CUE: An Intelligent Edge Computing Framework

Boran Yang, Dapeng Wu, and Ruyan Wang

Abstract

The worldwide popularity of smart mobile devices is ushering us into the UGC era, and the UGC data explosion posts formidable challenges and insatiable demands for network bandwidth, which can be effectively handled by the emerging EC. However, the heterogeneity of EC devices and resources should be properly addressed to process UGC data in proximity to data sources. By taking UGC features and resource heterogeneity into account, we devise CUE, an intelligent EC framework based on "cloud-user-edge" cooperation. First, the CUE framework establishes a shared edge structure and virtualizes heterogeneous computation, storage, and communications resources. Second, a virtual resource bank (VRB) is employed to issue virtual resource coins (VRCs) for resource exchange. Finally, the processing (i.e., computation offloading) and caching of UGC data are implemented at the network edge. Remarkably, the proposed CUE framework can fully exploit the heterogeneous EC resources, protect sensitive user data, reduce network traffic load, and accommodate the UGC prosperity in the post-cloud era. To the best of our knowledge, CUE is the very first framework for heterogeneous EC resource sharing, where UGC is innovatively involved to form closed-loop VRC recycling and to support many other promising functions (e.g., trust management and VRC monetization).

Introduction

Various types of extensively deployed Internet of Things (IoT) sensors are collecting massive data, which can be uploaded to and processed by the powerful cloud computing at Internet data centers (IDCs). As the number of sensors and the quality of collected data grow relentlessly [1], the big sensor data will certainly confront the bottleneck of network transmission capability in the near future. Accelerated by the technological breakthroughs and mature markets of digital cameras, portable storage, and smart mobile devices, the dramatic transformation from content consumers to content prosumers is completing, and we are now stepping into the user generated content (UGC) era. UGC is contributing to the major traffic of mainstream content sharing and social networking applications, facilitating the prosperity of live streaming and online courses, producing non-negligible data traffic load on core networks, and posting formidable challenges and insatiable demands for network bandwidth. Cloud computing is widely employed by IDCs to efficiently process computation intensive tasks. However, cloud computing is restricted by the network bandwidth bottleneck and cannot fully exploit its powerful computing capability to process the surging UGC data. As a necessary and supplementary extension of cloud computing, edge computing (EC) offers computation offloading, data caching, data processing functions, and fast service responses to dramatically alleviate the explosively growing backbone traffic and bandwidth consumption of IDCs.

To reduce the data transmission cost, service providers expect to process the collected user data near their sources, and this urgent requirement from the information technology (IT) industry promotes EC development. EC [2] offloads the computing loads from the remote cloud (e.g., IDC) to the network edge (e.g., EC server), by which the traffic load of backbone networks can be substantially reduced [3]. The "edge" here is commonly defined as the set of any computation, storage, and communications resources between data sources and the cloud. Another feature worth mentioning is that processing user data at the network edge can dramatically reduce the end-to-end delay and service response time, and prolong the battery life of energy restrained user devices. In practical applications, the computing tasks offloaded to edge devices have to be synchronized with remote cloud, the task synchronization can run in the background, and the synchronization delay is imperceptible to users. Furthermore, by reducing the transmission of user data in core networks, we can avoid unnecessary data leakage, enhance data security, and protect user privacy.

To minimize the data transmission cost, network operators and service providers are relentlessly exploring innovative EC solutions. For instance, China Telecom spares no effort to offload multicasting iTV services from IDCs to broadband remote access servers (BRASs) at the network edge, which improves the quality of service and quality of experience (QoS and QoE). With the distributed storage of iTV source data at BRASs, the so-called multicast offloading technology responds rapidly to user requests from the network edge to reduce traffic loads of backbone networks and overall service delay.

We are inspired by the following research work to devise a "cloud-user-edge" cooperation-based EC framework (i.e., CUE). N. C. Luong *et al*. mentioned in [4] that economic and pricing models could be exploited to manage cloud resources. M. Chen *et al*. presented Edge-CoCaCo, a joint optimization model of computation,

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The authors are with Chongqing University of Posts and Telecommunications.

caching, and communications at the edge cloud in [5]. In [6], D. T. Nguyen *et al*. considered the node heterogeneity in EC and services in multi-resource scenarios, proposed a resource sharing solution, and emphasized the impact of various resource types. In [7], M. Chen *et al*. emphasized that an efficient offloading scheme could optimally allocate computing resources for tasks to minimize the delay while saving the battery life of smart devices. In [8], Z. Zhou *et al*. devised the robust mobile crowd sensing (RMCS) framework by combining deep-learning-based data validation with EC-based local data processing. T. Hou *et al*. designed a transfer-learning-based proactively cooperative caching strategy for mobile edge computing in [9] to improve the cache hit rate. Y. Cao *et al*. mentioned in [10] that the secured transmission of user data is a major challenge in emerging fifth generation (5G) communications.

The above algorithms and frameworks confirm the heterogeneity of devices and resources, and necessitate resource exchange in EC. Besides, the proliferating UGC is adding a non-negligible share to backbone traffic. However, to the best of our knowledge, no existing research considers UGC characteristics and resource heterogeneity in EC resource management, which motivates us to design the CUE framework, as shown in Fig. 1. First, the shared edge structure is established and heterogeneous resources are virtualized in the resource plane. Second, virtual resource coins (VRCs) are issued by a virtual resource bank (VRB) for resource exchange. Finally, the offloading, caching, and other operations are implemented at the network edge on content in the data plane. Our proposed CUE has the following major contributions.

- A shared edge structure is established to fully exploit the idle EC resources for the sake of structural security and centralized management, enabling the customizable usage of heterogeneous data and fair resource sharing between edge devices, device owners, and content publishers.
- A virtual resource exchange based on VRCs is proposed for users to trade heterogeneous communications, computation, and storage resources, and support content publishers. UGC is involved to consume the surplus VRCs, forming the closed-loop VRC recycling.
- The resource density is creatively employed in pricing strategy to motivate resource sharing and guarantee EC coverage, whereas buying and tipping UGC, as distinctive social interactions in content sharing platforms, are innovatively considered in resource exchange.
- The potential contributions of massive powerful edge devices owned by individuals are utilized to process and cache UGC in proximity to data sources, further reducing the end-to-end service delay and network traffic load.

Resource Virtualization

Shared Edge Structure

In our proposed CUE framework, communications, computation, and storage resources are virtualized for fair resource sharing between not only edge devices but also device owners and content publishers. Generally, Internet service providers (ISPs) or individuals may possess multiple edge devices including desktops, tablets, cell phones, and edge servers. For the sake of structural security and centralized management, we propose to establish a shared edge structure to pool the virtualized resources. As the smallest elements in the network edge, the above mentioned heterogeneous edge devices form private edges dynamically according to ownership, where device owners can process sensitive user data within their own security domains (i.e., private edges). Furthermore, shared edges can be established among private edges to make full use of idle computing resources to cooperatively process computation intensive tasks.

As data security gains worldwide attention from governments, academia, and industry, the shared edge structure enables users to clearly customize and define the distribution range and usage of various user data. For instance, users have noticeably differentiated privacy requirements for the uploaded video data of suspect tracking and live streaming. The raw video data of live streaming is transmitted by users to edge devices, further cooperatively processed by the shared edge, and finally uploaded to remote cloud for sharing. However, suspect tracking exploits image processing technologies to search the raw video data collected by various cameras (e.g., dashboard cameras, surveillance cameras at residences and malls), which is essentially different from the live streaming UGC data and always contains too much private information to be willingly provided by users. Due to data security and identity privacy concerns [11], users prefer to process sensitive video data within their own private edges. In the proposed shared edge structure, sensitive raw video data is uploaded to trusted private edges for image processing (e.g., face recognition and plate recognition), and then the abstract results are transmitted to remote cloud. Processing sensitive data within private edges can avoid security risks caused by unnecessarily exten-

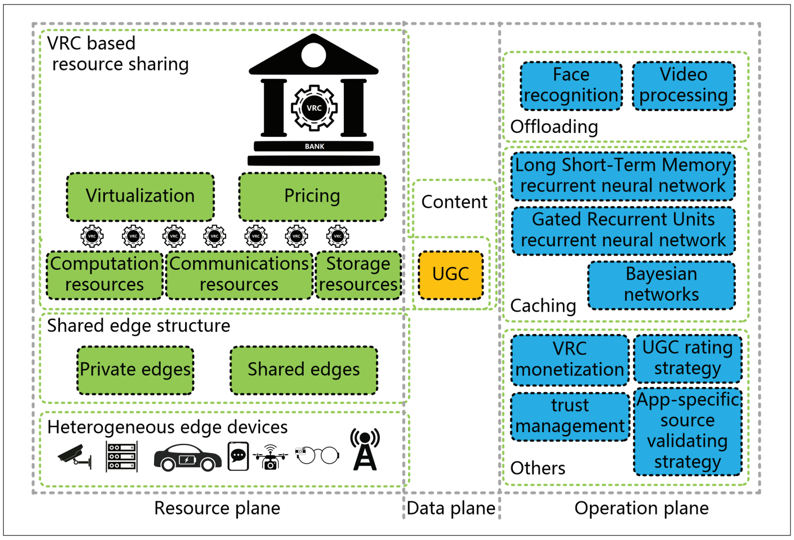

FIGURE 1. The CUE framework exploits a shared edge structure to manage heterogeneous edge devices and virtual resource coins for resource exchange, supporting offloading, caching, and other functions.

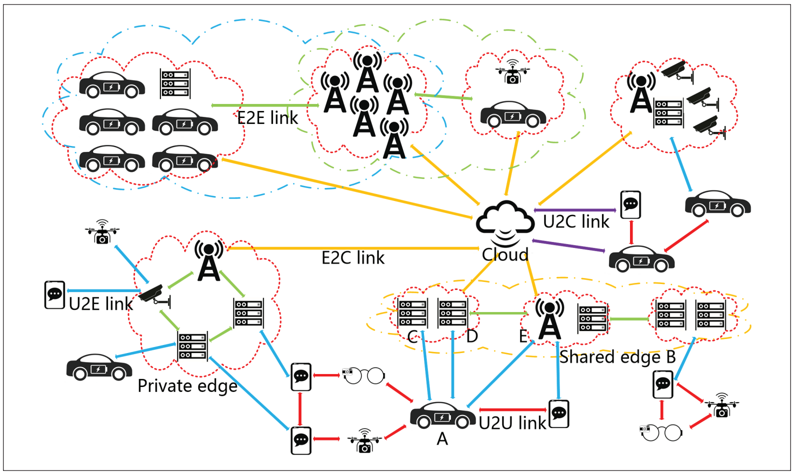

FIGURE 2. The shared edge structure facilitates dynamic sharing of heterogeneous edge resources and enables a wide variety of applications for users.

sive propagation of user data. Besides, the shared edge structure fundamentally supports the CUE framework to share communications and storage resources. Specifically, we employ communications costs between private edges and computation loads of private edges to initially construct the topology of shared edges. For instance, shared edge B in Fig. 2 incorporates three private edges and their respective edge devices, providing heterogeneous resources for task offloading user A.

Virtualization of Heterogeneous Resources

Since the EC concept was originally proposed to complement and extend powerful cloud computing, the relatively limited computation resources of edge devices owned by ISPs or individuals should be virtualized first. In terms of the state-of-the-art EC architecture, all research efforts are dedicated to efficiently exploit the limited edge resources to enhance the QoS and QoE [12]. Before sharing computation resources and affording computation offloading services to requesters, edge devices must virtualize the available resources. Typically, lightweight virtual machines (e.g., Docker) are adopted to virtualize computing services.

EC emerges to compensate for the unsatisfactory network bandwidth growth and offload computing tasks to the network edge for reducing traffic loads of core networks. As many research results suggest, the link quality of the last hop communications to user equipment is one of the most crucial factors in computation offloading. Besides, the shared edge structure is initialized partly based on communications costs. Therefore, communications resources should also be virtualized for maximum utilization. Communications links in EC can be divided into the following types: edge to cloud (E2C), E2E, user to edge (U2E), user to cloud (U2C), and user to user (U2U). Although the revolutionary 5G will further enhance the quality and capacity of U2C links and lower the corresponding communications costs, 5G connections may somehow be unavailable or insufficient for large size data transmission. Due to the limited link capacity and dynamic channel quality, we employ link quality evaluation in the CUE framework for users to reasonably offload computing tasks to the cloud or edge. Besides, the quality evaluation of E2E links can support the shared edge establishment among private edges. Specifically, the communications resources can readily be virtualized with link quality evaluation.

Despite the explosive increase in data quality and volume, many edge devices nowadays have idle storage resources, which can be exploited for content caching to reduce end-to-end delay, especially for video services. Currently, existing cache placement and cache delivery strategies are mainly motivated by the limited storage sizes of edge devices or content distributing nodes and naturally based on content popularity evaluation. However, due to privacy and security issues, device owners are always reluctant to share the storage resources of their edge devices. Doubtlessly, certain incentive mechanisms should be employed at the network edge to promote content caching. Therefore, edge storage resources should be formatted uniformly to achieve the virtualization, which is necessary for enhancing the storage utilization and enabling responsive video services.

Based on the above resource virtualization, the CUE framework abstracts the communications, computation, and storage resources into tradeable services and enables an innovative way to schedule heterogeneous resources. Moreover, the heterogeneity of edge and user devices can be eliminated by resource virtualization.

Resource Exchange

Since the computation and storage resources at the network edge are always insufficient, and the communications resources between cloud and users are still deficient due to the ever-increasing service quality, these nontrivial resources should be reasonably scheduled and managed to enhance the EC performance.

Virtual Resource Bank and Coins

In the CUE framework, we design a virtual resource exchange for users, and the involved virtual resources include the above communications, computation, and storage resources and the UGC. The CUE framework first employs a VRB for resource pricing and transaction confirmation. The VRB issues VRCs for users to trade resources and support content publishers. Obviously, the key challenge lies in the design of resource pricing strategy. If the resource prices are globally fixed, VRCs can be extracted unevenly to resource-rich or resource-intensive private edges and exaggeratedly possessed by these edge device owners, damaging the resource sharing willingness of the other indispensable edge devices. Therefore, the VRB considers the resource density in the pricing strategy to address the above problem, motivate resource sharing, and guarantee coverage. Machine learning technology is widely applied in various pricing mechanisms (e.g., Airbnb pricing), and we employ and modify a deep reinforcement learning (RL) model for VRB to update the resource pricing. The prices of heterogeneous resources are input, learned, and adjusted by the deep RL model to optimize the resource sharing. Apparently, reasonable resource prices can motivate device owners to share available resources. By promising to provide a certain number of resources (i.e., resource commitment) or other types of services (e.g., mobile crowd sensing), edge device owners can obtain prepayments from VRB and then spend the VRCs to purchase resources, as shown in Fig. 3. Specifically, VRCs are powered by blockchain technology so as to validate each resource transaction, prevent forgery attacks, and achieve dependable reputation evaluation.

Resource Pricing

First, the VRB sets the initial prices for virtualized communications resources according to the resource density and the overall traffic load level of edge devices. Users can either buy communications resources with VRCs or sell communications resources for VRCs according to the price set and updated by the VRB. Traditionally, incentive mechanisms are adopted by many data transmission paradigms (e.g., device-to-device, D2D) to encourage collaborative data forwarding. The similar challenge at the network edge is solved by the CUE framework with VRCs. Moreover, except for communications resources of edge devices, VRCs also facilitate the sharing of U2U communications resources.

Subsequently, the initial prices of virtualized computation resources are set by the VRB according to the resource density and the average energy cost per CPU cycle. Due to the privacy concern, users generally offload computation intensive tasks to their private edges. However, some computationally demanding tasks may require either a huge number of resources or an immediate response, which cannot be locally supported by private edges. Therefore, VRCs can be used to exchange computation resources among edge device owners. Besides, a user with a task offloading smart device may roam to the coverage of other private edges during the processing of the offloaded task, resulting in complex computation migration and resource usage. Fortunately, the CUE framework exploits VRCs to facilitate the complex resource sharing and require no extra incentive mechanism to motivate device owners. For instance, as shown in Fig. 3, after offloading a video processing task to its own private edge, the drone of the device owner on the right roams to the coverage by edge devices of the device owner on the left, spends VRCs to access the resources of this device owner, and then receives the task results, where the drone owner has to pay for the provided communications and computation resources if the offloaded task is migrated to and processed by the left edge devices.

Furthermore, storage resources at the network edge are currently underutilized, because edge devices and smart devices are always equipped with inexpensive, large, and underexploited storage. So far, many content caching mechanisms are proposed by researchers to explore the edge storage for delay-sensitive video content delivery, but most of them ignore the fundamental motivation for edge devices owned by individuals to share their storage. Therefore, the VRB in the CUE framework sets the price of virtualized storage resources to promote storage sharing. However, the purchase of storage resources is substantially different from that of the aforementioned two resources, because a requested content item must be cached beforehand by edge devices and then sold for VRCs. Besides, UGC publishers can selectively purchase and actively exploit storage resources at the network edge to improve the content QoS and QoE. Consequently, this active storage resource exchange involves the storage time and UGC size. In terms of these characteristics, virtualized storage resources at the network edge are priced according to the weighted content sizes and storage time.

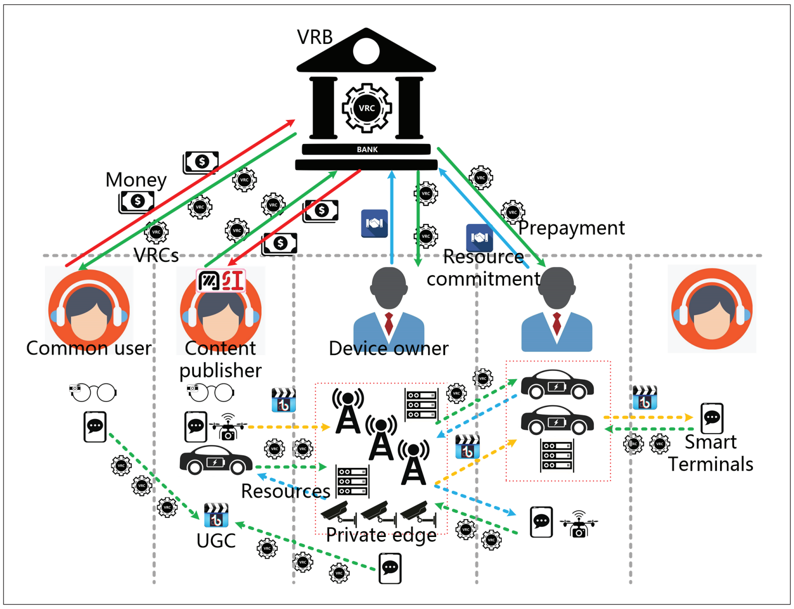

FIGURE 3. Heterogeneous resource exchange based on virtual resource coins unleashes the potential of abundantly available edge devices.

Lastly, UGC items, as a special type of virtual resources, should be properly priced to not only encourage publishers but also recycle the issued VRCs, closing the currency loop. Despite the emerging for-profit knowledge market, UGC sharing is originally actuated by the interest of publishers, and publishers expect to receive views, likes, and comments. Gradually, some UGC publishers earn income through advertisements, and a few publishers even sell UGC items for money. On the contrary, UGC viewers are increasingly likely to ”tip” publishers, which is a typical social interaction in many content sharing platforms. Therefore, the CUE framework employs a UGC rating strategy and combines an app-specific source validating strategy for users to exchange UGC items and tip UGC publishers. With the app-specific source validating strategy, UGC publishers can be clearly identified to receive a tip or payment. Besides, the UGC rating strategy can exploit the one-click responses from reviewers to evaluate the content quality, which further provides a reference for users to buy or tip UGC items, for platforms to analyze user reputation, and for publishers to acquire viewer feedback. Specifically, prices of UGC items are set by publishers, and tips are determined by viewers in VRCs.

The resource pricing is constantly updated and maintained by the VRB with the modified deep RL model. In the CUE framework, device owners exchange virtualized communications, computation, and storage resources with VRCs, and

Generally, caching the data of delay-sensitive video services at the network edge can dramatically enhance the QoS and QoE. Noticeably, the app usage of video services is as regular as daily routines. For instance, users are more likely to enjoy video services after lunch and dinner and less likely late at night and early in the morning.

users buy and tip UGC to spend VRCs, forming the closed-loop recycling of VRCs. Besides, VRCs can be exploited collaboratively with behavior evaluation mechanisms to manage the reputations of edge devices, device owners, content publishers, and common users. When detecting malicious behavior (e.g., VRC forgery, false forwarding, and fake results of offloaded tasks), the VRB serves as the reputation management center to record, punish, and fine the corresponding misbehavior. Traditional reputation/trust management mechanisms attenuate the trust values of nodes according to the detected malicious behavior and reject nodes with too much misbehavior, which can be perfectly complemented by the VRB to either encourage resource sharing or punish misbehavior.

VRC-Based Resource Exchange

In terms of computation offloading, users can partially or completely offload computing tasks to edge devices or remote cloud. Users in the CUE framework make task offloading decisions according to data privacy levels, delay restraints, available resources, and resource costs. For instance, user A within the coverage of shared edge B offloads tasks with low data privacy levels to edge device D instead of to C and E because of the reduced task processing delay satisfying the delay restraint and the minimum resource cost among all computation offloading options, as shown in Fig. 2. Another advantage of VRCs worth mentioning is that they can be spent by users to dramatically enhance communications quality through buying communications resources with high link quality or to deliberately extend the battery life of smart devices through offloading as many tasks as possible to the efficient network edge. Besides, the promising wireless energy transfer from wired edge devices to discharging smart terminals can be supported and further enhanced by VRC-based computation offloading and collaborative communications. Since smart terminals (e.g., drones, electric vehicles, tablets, and cell phones) in the current market have ever-increasing processing capabilities even stronger than traditional desktops, when charging their batteries, we can selectively add them to private edges to strengthen the computation and communications capabilities in scenarios where smart devices are fully charged and still plugged in.

Due to the popularity and proliferation of UGC, the surging content quality and quantity and the corresponding processing demands spur the development of EC. Noticeably, in the post-cloud era, EC, as the data processing and transmitting intermediation between users and cloud, can provide not only content caching but also data processing services for UGC producers. Therefore, both offloading of UGC processing tasks and caching of UGC data should be comprehensively evaluated to fulfill the insatiable resource demands of UGC-related EC killer applications. Existing content caching strategies are mostly based on popularity prediction and selfless caching infrastructures of ISPs, ignoring the potential contributions of massive powerful edge devices owned by individuals. On one hand, content distributing platforms or ISPs exploit content caching strategies to optimize the content placement and delivery from the cloud to the network edge. On the other hand, UGC data can be uploaded to, and processed and cached at, the network edge to mitigate traffic loads of core networks. Therefore, the CUE framework records and analyzes content request histories (i.e., content item ID, timestamp, requester ID), with the long short-term memory recurrent neural network [13] to evaluate popularity and identify globally popular content items. These items further serve as references for edge devices to cache content for purposes of enhancing QoS or earning VRCs. However, edge devices may delete processed UGC items after uploading them to remote cloud to release the cache space. If other users request the deleted UGC item, the edge device will have to fetch it from cloud, increasing the traffic load of core networks. Besides, due to the limited coverage of edge devices and social relationships, users within the same physical area accessing the same edge device are logically likely to request the same or similar content items. Whether to cache a certain processed UGC item at edge devices depends on the local popularity of this UGC item. By deploying low-complexity gated recurrent units (GRU) in the recurrent neural network at the network edge, the CUE framework learns the local request histories, abstracts the similarity of local content requests, and predicts the locally popular content items. For instance, if the processed UGC items of a given publisher are frequently requested by users accessing the same edge device, the probability of his/her next UGC item being requested is high, and caching these locally popular content items achieves high gains. Thus, edge devices cache differentiated locally popular content items to reduce the core network traffic and earn VRCs.

Conversely, from the perspective of UGC requesters, a requested content item may not be cached by any edge device, and the remote cloud sends the item via an edge device to the content requester. However, if a requested content item is already cached by some edge devices, the requester evaluates content transmission costs in combination with the above source validating strategy to select the proper data source.

To reasonably exploit the edge resources, the CUE framework analyzes the app usage of users for cache update. Generally, caching the data of delay-sensitive video services at the network edge can dramatically enhance the QoS and QoE. Noticeably, the app usage of video services is as regular as daily routines. For instance, users are more likely to enjoy video services after lunch and dinner and less likely late at night and early in the morning. By deploying Bayesian networks at private edges due to data security and identity privacy requirements, device owners can locally learn the app usage of video services, predict the time of users accessing edge devices and requesting video content, and update the caching strategies. Processing the sensitive data of app usage within private edges ensures data security and identity privacy. Besides, the distributed data analysis at private edges provides excellent scalability.

Challenges and Opportunities

In addition to the VRC-based exchange of heterogeneous EC resources, the CUE framework highlights multiple unexplored research opportunities. The following challenges should be handled skillfully to significantly enhance the utilization of EC resources.

Social characteristics [14] among device owners and content publishers should be thoroughly studied in resource sharing and VRC transactions. For instance, device owners who are friends supposedly provide each other with resources at discounted prices or even for free. Besides, a social-relationship-based trust relationship may incur security vulnerabilities, threatening the task offloading and data transmission.

To further promote EC resource sharing and incentivize UGC publishers, the monetization of VRCs should be further studied. Apparently, interdisciplinary research collaboration efforts should be made to answer the following questions. What is the appropriate VRC penalty for a given type of misbehavior? How can we protect the copyright of UGC publishers against content theft? Can VRC support applications in mobile crowdsensing and the Internet of Vehicles?

The plugged charging states of powerful smart terminals should be penetratingly evaluated and exploited to dynamically complement the EC resources, where VRCs play an indispensable role in heterogeneous EC resource exchange. Also, energy harvesting technology can be employed to extend the battery lifetime of EC devices, unveiling research opportunities in VRC-based resource sharing among energy harvesting edges.

The cooperation between the app-specific source validating strategy and trust/reputation management should be studied to exploit the potential of VRCs and the social relationships among edge device owners and content publishers. For instance, a popular UGC publisher of a given content sharing app is likely to have a high reputation, which can be employed to evaluate the trust relationship among device owners. Besides, VRCs enable reputation management mechanisms to borrow concepts from statistics and economics to refine the reputation evaluation of edge devices.

Parameter	Value
Edge devices	20–50
Device owners	5–20
Shared edges	3–10
E2C bandwidth	10Mb/s–1Gb/s
E2E bandwidth	1–20Mb/s
Content request frequency	5–100R/h
E2C energy cost	$2*10^{-8}$ J/bit
E2E energy cost	$0.15*10^{-8}$–$0.6*10^{-8}$ J/bit
Data caching energy cost	$1*10^{-9}$ W/b

TABLE 1. Simulation parameters.

Simulation Analysis

The cache hit rate (CHR) and energy saving rate (ESR) evaluating the content caching efficiency and energy efficiency of our proposed CUE framework are simulated in this section. In the simulation, $1*10^4$ content items are generated; their sizes follow a normal distribution with an average of 100 Mb, and their content popularity follows a Zipf-Mandelbrot distribution with shape parameter $\alpha = 0.8$ and shift parameter $q = 10$ [15]. Other parameter settings are given in Table 1.

As shown in Fig. 4a, when the cache size of edge devices is large enough to store all content items, the CHR reaches 100 percent, which is surreal in practical scenarios with surging content quality and volume. In addition, the CUE framework facilitates EC resource sharing to process

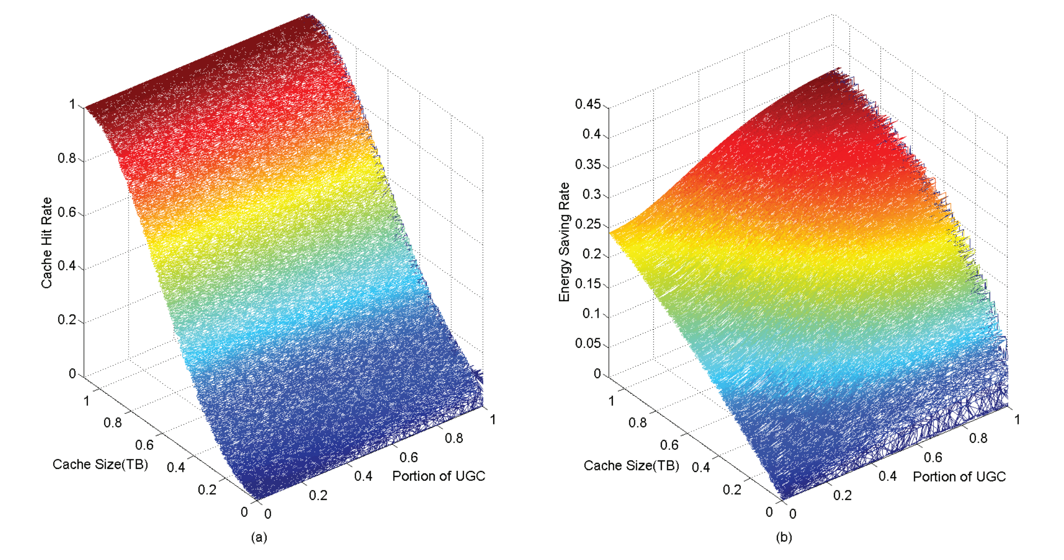

FIGURE 4. a) CHR vs. cache size and UGC portion; b) ESR vs. cache size and UGC portion.

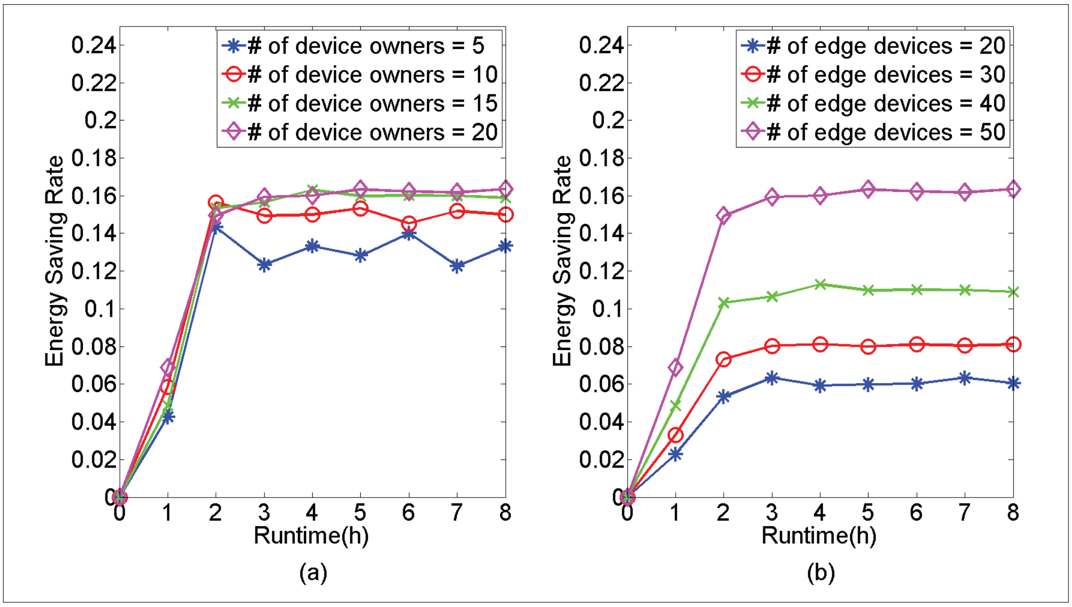

FIGURE 5. a) ESR vs. runtime and device owner number; b) ESR vs. runtime and edge device number.

and cache UGC items in proximity to data sources and content requesters, enhancing the CHR by around 20 percent. Figure 4b shows the ESR of the CUE framework. The practical cache size of edge devices is limited, and the topology between edge devices and cloud is extremely complex, resulting in high data transmission cost. However, the heterogeneous EC resources can be fully exploited and shared with VRCs, UGC can be processed and cached at the network edge to reduce the data transmission in core networks, and therefore the CUE framework can achieve an ESR even higher than 36.8 percent in practical scenarios.

Figure 5 depicts the impacts of runtime and device owner/edge device numbers on ESR. Apparently, ESR increases and then stabilizes as runtime grows, inviting us to explore the correlation between framework convergence and network scale in future work. Noticeably, increasing the number of device owners smooths the ESR because a few device owners may run out of VRCs, affecting the resource exchange. This highlights the impact of resource pricing and VRC circulation on heterogeneous resource sharing. Besides, the network scale also contributes to the ESR, proving that the CUE framework is scalable and can exploit the abundantly available edge devices. However, the optimal deployment of edge devices remains cost prohibitive, and the otherwise idle edge resources should be better utilized. Therefore, motivated by these insights, we plan to further investigate the relationship between VRC circulation and CUE framework performance. Evidently, in the post-cloud era with an unbreakable data transmission bottleneck and enormously growing UGC demands, processing and caching UGC data at the network edge are applicable solutions.

Conclusion

In this article, we fully consider the heterogeneity of EC resources, along with the typical tipping/buying interactions and features of surging UGC data to devise the CUE framework. The CUE framework first establishes the shared edge structure to extend the limited computing capability of individual private edges and fully exploit their idle resources. Subsequently, the heterogeneous EC resources are virtualized and VRCs are issued by a VRB to facilitate resource exchange. Remarkably, UGC is involved in consuming surplus VRCs, forming closed-loop VRC recycling and providing an inspiring solution for related research fields. The potential contributions of massive powerful edge devices owned by individuals are utilized to process and cache UGC in proximity to data sources, further reducing the end-to-end service delay and network traffic load. To the best of our knowledge, CUE is the very first framework for heterogeneous EC resource sharing, accommodating the UGC era and providing many promising research challenges.

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Biographies

Boran Yang received his B.S. and M.S. degrees in 2013 and 2016 from Chongqing University of Posts and Telecommunications, where he is currently pursuing a Ph.D. degree. His research interests include edge computing, edge resource sharing, and network security.

Dapeng Wu [SM] is currently a professor at Chongqing University of Posts and Telecommunications, China. He has authored more than 100 publications and two books. He is the inventor and co-inventor of 28 patents and patent applications. His research interests are in social computing, wireless networks, and big data. He is serving as TPC Chair of the 10th Mobimedia and a Program Committee member for numerous international conferences and workshops. He has served or is serving as an Editor and/or Guest Editor for several technical journals, such as Elsevier *Digital Communications and Networks*, and ACM/Springer *Mobile Network and Applications*.

Ruyan Wang is the Dean of the School of Communication and Information Engineering, Chongqing University of Posts and Telecommunications. He has authored more than 150 publications. His research interests include network performance analysis and multimedia information processing. He is a Senior Member of both the China Institute of Communications and the Chinese Institute of Electronics. He is a recipient of the Dani-an Huang Team award from the Ministry of Education of the People's Republic of China for his research and education dedication.