IF-RANs: Intelligent Traffic Prediction and Cognitive Caching toward Fog-Computing-Based Radio Access Networks

Long Hu, Yiming Miao, Jun Yang, Ahmed Ghoneim, M. Shamim Hossain, and Mubarak Alrashoud

Abstract

The rapid development of wireless communication technology and smart devices has made the traditional cloud-based Internet of Things architecture unable to meet the stringent requirements of 5G mobile communication networks. In order to realize high-reliability and low-latency communication for 5G, F-RANs have become a potential evolution path. However, F-RANs still face several challenges regrading infrastructure, network traffic, and caching mechanism. From the point of view of integrating AI, F-RANs, and cloud, this article proposes intelligent traffic prediction and cognitive caching toward IF-RANs. First, a traffic flow prediction algorithm is developed that is based on LSTM with an attention mechanism. The algorithm can effectively predict real-time traffic of different data types. Then, for caching policy, cognitive caching based on LSTM and collaborative filtering is proposed to reduce the total communication delay. The experimental results demonstrate the effectiveness of the proposed IF-RANs in improving the accuracy of real-time prediction and reducing communication latency.

Introduction

In recent years, mobile networks have become increasingly popular with the evolution of wireless communication techniques, the infrastructure of telecommunications, data processing, and computing capacity. Smart devices, such as smartphones, smart robots, wearable devices, unmanned aerial vehicles, and autonomous vehicles, are used everywhere. The development of fifth generation (5G) mobile cellular networks and the wide use of smart mobile devices have significantly increased the mobile traffic flow. According to a recent report, the average household's mobile traffic flow was close to 4 GB in May 2018 compared to 2.39 GB in November 2017, and the global mobile data flow was about 7201 PB/month in 2016. It is predicted to reach 48,270 PB/month in 2021 [1].

The rapid increase in the flow of mobile traffic puts heavy pressure on existing mobile communication techniques and frameworks.

Communication Latency: For users, quality of experience (QoE) is proved not only by the intelligence and personalization of services, but also by the real-time interactions. The sharp increase in the mobile traffic flow can cause a shortage of computing and networking resources.

Conflict of Bandwidth Resources: With the increase in intelligent services and applications, the traditional Internet of Things (IoT) is gradually becoming overwhelmed in the current heterogeneous radio access networks (RANs). Several wireless communication techniques (mobile cellular networks, low-power wide area networks, and short-distance low-consumption communications) will be extensively used. With the increase of traffic flow, the problems of wireless-channels conflict, and bandwidth-resource occupation will become extremely severe. This greatly influences the reliability of transmission.

Increasing Computing Pressure of the Base Station and the Cloud: In order to meet the extremely high requirements of real-time augmented/virtual reality, self-driving automobiles, affective interactions, health surveillance, and remote medical treatment, the computing and communication pressure on both the base station and the remote cloud is increasing with each passing day without an efficient caching mechanism [2].

The traditional cloud computing mode can no longer meet the needs of users due to the massive data and congestion in the transmission process of the IoT as well as the ultra-high latency from the edge to the cloud. Therefore, in order to support 5G scenarios, Cisco has proposed fog computing to cope with the extension of cloud computing to personal computing in order to achieve distributed computing and decentralized processing [3]. Currently, fog-computing-based radio access networks (F-RANs) have become a potential evolution path for 5G [4]. However, F-RANs face tough challenges in order to meet some stringent requirements, such as high reliability and low latency, due to the massive fog-user equipment (F-UEs) of RANs.

Artificial intelligence (AI) is a branch of computer science that researches and develops theories, methods, technologies, and application systems for simulating, extending, and expanding human intelligence [5]. AI tries to understand the essence of intelligence to produce a new intelligent machine that can respond in a similar way to human intelligence. AI research includes robots, language

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With the increasing number of smart devices, the development of RAN makes it difficult for the existing computing models or infrastructures to efficiently process massive data. However, it is unrealistic to improve the storage of massive data and computing power in a short time. In addition, the traditional cloud models are not suitable for time-sensitive applications.

recognition, image recognition, natural language processing, and expert systems. Since the birth of AI, both theory and technology have become increasingly mature, and the field of applications has been expanding. For example, AI researchers use deep learning technology to process and mine unstructured collected data (e.g., video, image, audio, and physiological signals) in depth, and ultimately provide more intelligent cognitive services for human beings. Fog computing has begun to use AI to enhance its quality of service (QoS) and QoE. In addition, fog access points (F-APs) combined with AI technology are expected to promote the development of fog computing by providing distributed AI services.

Over the past decade, RAN, fog computing, and AI technologies have undergone rapid changes in platform and application scope. The age of cognitive computing and big data analysis has started and can be seen everywhere, including the widespread use of smartphones, cloud computing and fog computing applications, and the revival of AI in practice, from extended supercomputers to a wide range of deployment of RANs. With these new computing and communication methods and requirements, it is essential to upgrade the RAN ecosystem and design a new network architecture to transmit, store, process, learn, and analyze massive data. By introducing fog computing, AI, and caching, F-RANs based on intelligent traffic prediction and cognitive caching (IF-RANs) can be designed. Such networks can help people to efficiently overcome the shortcomings of labor-intensive and time-sensitive computing tasks.

The main contributions of this article are as follows:

- The drawbacks of traditional cloud-based IoT architecture are discussed, and the evolution and challenges of F-RAN are summarized.
- A new IF-RAN architecture with improved traffic prediction and caching algorithms is proposed by integrating AI, fog computing, and RAN.
- A traffic prediction model based on long short-term memory (LSTM) and a cognitive caching strategy based on collaborative filtering are proposed for IF-RAN architecture.

The remainder of this article is organized as follows. The following section investigates the related works in the field of F-RAN and summarizes the shortcomings of existing research. We then introduce the problems of traditional cloud-based IoT architecture as well as the evolution process and development direction of F-RANs. Following that, a new IF-RAN architecture is proposed. The IF-RAN is described in detail from three aspects: network architecture, traffic prediction model based on LSTM, and cognitive caching strategy based on collaborative filtering. Then an IF-RAN simulation environment is developed, while experiments are conducted on traffic prediction accuracy and the impact of caching strategy on delay. Finally, we conclude this article.

Related Work

With the increasing number of smart devices, the development of the RAN makes it difficult for the existing computing models or infrastructures to efficiently process massive data. However, it is unrealistic to improve the storage of massive data and computing power in a short time. In addition, the traditional cloud models are not suitable for time-sensitive applications. The new trend is to deploy data processing locations as close as possible to data generation points. In [6], a Fog-of-IoT paradigm (a distributed computing network) has been designed based on 5G access networks, fog computing, and IoT. In order to support highly desired low-latency computing and communications services, F-RAN architecture has been proposed in [7] by distributing computing-intensive tasks to multiple F-APs. Thus, computing resources are efficiently decentralized from the cloud to the edge of the network. Aiming at reducing the delay of IoT services, the general framework of fog cloud application based on IoT was introduced in [8], and a collaboration strategy of delay minimization and fog-capable uninstallation strategy was proposed. Both [9, 10] argued that the cloud is increasingly inadequate to support emerging systems and applications, such as IoT, 5G wireless systems, big data analysis, and learning-based edge computing. These gaps can be filled by bringing computing, network, management, and control functions to cloud computing through fog computing or fog networks. However, the above-mentioned research works did not combine RAN with AI. Moreover, such system architectures lack sufficient intelligence because they fail to introduce data analysis technologies such as machine learning and deep learning.

Recently, some researchers have presented their own opinions on the combination of fog computing, RAN, and AI technology. In [11], the applications of fog computing in IoT, 5G, and AI were investigated, and the opportunities and challenges of fog computing in these areas summarized. In order to reduce the delay caused by data transmission to cloud in real-time remote health monitoring application, the concept of fog computing is introduced in the intelligent gateway, and the concept of remote patient health monitoring in smart home has been proposed in [12]. In [13], a technology forecast model based on extensive descriptions of developments by field as well as interaction traits was proposed. However, these research works failed to propose a feasible F-RAN fusion framework, and did not consider the large-scale data interaction, communication, and caching scenarios.

Challenge and Research Motivation

Traditional Cloud-Based IoT Architecture

According to the investigation above, the shortcomings of traditional cloud-based IoT architecture are summarized in Fig. 1. IoT is widely used in RAN through multiple communication sensing technologies such as intelligent sensing, identification technology and pervasive computing. It is an application expansion of the Internet that connects various devices, such as computers, household appliances, transportation, mobile phones, and other portable devices. These devices contained several types of sensors. Each sensor is an information source. The content and the format of information captured by different types of sensors are different, including structured data such as digital and coincidence, as well as massive unstructured data such as image, video, audio, text, and hypermedia. The sensor collects the environmental information periodically according to a certain frequency and constantly updates the data. Moreover, it is a ubiquitous network based on the Internet. The Internet/central cloud is still the important foundation and core of IoT technology. Through the integration of various wired and wireless networks and cloud, the information of objects can be transmitted accurately in real time. The information frequently collected by the sensor needs to be transmitted through the network. However, the massive amount of information will lead to extremely serious network load.

Improvement and Conceptual View

The traditional cloud-based IoT architecture adopts the central control mode. However, it faces a series of challenges such as network congestion, lack of intelligence, low QoE, poor QoS, and high delay due to the massive multidimensional data generated by IoT as well as the delay-sensitive requirements of various intelligent applications and services. Bear in mind that factors such as delay, bandwidth, and packet loss rate can affect QoS, while the transparency of intermediate media, end-to-end network QoS, and user expectations will have impacts on QoE. In order to solve the above problems about network interaction, distributed computing and communication are effective means. The F-RAN is regarded as a new IoT architecture that combines the fog computing and the RAN. The fog cloud acts as a bridge between the edge devices and the cloud, playing the roles of streaming and caching. Therefore, the F-RANs are helpful to promote 5G applications with wide coverage and low latency. Currently, AI is a research hotspot in the field of communication to tackle the challenge of service intelligence. Therefore, the machine learning technology is used to assist the cognitive computing (prediction and caching) for IF-RANs architecture in this article.

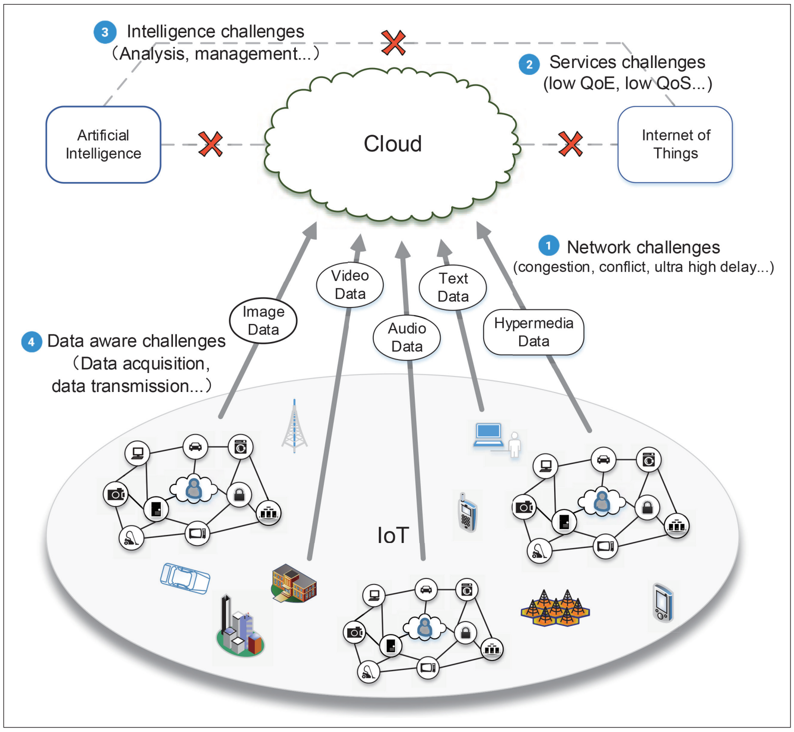

FIGURE 1. Traditional cloud-computing-based IoT architecture and challenges.

System Architecture

Based on the above-mentioned shortcomings of traditional cloud-based IoT architecture and the evolution of F-RANs, F-RAN architecture is designed with intelligent traffic prediction and cognitive caching algorithms (IF-RANs), as shown in Fig. 2. The IF-RAN architecture consists of three infrastructure parts and two algorithm parts. The infrastructure parts include local, fog, and cloud. Cloud computing relies on thousands of data centers around the world. It uses virtualization to meet the needs of a larger number of users at the same time. The fog computing in the middle layer relies on F-APs, and is a bridge and a good complement between cloud computing and F-UEs. Fog computing, as a marginalized evolution form of cloud computing, aims to provide computing services to the IoT devices with high performance, low latency, and high bandwidth. The F-APs (including wireless access points, base stations, and routers) play a connecting role. The intelligence is pushed to the local area network (LAN) level to collect, interact with, aggregate, and calculate the local environmental information of a large number of edge devices, and then transmit the relevant information to the cloud. Due to the close distance between F-APs and local, the F-UEs can not only rely on D2D technology, but also directly connect to F-APs through wireless channels. In this way, the computing task does not need to go through a long transmission network to the remote core network for processing. Sometimes, the users can directly request or obtain the cached content in F-APs, which effectively reduces the communication delay. Thus, the entire network can better support the delay-sensitive computing tasks.

In the algorithm part, the data cognitive engine uses the LSTM algorithm [14] to predict the traffic flow of F-UEs' requests and determine the peak value of traffic, which is helpful to assist in planning the network scheduling and reducing the communication load. The resource cognitive engine uses the cognitive caching strategy based on the mixed LSTM and collaborative filtering algorithm to make up for the shortage of limited computing and communication resources of F-APs. This helps to improve the cache hit rate and reduce the network latency. The two cognitive engines complement each other and provide users with personalized services and content, which will help the IF-RANs to achieve breakthroughs in computing intelligence, distributed networks, high-quality services, and data recognition.

Traffic Prediction Based on LSTM

In IF-RANs, the F-UEs sends the content requests to the core network in real time. Once the request is initiated, the data packet is transmitted to the F-APs via the wireless channel. However, the network bandwidth resources are limited, while too many concurrent requests at the same time will lead to network congestion and affect the efficiency of data transmission. Therefore, it is essential to predict the real-time peak traffic in advance to assist wireless access scheduling.

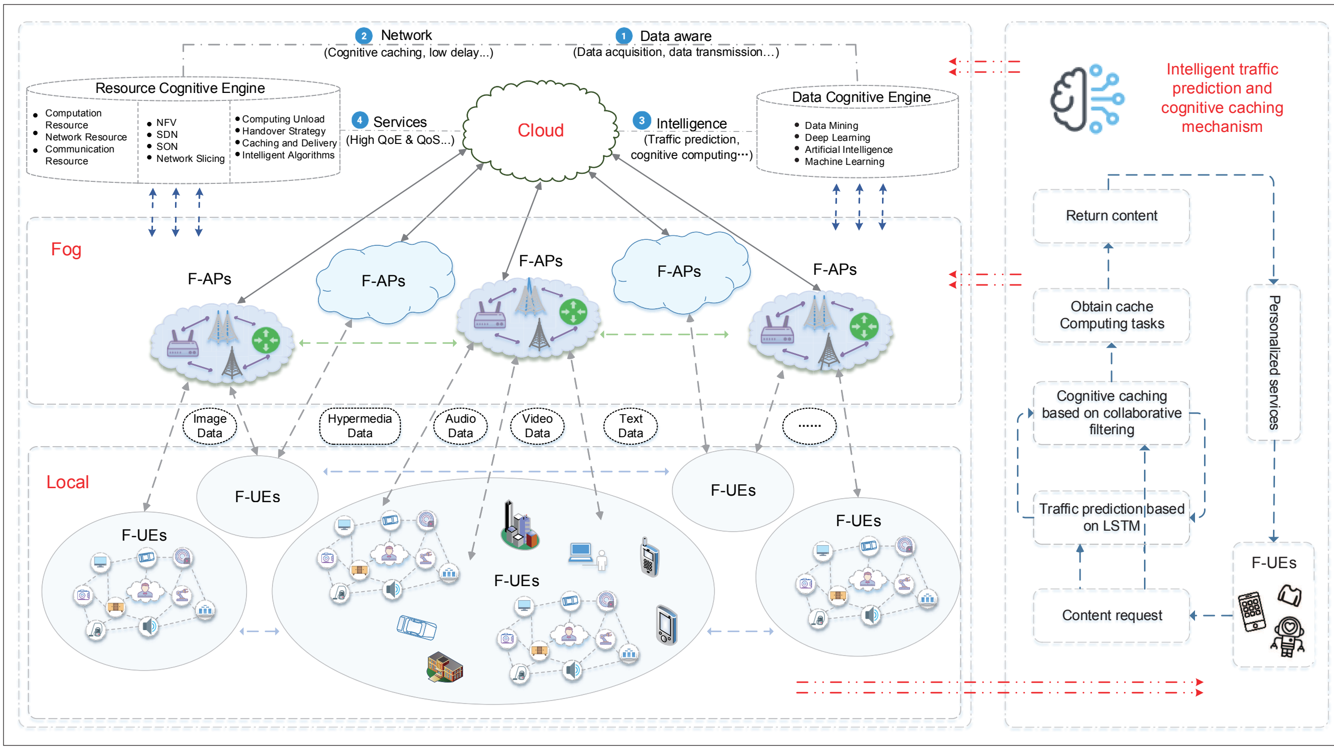

FIGURE 2. Intelligent traffic prediction and cognitive caching toward fog-computing-based radio access network architecture.

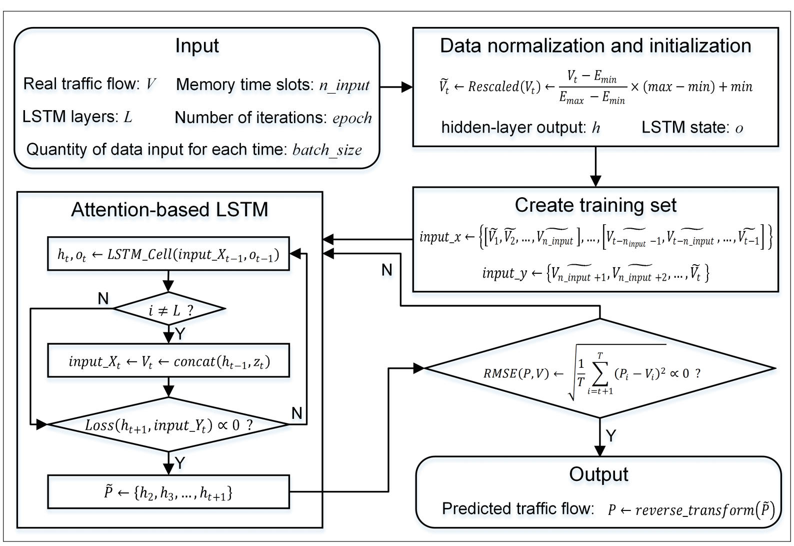

FIGURE 3. LSTM-based traffic prediction algorithm.

In order to improve the dynamicity and accuracy of prediction, the LSTM algorithm is selected since it has several advantages in long-term time series prediction compared to the existing machine learning algorithms. Thus, a traffic prediction model based on LSTM is proposed, as shown in Fig. 3. First, data normalization operation is performed on real traffic flow $V = \{V_1, V_2, \ldots, V_t\}$ and the input data $input_x$ and $input_y$ of an LSTM cell is generated. At the same time, the network parameters are defined and initialized, including the memory time slots n_{input}, the number of iterations *epoch*, the quantity of data input for each time $batch_{size}$, the LSTM layers L, the hidden-layer output h, and the LSTM state o of the LSTM cell. The main part of the algorithm consists of multiple stacked LSTM layers, attention layers, and a full connection layer. Then the normalized dataset is input into the neural network, and the traffic characteristics h_t are extracted through multiple stacked cyclic attention-based LSTM layers. Finally, an output sequence $P = \{P_2, P_3, \ldots, P_{t+1}\}$ is obtained by combining the features extracted from the front with a full connection layer. Here, P_{t+1} represents the predicted traffic value at the next time. In this process, the accuracy of traffic prediction needs to be improved as much as possible, that is, $RMSE(P, V) \propto 0$. In this way, the network can predict real-time traffic more accurately in order to better configure communication resources, avoid congestion, and meet high reliability and low latency requirements.

Cognitive Caching Based on Collaborative Filtering

The diversity of 5G applications, the high concurrency of user requests, and the density of time-sensitive intelligent services exert significant pressure on the limited computing and storage capacity of F-APs. If F-APs can find the original cached data from the storage unit and send it back to the users in time when the users initiate the content requests, it would alleviate the network congestion, reduce computing and communication delay, and also provide good user experience.

However, "what to cache," "where to cache," and "how to cache" are the three core issues of fog computing caching strategy, as shown in Fig. 4.

What to Cache: Typically, the data types requested by 5G users include text, video, audio, image, and hypermedia. It should be ensured that the cached content is popular, that is, the caching program is started when the request content of different users is similar. In this way, the hit rate of cache can be improved, and the cost caused by invalid cache can be reduced.

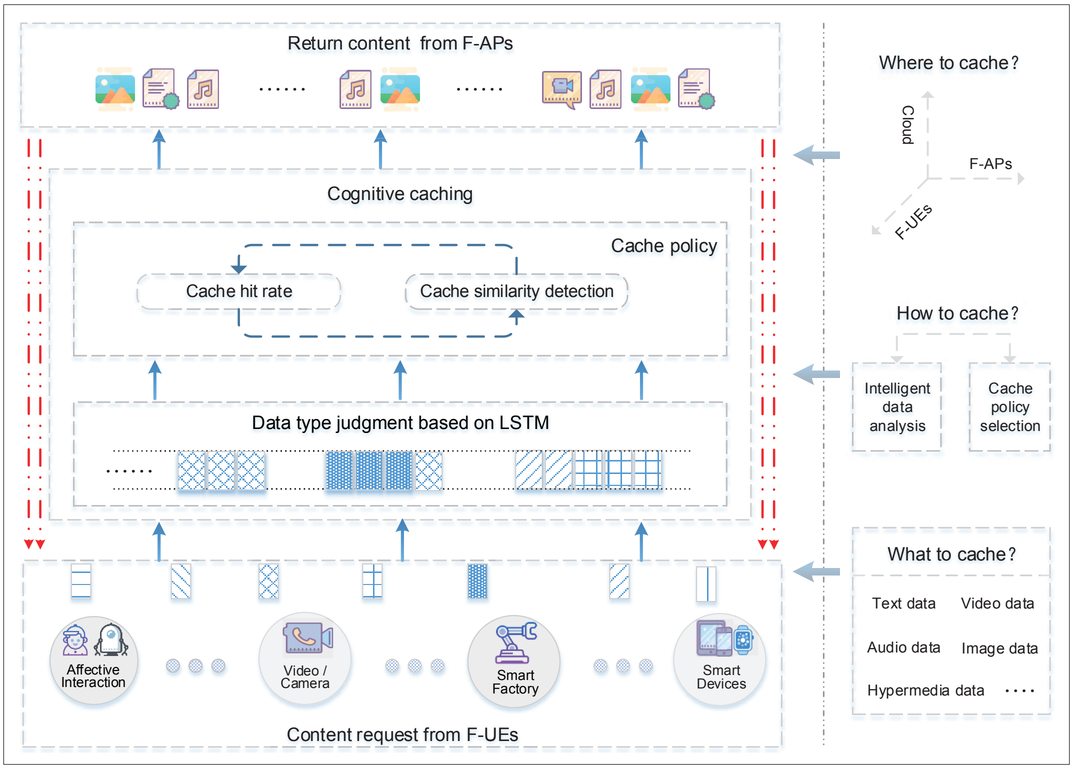

FIGURE 4. Cognitive caching strategy based on LSTM and collaborative filtering.

The existing caching strategies are usually based on the optimization model of human intervention, which is constructed by experts with domain knowledge. Although this knowledge-driven model is cost-effective, it is inefficient in implementation. Therefore, a cognitive caching strategy based on LSTM and collaborative filtering is proposed.

Where to Cache: Although F-UEs, F-APs, and clouds all have caching capabilities, considering the overall structure of IF-RANs, it is necessary to deploy intelligent caching strategies on F-APs under high concurrent requests in order to promote distributed computing and communication.

How to Cache: The existing caching strategies are usually based on the optimization model of human intervention, which is constructed by experts with domain knowledge. Although this knowledge-driven model is cost-effective, it is inefficient in implementation. Therefore, a cognitive caching strategy based on LSTM and collaborative filtering [15] is proposed in this section. For content caching with similar popularity, the caching model of collaborative filtering is adopted. The model can be used to predict the content of the user's forthcoming requests, help to dynamically adjust the computing resources, and reduce the computing delay. However, before determining the cache content, the content of user requests needs to be divided into fine-grained partitions, that is, determine the data type of requests. Here, the LSTM algorithm shown above is used to predict the data type. The prediction results of data types are obtained before content matching is performed in the corresponding collaborative filtering caching model.

Experimental Results

A simulated IF-RANs environment including 15 F-UEs (Android 4.4 operating system, 1.2GHz quad-core CPU, 1GB DDR3 SDRAM, and 32G NAND Flash) to support the local computing, 3 F-APs (CentOS 7 operating system, 3.4GHz octa-core CPU, 16GB DDR3 SDRAM, and 1050G NAND Flash) to support the fog computing, and a GPU server (Ubuntu 16.04 operating system, 3.5GHz 6-core CPU, 32GB DDR3 SDRAM, and NVIDIA GTX1080ti*2 GPU) to support the cloud computing was built.

In the experimental environment, F-UEs request three types of content (text data, image data, and video data) from F-APs. A total of 5000 historical logs were collected from F-APs and divided into training dataset (3500 pieces of data) and test dataset (1500 pieces of data). The datasets were used for training and testing the traffic prediction model and the cognitive caching model. Figure 5 shows the real-time traffic prediction results of three different types of data based on an LSTM traffic prediction model. In order to display the predicted results intuitively, the experimental results of 150 s (from 300 s to 450 s) are randomly selected from the test dataset. From the volume of data, the text data traffic (Fig. 5a) is significantly smaller than audio data traffic (Fig. 5b) and video data traffic (Fig. 5c). Therefore, there are text data requests almost every time, and the difference between the high and low peak traffic is obsolete. In contrast, the peak value of audio and video data will obviously fluctuate over the period of time. However, the proposed algorithm can effectively capture the changes of different data traffic. The experimental results show that the proposed algorithm can accurately predict the trend of real-time traffic. Therefore, it can provide traffic information for IF-RANs.

In another experiment, the effects of different caching strategies on the latency of user requests are tested, as shown in Fig. 6. Three caching strategies, namely random caching strategy, popularity caching strategy, and IF-RANs with cognitive caching strategy, are selected for comparison. The average data size is set as {40,50,60,70,80}. It can be seen that the proposed strategy can effectively reduce the latency of request processing. The higher the cache hit rate, the lower the computation latency and the lower the overall latency. The

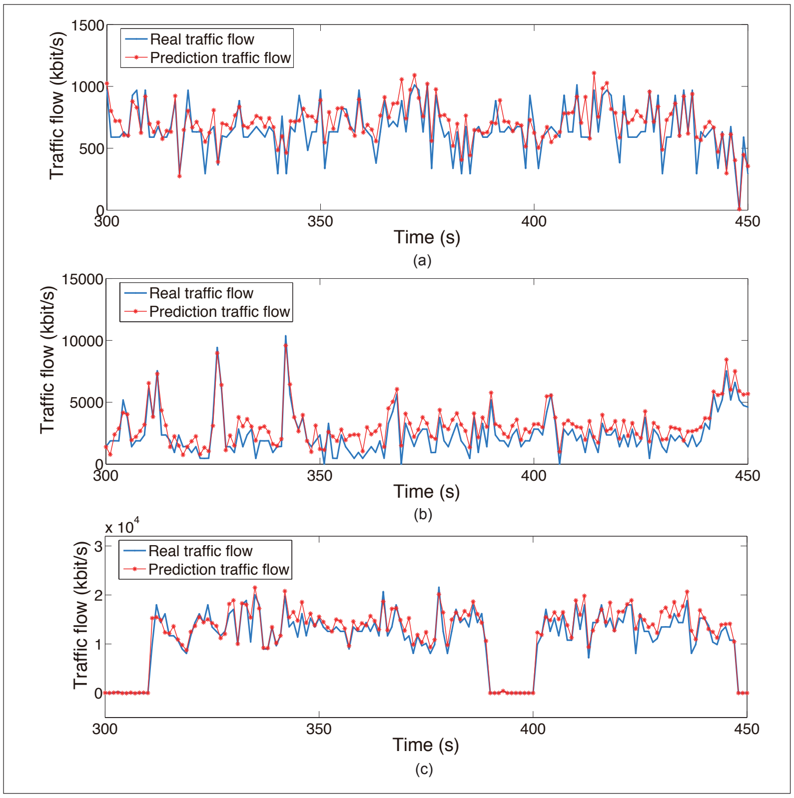

FIGURE 5. Multi-type traffic prediction results based on LSTM: a) text traffic prediction; b) audio traffic prediction; c) video traffic prediction.

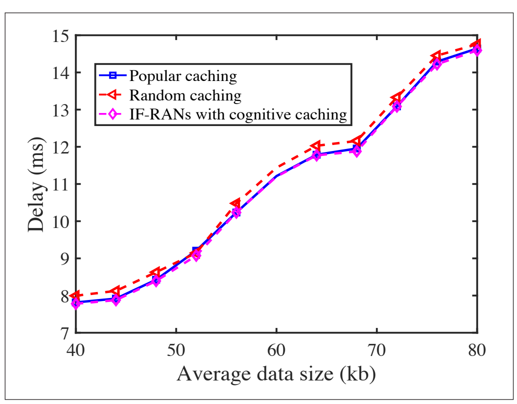

FIGURE 6. Effects of different caching strategies on communication delay.

random caching strategy is not intelligent enough because it cannot select what users need most for caching. The proposed strategy still has lower computation and communication latency than popular caching strategy at the expense of LSTM determining the type of content request. This advantage will be more significant with the increase of data size.

Conclusion

In this article, intelligent traffic prediction and cognitive caching toward F-RANs are proposed. First, the traditional cloud-based IoT architecture is discussed, and the development history of F-RANs in view of its shortcomings is summarized. In order to meet the requirements of 5G applications about high reliability and low latency of communications, an attention-based LSTM algorithm is used to predict the service traffic flow with different requested data types. Then a cognitive caching strategy based on LSTM and collaborative filtering is designed. The performance of the proposed LSTM-based traffic prediction algorithm and cognitive caching strategy is evaluated using simulation of IF-RAN architecture in a real environment. The experimental results verify that the proposed method can accurately predict traffic flow type and is capable of effectively reducing the communication latency.

In the future, the authors plan to further research the resource allocation based on the proposed intelligent traffic flow prediction algorithm toward IF-RANs. Furthermore, a fine-grained caching mechanism, that is, content caching based on service type and data type, will be an important research direction in the resource cognitive engine (part of IF-RANs). Moreover, the coupling relationship between traffic prediction and content caching will be further refined.

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