Synergy of Big Data and 5G Wireless Networks: Opportunities, Approaches, and Challenges

Ning Zhang, Peng Yang, Ju Ren, Dajiang Chen, Li Yu, and Xuemin (Sherman) Shen

Abstract

This article presents the synergistic and complementary features of big data and 5G wireless networks. An overview of their interplay is provided first, including big-data-driven networking and big data assisted networking. The former exploits heterogeneous resources such as communication, caching, and computing in 5G wireless networks to support big data applications and services, by catering for big data's features such as volume, velocity, and variety. The latter leverages big data techniques to collect wireless big data and extract in-depth knowledge regarding the networks and users to improve network planning and operation. To further illustrate the mutual benefits, two case studies on network aided data acquisition and big data assisted edge content caching are provided. Finally, some interesting open research issues are discussed.

Introduction

Driven by the emerging Internet of Things (IoT) and proliferation of mobile devices, the number of connected devices is predicted to reach 50 billion by 2020. In the meanwhile, a vast array of multimedia services are blooming rapidly. As a result, data generation is expanding at an astonishing pace. Every minute, Youtube users upload 400 hours of new video, while Instagram users generate 2.5 million posts. According to IBM's recent report,[1] each day, 2.5 quintillion bytes of data is created. It is predicted that the amount of data generated in 2020 will be 40 trillion gigabytes, 44 times greater than that in 2009.[2] With such a data explosion, we are evolving to the era of big data [1].

Big data exhibits the following big "V" features: *volume*, *velocity*, *variety*, and *value* [2, 3]. Volume indicates that the data scale is extremely big, while velocity means data collection and processing need to be conducted in a timely way to explore the potential value. Variety suggests great heterogeneity in data types and data structure (e.g., geospatial data, audio, video, smart metering reading, and log files). Moreover, these data are usually associated with a variety of applications, such as stock trading, healthcare, advertising, and smart grid. Lastly, such wealth of data opens up new opportunities to explore the great potential value. To deal with high complexity and massive scale of big data, it usually resorts to cloud computing/data centers with great computing and storage capacities. However, the cloud/data center usually resides in remote areas, which are far away from the data sources. Therefore, the following procedure is usually performed:

- *Data acquisition*: Gather various data.
- *Data preprocessing*: Perform certain operations on raw data, such as data aggregation, compression, and encryption.
- *Data transportation*: Move data toward data centers.
- *Data analysis*: Apply data mining or analytics to unlock the hidden value of data for decision making.

Fueled by soaring mobile data and diverse applications, wireless systems are evolving toward next generation (5G) wireless networks, by incorporating massive communication, caching, and computing resources. To accommodate tremendous traffic, communication infrastructures such as small cell base stations are expected to be densely deployed, to improve coverage and boost network capacity. To mitigate backhaul congestion and support low-latency services, caching techniques are employed to store popular contents in either the network edge or core network [4]. By providing contents at the proximity of users, redundant transmissions can be avoided and latency reduced. In addition, mobile cloud computing or edge computing is also integrated into wireless networks by extending cloud resources to wireless domains, facilitating computation-intensive applications [5] such as augmented reality and interactive gaming. In summary, the 5G wireless network will be a convergence network, encompassing communication, caching, and computing capabilities.

5G wireless networks will play a very important role in the big data processing chain due to the ubiquitous coverage as well as in-network storage and computing capabilities [6]. For instance, IoTs or mobile devices can help to collect data, while the edge caching/computing can perform local storage/processing, such as data compression and aggregation. Consisting of radio access network (RAN) and core network segments, 5G wireless networks can transport data toward data centers. Therefore, 5G wireless networks can act as the bridge between data sources and data centers. To better support big data, the features of big data should be taken into consideration for network design and operation. To accommodate

[1] "10 Key Marketing Trends For 2017," IBM, Jan. 2017

[2] Big Data: "The next frontier for innovation, competition and productivity." McKinsey Global Institute (MGI), May 2011.

Digital Object Identifier: 10.1109/MWC.2018.1700193

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big data volume, network capacity should be significantly increased. To cater for velocity and variety, differentiated networking is expected to be provisioned by integrating appropriate network resources to satisfy diverse service requirements in terms of latency, security, and reliability.

Big data can also improve the performance of wireless networks. Through big data analytics, knowledge and insight on the data can be unearthed, which can help efficiently manage network resources, maximize the revenue, and enhance users' experience. For example, from the network's perspective, by extracting the spatio-temporal traffic distributions, traffic can be efficiently balanced. From the users' perspective, the usage patterns, habits, mobility patterns, and preferences of users can be extracted, helping to provide context-aware service and improve users' experience.

In this article, we aim to provide an overview of the interplay between big data and 5G wireless networks, and to demonstrate their synergistic and complementary features. We first present big data driven networking and discuss how 5G wireless networks can accommodate big data's features (ie., volume, velocity, and variety) by exploiting heterogenous resources (i.e., communication, caching, and computing). Then we elaborate big data assisted networking to illustrate that big data analytics can be leveraged to improve network efficiency and user experience. Big data use cases in 5G wireless networks are summarized, and the effects of big data features on network operations are also discussed. In addition, two case studies are provided to further demonstrate the mutual benefits. Finally, some research directions are discussed.

Big Data Driven Networking

Massive data is first collected from various sources, and then preprocessed and transported through networks to data centers, where different data analytic techniques, such as data mining, stochastic modeling, and machine learning, are performed to reveal the insight or knowledge. In this section, we first present the evolution of 5G networks, then elaborate how the wireless network is involved in the big data processing chain, and last discuss how the wireless network supports big data by accommodating big data's features.

5G: Convergence of Communication, Caching, and Computing

The 5G wireless network is envisaged to embed various resources to support massive traffic and various services. It will be characterized by the convergence of communications, caching, and computing capabilities.

Communication: The 5G wireless network will exhibit great heterogeneities in communication infrastructure and resources. Heterogenous infrastructure such as various small cell base stations (SBSs) will be densely deployed; heterogenous communication resources will be integrated, such as various spectrum bands; and multifarious communication techniques will be employed to improve efficiency.

Caching: While SBSs are densely deployed to accommodate the vast amount of traffic, a heavy burden will be imposed on the backhaul. In-network caching is a potential solution to mitigate backhaul congestion, which can store popular contents closer to users and reduce redundant transmissions to remote servers. Caches can be deployed in RANs, core networks, or both, to achieve different performance-cost trade-offs [4].

Computing: Due to scalability, low cost, and on-demand computing power provision, cloud computing empowers wireless networks to efficiently support computation-intensive applications such as augmented reality. The main idea is to offload users' computation-heavy tasks to the cloud. In this regard, different cloud platforms such as mobile cloud computing, mobile edge computing, cloudlet, and femto-cloud computing are proposed or under deployment at various positions in wireless networks [5, 7].

5G Wireless Networks: The Bridge

By exploiting those heterogenous resources along with ubiquitous coverage, 5G wireless networks can act as the bridge between data sources and data centers by facilitating data acquisition, preprocessing, and transportation, as shown in Fig. 1.

Data Acquisition: IoT enables physical objects to exchange data and be managed efficiently, resulting in tremendous numbers of connected devices, such as automobiles, drones, and smart meters. IoT can generate massive data or gather enormous data through various in-built sensors (e.g., humidity sensors, light sensors, and temperature sensors). In addition, pervasive mobile phones also have great potential to collectively collect different types of data thanks to various embedded sensors. This emerging data acquisition platform is referred to as mobile crowdsensing. By exploring the power of the crowd, mobile crowdsensing is appealing for cost-effective large-scale data collection.

Data Preprocessing: With raw data collected in the previous phase, the data needs to be stored and preprocessed before transmission, such as through data compression and data aggregation to reduce redundancy. Moreover, the locally collected data in a geographic area can also be analyzed to promote location awareness and context awareness to facilitate location-based services (e.g., augmented reality) and improve user experience. With in-network caching and computing capacities in either the RAN or the core network, 5G wireless networks can facilitate data storage and preprocessing. Note that where to store and process the data depends on the applications and targeted area/scale. For instance, a base station (BS) can process data collected in its coverage to extract the traffic variation patterns in the time domain for efficient operation, while caching and computing facilities in RANs (consisting of thousands of BSs) can process data collected in a relatively larger area to balance traffic among BSs. It is of great importance to determine where, what, and how to store and process the relevant dataset, based on the service requirement and resource constraints.

Data Transportation: 5G wireless networks encompassing RANs and core network segments can transport data toward data centers for analysis. Data will be transported from a RAN to the core network, and finally reach data centers. In data transportation, the heterogeneity in network infrastructure, resources, and techniques as well as the heterogeneity in data should be carefully

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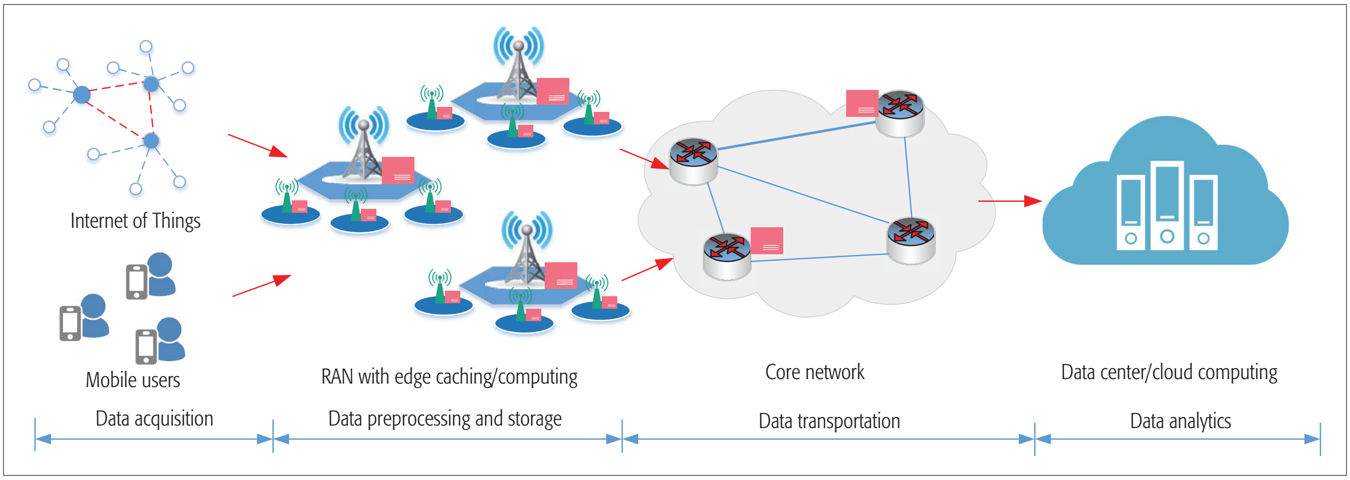

FIGURE 1. Big data driven networking.

considered. Different datasets (e.g., healthcare data and smart metering data) associated with various target applications may have distinct requirements in terms of end-to-end delay, reliability, and security. Heterogenous resources spanning from access to core networks should be provided to ensure real-time processing, reliable transmission, data confidentiality, and integrity protection during transportation.

Networking for Big Data

To better support big data and unearth its great value, big data's features such as volume, velocity, and variety should be efficiently accommodated by 5G wireless networks. First, big data volume requires network capacity to be significantly boosted. The approaches to boosting wireless network capacity mainly include spectrum expansion, spectrum efficiency enhancement, and network densification. The basic idea is to add more spectrum resources, enhance spectrum utilization, and improve spatial spectrum reuse. Second, the velocity needs the data to be collected, preprocessed, and delivered rapidly. Last, the variety of data, which is also associated with various applications, should be supported in data processing and transportation by satisfying the corresponding requirements. In fact, big data volume is mainly tackled through network deployment, while velocity and variety are supported through efficient network operation (i.e., how to utilize the infrastructure/resources to meet different requirements).

In the big data processing chain, communication, computing, and storage resources are needed at appropriate locations along the path from data source to data centers, to facilitate data acquisition, preprocessing, and storage. To cater for the velocity and variety, it is of significance to provision customized service-oriented end-to-end networking,[3] which integrates appropriate heterogenous resources and functions according to distinct requirements from big data applications and use cases. In essence, it provisions appropriate network-wide resources as a whole along the path from data source to data centers, to facilitate the big data processing chain. Since multiple big data applications (e.g., for power grid, financial analysis, e-health) should be supported over the same infrastructure simultaneously, the network-wide resources have to be shared efficiently.

An emerging solution for service-oriented networking is network slicing [8], which creates different slices over the same physical infrastructure, spanning from the access domain to the core network domain. Different slices operate independently and share the same resource pool. A network slice is a set of network resources for a given application or use case. It can be customized to meet the corresponding end-to-end service requirement such as latency and reliability. The key for network slicing is to partition network-wide heterogenous resources for different slices to support various use cases efficiently. Therefore, it is important but challenging to efficiently utilize network resources while satisfying the service requirements of various applications or use cases.

With the development of network functions virtualization (NFV), NFV can greatly facilitate network slicing. NFV enables network functions to be created in virtualized environments rather than on dedicated hardware platforms, thereby significantly improving network scalability and flexibility. In the core network, with NFV, a number of virtualized network functions (e.g., traffic splitting, data aggregation, deep packet inspection, and firewall) the data stream needs to go through can be composed, which is referred to as a service function chain (SFC) [9]. In other words, based on the service requirement of application or use case, an SFC can be generated on demand by composing different virtual network functions and determining their execution sequence. Different SFCs can be created for distinct applications/use cases and embedded over the same physical infrastructure. Moreover, with virtualization, the capacity of virtual functions can be dynamically scaled out or in to adapt to the dynamics in networks and service requirements. In a RAN, if NFV is supported, RAN slicing can be conducted by creating virtual RAN comments, such as virtual BSs for different slices. Otherwise, network slicing is performed based on resource scheduling. For instance, at a specific RAN component such as a BS, through efficient scheduling, its resources can be allocated to and shared by multiple slices. Moreover, by carefully allocating resources, the service requirements of different slices can be satisfied.

In essence, network slicing mainly targets how to incorporate communication, computing, and caching resources as a whole to provision

[3] In this work, the term "end-to-end" means the path from data source to data centers.

service-oriented networking for big data applications. It relies on network-wide resource management. An enabling platform is the emerging software defined networking (SDN) [10]. With the centralized control and network programmability brought by SDN, network-wide resource management can be greatly simplified to facilitate network slicing. In RANs, resource allocation for different slices can be performed in a centralized way by SDN controllers, while in core networks, SDN controllers with network hypervisors can schedule different data flows to create different slices or virtual networks. With the SDN platform, RAN slicing and SFC can be orchestrated to have complete end-to-end network slicing.

Big Data Assisted Networking

5G wireless networks can facilitate the big data processing chain, and by the same token, wireless big data also has great potential in improving network performance and user experience. By analyzing wireless big data, insightful features or knowledge can be extracted, such as spatial and temporal traffic distributions, user preferences, and mobility patterns [11, 12]. With such information, network efficiency can be significantly enhanced. In this section, we first present the benefits of exploiting wireless big data. Then we discuss how big data can facilitate network operation to achieve those benefits.

Wireless Big Data: Opportunities

Wireless big data can be exploited to improve network performance in aspects of network management, deployment, operation, and service quality enhancement. Table 1 gives some examples and use cases of wireless big data.

Network Management: Network equipment can generate alarms and monitoring data. These data, gathered from network probes and sensors, can provide real-time information regarding the network. Through data mining and data analytics, real-time diagnostics can be performed to automatically detect network faults and anomalous behaviors, and even identify the corresponding causes. Then appropriate measures can be conducted to recover from the faults. Furthermore, the massive network data can also be utilized to train prediction models to predict future network events, whereby proactive actions can be performed in advance to avoid network faults or service failures. By doing so, network reliability can be significantly improved without much manual effort for maintenance.

Network Optimization: Wireless traffic and user requests exhibit great dynamics in different geographic areas over time. The spatial and temporal distribution extracted from relevant datasets can optimize network deployment and operation.

Network Deployment: When deploying BSs, the spatial traffic load statistic obtained from data analysis can help to determine the number and appropriate locations of BSs so as to minimize deployment costs while provisioning guaranteed quality of service (QoS). In addition, when deploying edge caches, if the statistics of content requests can be obtained, the cache size equipped at BSs can be optimized to achieve cost effectiveness while meeting the required content hit probability.

Network Operation: During operation, by analyzing real-time network data, network operation can be intelligently adjusted to improve efficiency. For instance, through data mining, the traffic demand pattern over time can be obtained, and SBSs can be dynamically turned on or off to save energy. Moreover, with limited cache size, only popular contents are stored to serve users in the vicinity. However, content popularity varies over time at different locations. By analyzing the historical user request information, the time-varying content popularity can be learned to update the cached contents effectively so as to maximize content hit rate.

Improved QoE: In addition to network data, individual users' data usage profiles also exhibit personal features, such as content request preference, mobility pattern, and daily usage habits. Analyzing those data has the potential to provide personalized and context-aware service to improve user experience. For instance, with the trajectory data, users' mobility pattern can be learned so that seamless handover can be facilitated (e.g., through pre-storing the required contents on the predicted path). In addition, by analyzing a user's usage pattern, the context can be identified, such as the running applications, communication scenarios, perceived service quality, and user satisfaction. Then context-aware resource allocation or content delivery can be conducted, for example, switching the user to different wireless systems (WiFi or cellular) or adjusting transmission parameters related to transmission power, modulation, and coding.

Big data examples	Improving network performance
Channel statistics	Channel modeling, power control
Spectrum usage	Mobile access control, spectrum sharing, and unlicensed band utilization
Topology dynamics	Routing, loop, and black hole detection
Traffic statistics	Load balancing, network utilization
Network monitoring data	Fault detection, diagnostics, and troubleshooting
User distribution and mobility pattern	Seamless handoff, infrastructure deployment
User usage pattern	Context-aware service, anomaly detection
System logs, network traffic	Fraud detection, intrusion detection systems

TABLE 1. Big data for improved network performance.

Big Data Assisted Operation

In practice, network state is constantly changing due to fluctuations in traffic generated from users and various network events such as link failure and congestion. Manual re-configuration is cumbersome, inefficient, and error-prone. As a promising networking architecture, SDN can achieve agile network management, where logical SDN controllers dynamically control and reconfigure underlying infrastructure through open interfaces. Generally, SDN operates in a three-phase loop:

- *Network abstraction*
- *Controller decision making*
- *Policy enforcement*

Network abstraction gathers network state information to SDN controllers through control channels. Network events including topology changes, diverted packets, and traffic statistics are dynamically reported to the controllers. Then SDN controllers

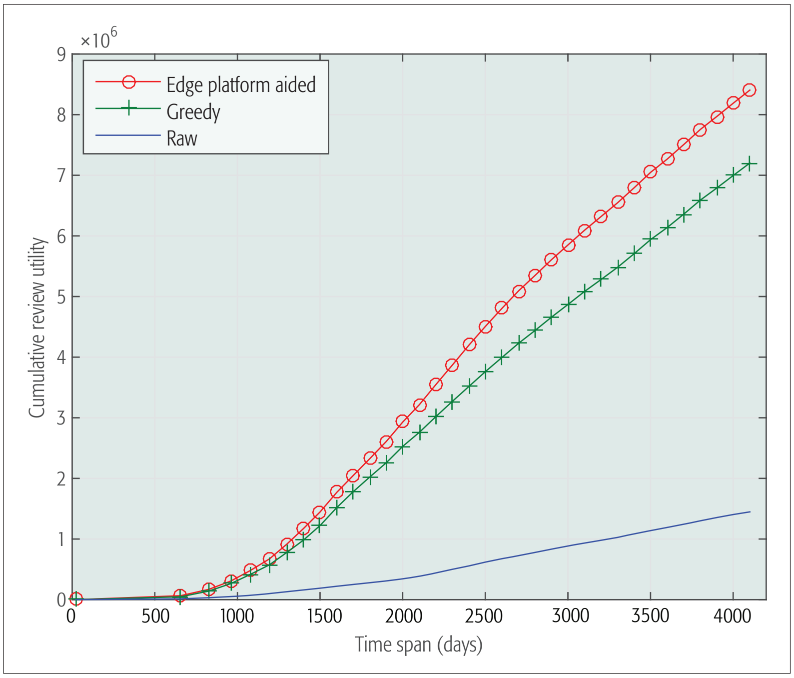

FIGURE 2. Comparison of cumulative utility of the crowdsourcing platform.

can make informed management decisions related to resource allocation, network re-configuration, and so on. Considering the scale and volume of information, big data techniques can be employed to facilitate informed decision making. Through big data analytics, in-depth knowledge of the network states can be extracted or certain events can be predicted to guide the decisions of SDN controllers. Last, the control decisions made by SDN controllers will be enforced to substrate networks through application programming interfaces [13]. Through incorporation of SDN with big data, networks can operate in an automatic manner, and round-the-clock optimization can be enabled.

Data acquisition, preprocessing, and analysis are actually embedded in the SDN operation loop. To achieve timely and efficient network management in SDN, various data regarding the network are collected. The *volume*, *velocity*, and *variety* of the collected data is of great importance for decision making of SDN controllers. First, *volume* influences the quality of control decisions, including efficiency, fairness, and network utility. The higher the volume of network abstraction, the better situation awareness the controller can have, and hence better control decisions can be expected. Second, velocity on the control channel should be guaranteed. It contributes to fast responsiveness to network events. In worst cases, the control decision might be invalid due to the unacceptable latency. Third, variety determines the granularity of network control. If diverse network information can be collected, more fine-grained control and management can be achieved.

Case Studies

In this section, two case studies are provided to demonstrate the synergies of big data and wireless networks. We first show how big data acquisition could be improved with the aid of network edge resources. Then we investigate the benefit of big data analytics on edge caching.

Edge Assisted Spatial Data Acquisition

By extending computing and storage resources to the proximity of mobile users, edge computing can significantly benefit location-based data acquisition or spatial crowdsourcing, where many workers are recruited to collect spatial data. First, relaying on the distributed edge platform, spatial crowdsourcing can be conducted in a fine-grained and context-aware manner. Second, preprocessing the collected data on the edge of the network helps to reduce the traffic burden in core networks. Third, edge computing can provide mobile users with more secure and reliable services by offering processing resources. For example, the edge platform could be harnessed for malicious user detection during data collection.

In spatial crowdsourcing with a limited budget, it becomes very crucial to select workers to collectively accomplish crowdsourcing tasks. With aid of the edge platform, workers' historical performance information could be stored and exploited to improve worker selection. To demonstrate it, we conduct an experiment based on the online Yelp dataset.[4] Yelp publishes crowdsourced customer reviews on local businesses, and this dataset contains 2.7 million reviews from 687,000 users on 86,000 businesses in 10 cities. We use this information to emulate spatial crowdsourcing applications, where Yelp users are considered as workers, and reviewing a local business are regarded as a spatial task. The more descriptions the worker contributes in the review comments, the higher utility is obtained. We divide the dataset into daily instances, and only a subset of workers can be selected to review local businesses every day. The edge platform can store and analyze users' historical information to predict a worker's future performance on reviewing tasks. By doing so, worker selection can be improved in spatial crowdsourcing, leading to higher platform utility.

As shown in Fig. 2, edge platform aided worker selection can significantly improve the performance of spatial crowdsourcing. This is due to the fact that, based on the historical data, the platform can make a fairly good prediction of a worker's future performance and then make informed decisions.

Big Data Assisted Edge Caching

In edge caching, the cached contents should be dynamically updated due to the changing content popularity over time. To analyze the popularity of contents, we crawled the statistics of a random set of videos from YouTube from 2013 to 2017. Figure 3a shows the daily view amount of a video since it was uploaded. The normalized popularity score of this video is also illustrated based on comparison with other randomly crawled videos. Both the daily view amount and popularity score fluctuate continuously across the time span. As a result, contents cached at the edge should be constantly updated.

However, the uncertainty of future content popularity makes popularity-based caching a difficult problem. Through data analytics on video view statistics, prediction of future content popularity can be made to improve the content hit rate. In this case study, we use a simple linear model to predict content hit rate. Specifically, let

[4] Round 8 Yelp Data Challenge, accessed December 2016; https://www.yelp.com/dataset_challenge

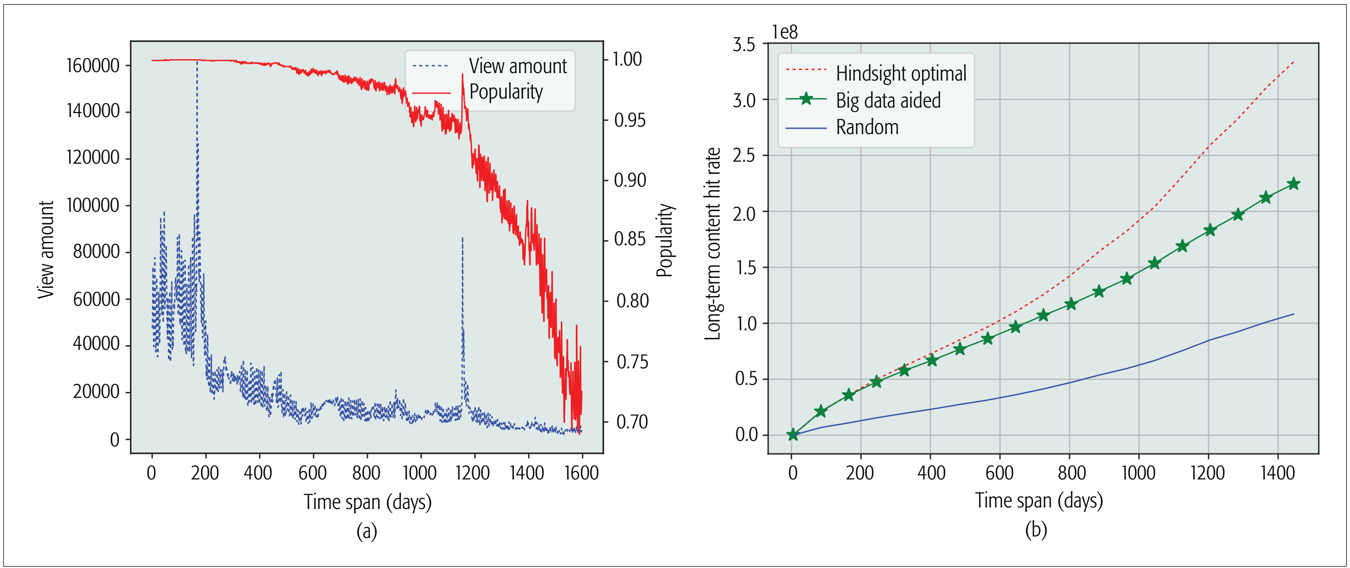

FIGURE 3. a) Data statistics: the daily view amount and popularity curves of a YouTube video; b) the comparison of big data aided caching with other schemes in terms of long-term video hit rate.

$h_{c,t}$ be the predicted hit rate of content c at time slot t, and $\mathbf{x}_{c,t} \in \mathbb{R}^d$ be the d-dimensional historical statistical vector. Then we have

$$\mathbb{E}[h_{c,t} \mid \mathbf{x}_{c,t}] = \mathbf{x}_{c,t}^{\mathrm{T}} \theta_c^* + \eta_t, \tag{1}$$

where $\theta_c^* \in \mathbb{R}^d$ is the featured parameter vector of content c, and η_t is the random noise. By applying standard ordinary least square linear regression, we can make unbiased estimation on the feature vector θ_c^* of each content, and hence make accurate future content popularity prediction. Figure 3b shows the performance of big data aided edge caching. It can be seen that exploitation of big data can significantly improve the cumulative content hit rate on the edge. The accuracy of the prediction highly depends on the amount of historical data. Meanwhile, the mathematical model of content popularity remains to be explored to further improve the accuracy of prediction.

Open Issues

In this section, some open research issues are discussed.

Big Data Aided Network Framework: Although big data can present tremendous opportunities to networks, the current wireless networks are mainly designed for information delivery. To harvest the benefits of big data and generate big values, a big data aided framework is urgently needed to analyze and make efficient use of the wireless data. The framework is expected to integrate the big data chain efficiently into the network by efficiently collecting, storing, processing, and analyzing data to enhance network operation. It is expected to discard the meaningless data and place storage and processing resources at appropriate locations.

Trade-offs among Communication, Caching, and Computing: 5G wireless networks provide heterogenous communication, computation, and caching resources. It is of great importance to efficiently utilize these heterogenous resources to support heterogenous big data applications. Note that there are trade-offs among communication, caching, and computing resources. For instance, extra computation resources can be traded to reduce the communication load. In addition, the intermediate or final results of computation may need to be stored as valuable resources. Storing all those data can incur high storage cost, while deleting those data may require re-computation when needed. To support different big data applications cost effectively, in-depth investigation is required to reveal the trade-off relationship among these heterogenous resources to provide guidance for resource provisioning.

Cooperative Edge Caching/Computing: With deployment of mobile edge caching/computing, the data collected from different sources can be efficiently stored and preprocessed. Due to the non-uniform data load distribution in both spatial and temporal domains, cooperative edge caching/computing is a promising solution to storing and processing massive data in a cost-effective way. Different caches can cooperatively form a distributed storage system, while distributed edge computing can provide parallel computing capabilities for data processing.

Customized Networking for Big Data: Network slicing or SFC has the potential to efficiently support multifarious big data services/use cases, by creating service-oriented networking over the physical network infrastructure. To satisfy service requirements such as delay, the end-to-end networking solution can be customized in terms of virtual topology, resource provisioning, and embedded functions. Moreover, multiple slices or SFCs should be well orchestrated to make efficient useof networking resources and satisfy their respective requirements. In addition, network slicing or SFC should adapt to dynamics in network condition and service requests.

Security and Privacy: Although big data can discover knowledge from massive data, it also raises security and privacy concerns. To explore the great value, the data sources should be trusted and authentic. During processing and transportation, the data should be prevented from being altered or modified. In addition, only authorized

With network slicing, heterogeneous resources can be better integrated to cater for the features of big data. On the other hand, with big data techniques, knowledge about networks and users can be provided to improve network design and operation. In addition, the big data processing chain can be incorporated into the SDN operation loop for round-the-clock network optimization.

entities can have access to the data to protect data from untrustworthy entities. Moreover, data mining on personal user data can violate user privacy such as location and habit information [14, 15]. For the spread of big data techniques, security and privacy issues should be well addressed.

Conclusion

In this article, we have investigated the synergistic and complementary features of big data and 5G wireless networks. By exploring communication, computing, and caching capabilities, 5G wireless networks can better support the big data processing chain. With network slicing, heterogeneous resources can be better integrated to cater for the features of big data. On the other hand, with big data techniques, knowledge about networks and users can be provided to improve network design and operation. In addition, the big data processing chain can be incorporated into the SDN operation loop for round-the-clock network optimization. This article sheds light on the research regarding synergies between big data and 5G wireless networks. To accelerate the pace of big data driven or big data assisted networking, significant research activities are expected in this exciting area.

Acknowledgment

This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Natural Science Foundation of China (No. 61702562), the National Natural Science Foundation of China under Grant No. 61231010, the National Nature Science Foundation of China (No. 61502085), and a China Postdoctoral Science Foundation funded project (No. 2015M570775).

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