V. C. M. Leung, Hierarchical Edge Caching in Device-to-Device Aided Mobile Networks: Modeling, Optimization, and Design, *IEEE Journal on Selected Areas in Communications*, Vol. 36, No. 8, pp. 1768-1785, August, 2018.

[55] T. X. Tran, D. V. Le, G. Yue, D. Pompili, Cooperative Hierarchical Caching and Request Scheduling in a Cloud Radio Access Network, *IEEE Transactions on Mobile*

Computing, Vol. 17, No. 12, pp. 2729-2743, December, 2018.

[56] X. Zhang, Q. Zhu, Collaborative Hierarchical Caching over 5G Edge Computing Mobile Wireless Networks, *2018 IEEE International Conference on Communications (ICC)*, Kansas City, MO, USA, 2018, pp. 1-6.

[57] A. Sharma, A. Venkataramani, R. K. Sitaraman, Distributing Content Simplifies ISP Traffic Engineering, *ACM SIGMETRICS Performance Evaluation Review*, Vol. 41, No. 1, pp. 229-242, June, 2013.

[58] M. Abdallah, C. Griwodz, K.-T. Chen, G. Simon, P.-C. Wang, C.-H. Hsu, Delay-Sensitive Video Computing in the Cloud: A survey, *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, Vol. 14, No. 3s, Article No. 54, August, 2018.

[59] J. Liu, Q. Yang, G. Simon, Congestion Avoidance and Load Balancing in Content Placement and Request Redirection for Mobile CDN, *IEEE/ACM Transactions on Networking*, Vol. 26, No. 2, pp. 851-863, April, 2018.

[60] P. Yang, N. Zhang, S. Zhang, L. Yu, J. Zhang, X. Shen, Dynamic Mobile Edge Caching with Location Differentiation, *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Singapore, 2017, pp. 1-6.

[61] M. Claeys, D. Tuncer, J. Famaey, M. Charalambides, S. Latre, G. Pavlou, F. De. Turck, Hybrid Multi-Tenant Cache Management for Virtualized ISP Networks, *Journal of Network and Computer Applications*, Vol. 68, pp. 28-41, June, 2016.

[62] T. Nakajima, M. Yoshimi, C. Wu, T. Yoshinaga, A Light-Weight Content Distribution Scheme for Cooperative Caching in Telco-CDNs, *2016 Fourth International Symposium on Computing and Networking (CANDAR)*, Hiroshima, Japan, 2016, pp. 126-132.

[63] T. Nakajima, M. Yoshimi, C. Wu, T. Yoshinaga, Color-based Cooperative Cache and its Routing Scheme for Telco-CDNs, *IEICE TRANSACTIONS on Information and Systems*, Vol. E100-D, No. 12, pp. 2847-2856, December, 2017.

[64] S. M. S. Tanzil, W. Hoiles, V. Krishnamurthy, Adaptive Scheme for Caching YouTube Content in a Cellular Network: Machine Learning Approach, *IEEE Access*, Vol. 5, pp. 5870-5881, March, 2017.

[65] S. Kastanakis, P. Sermpezis, V. Kotronis, X. Dimitropoulos, Cabaret: Leveraging Recommendation Systems for Mobile Edge Caching, *arXiv preprint arXiv:1806.02704*, June, 2018.

[66] E. Bastug, M. Bennis, M. Debbah, Living on the edge: The role of proactive caching in 5G wireless networks, *IEEE Communications Magazine*, Vol. 52, No. 8, pp. 82-89, August, 2014.

[67] S. O. Somuyiwa, A. György, D. Gündüz, A Reinforcement-Learning Approach to Proactive Caching in Wireless Networks, *IEEE Journal on Selected Areas in Communications*, Vol. 36, No. 6, pp. 1331-1344, June, 2018.

[68] A. Cloud, Pricing of Video on Demand (VOD). https://www.aliyun.com/price/product?spm=5176.8413026.702518.btn3.1b6211cfATNpn2#/vod/detail, 2018. Accessed 30-May-2018.

[69] A. Cloud, Pricing of Object Storage Service (OSS). https://www.aliyun.com/price/product?spm=a2c4g.11186623.2.11.W71feK#/oss/detail, 2018. Accessed 30-May-2018.

[70] C. Chang, P. Lin, J. Zhang, J. Jeng, Time Dependent Adaptive Pricing for Mobile Internet Access, *2015 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, Hong Kong, China, 2015, pp. 540-545.

[71] V. Jalaparti, I. Bliznets, S. Kandula, B. Lucier, I. Menache, Dynamic Pricing and Traffic Engineering for Timely Inter-Datacenter Transfers, *Proceedings of the 2016 ACM SIGCOMM Conference*, Florianopolis, Brazil, 2016, pp. 73-86.

[72] B. Zolfaghari, G. Srivastava, S. Roy, H. R. Nemati, F. Afghah, T. Koshiba, A. Razi, K. Bibak, P. Mitra, B. K. Rai, Content delivery networks: State of the art, trends, and future roadmap, *ACM Computing Surveys (CSUR)*, Vol. 53, No. 2, pp. 1-34, June, 2020.

[73] K. Velasquez, D. P. Abreu, M. Curado, E. Monteiro, Service Placement for Latency Reduction in the Fog using Application Profiles, *IEEE Access*, Vol. 9, pp. 80821-80834, June, 2021.

[74] T. Chen, B. Dong, Y. Chen, Y. Du, S. Li, Multi-Objective Learning for Efficient Content Caching for Mobile Edge Networks, *2020 International Conference on Computing, Networking and Communications (ICNC)*, Big Island, HI, USA, 2020, pp. 543-547.

[75] M. Ghaznavi, E. Jalalpour, M. A. Salahuddin, R. Boutaba, D. Migault, S. Preda, Content Delivery Network Security: A Survey, *IEEE Communications Surveys & Tutorials*, Early Access, pp. 1-28, June, 2021.

Biographies

Yuming Zhang is currently pursuing the Ph.D. degree in telecommunications and information system at the National Engineering Laboratory for Next Generation Internet Interconnection Devices, Beijing Jiaotong University, Beijing, China. His current research interests include SDN, NFV, MEC.

Bohao Feng is currently an Associate Professor of School of Electronic and Information Engineering, Beijing Jiaotong University. His research interests include software-defined networking, network functions virtualization, information-centric networking, service function chaining, 5G, mobile Internet.

Wei Quan is currently an Associate Professor with the School of Electronic and Information Engineering, Beijing Jiaotong University. His research interests include key technologies for network analytics, future Internet, 5G networks, and vehicular networks.

Hongke Zhang is a full Professor with the School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, China. His current research interests include network architecture, Internet of Things, Internet of Vehicles, and wireless communications.