Network Softwarization and Parallel Networks: Beyond Software-Defined Networks

Fei-Yue Wang, Liuqing Yang, Xiang Cheng, Shuangshuang Han, and Jian Yang

Abstract

The coexistence of various protocols for current network equipment leads to extremely complex network systems, which not only limit the development of network technologies, but also cannot meet the growing demands for cloud computing, big data, and service visualization applications, just to name a few. As a new network architecture, parallel networks are expected to revolutionize this situation and meet the evolving demands for network services. The main idea of a parallel network is to leverage upon software-defined networking to construct artificial networks, and then effectively optimize the network system operations via the interactions between actual and artificial networks. The foundation of the parallel network is the theory of ACP, composed of artificial societies, computational experiments, and parallel execution. By the computational experiments and analysis of the artificial network, a control strategy based on network traffic flow can be continuously updated and tracked on a real-time basis; meanwhile, the collected operating status of the actual network can also be used to optimize the model of the artificial network. These strategies can be applied to all types of network equipment to control network operations at various levels; thus, it is possible to allocate the network resources more effectively, improve the management and utilization of resources, and then provide new network solutions to effectively address the constantly evolving network demands for network performance, scalability, and security.

With the expanding network scale, continuously-innovating network business, and increasing network users, the current network infrastructure can hardly meet the demands of network development. A huge number of existing and expanded base stations bring high construction investments, facility usages, site rentals, operating expenses, and maintenance costs. However, the actual utilization rate of the existing base stations is still very low. Typically, the average network load is significantly lower than the peak network load. However, different base stations cannot share their processing capacity, thus rendering it difficult to improve the overall spectrum efficiency. Furthermore, proprietary platform means that operators have to maintain multiple heterogeneous (and at times even incompatible) platforms, which will result in high costs for expansion or upgrade.

Therefore, to meet the increasing network demands, new network infrastructure has become the focus of networking research and development worldwide. From a technical point of view, network layers could be reduced to effect the so-called delayering; from a management point of view, centralized management and decentralized maintenance are both necessary. Due to the clear hierarchy of the existing network architecture, it cannot rapidly self-adapt to meet network demands, especially for the case of bursty business traffic demands.

Software-defined networking (SDN) [1, 2] was proposed so that the decision making process of the network is moved from distributed network devices to a logically centralized controller, implemented as software running on commodity servers. SDN differs from traditional networking in several aspects:

- SDN separates the data plane, which forwards traffic at full speed, from the control plane, which makes decisions on how to forward traffic over larger timescales.
- SDN provides a well defined interface between the separated control and data planes, including a set of abstractions for network devices that conceal many details.
- SDN migrates the logic control plane to a logically centralized controller that exploits a global view of network resources and knowledge of application requirements to implement and optimize global policies.

The development of SDN [3] will highly improve the expansion and flexibility of the network. It is already becoming one of the most popular research topics in the field of information communication and is envisioned to play an important role in the development of next generation networks [4].

Due to the interdiscipline, multi-field, dynamic, and unpredictable characteristics, a network system can be regarded as a large-scale complex system. The application of parallel system methods [5, 6] in complex network systems is expected to significantly improve network operating status and meet the developing network demand. Parallel system refers to a complex system

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that consists of an actual system and its corresponding artificial or virtual counterparts (one or often more). Through the interactions between the actual and artificial one, a parallel system compares and analyzes behaviors of both systems, completes the prediction for respective future status, accordingly adjusts management and control mode, and derives effective solutions and objectives of learning and training.

The high cost of network system engineering experiments and the impact of actual conditions lead to the restriction of experiment feasibility, repeatability, and scientificity. Consequently, it is becoming an attractive issue to proactively derive comprehensive and accurate evaluation, correction, and prediction for network system improvement. Therefore, the parallel network concept was first proposed in [7]. In this article, we present the overall approach and briefly describe the concepts and methods of parallel network system based on artificial societies, computational experiments, and parallel execution (ACP) theory, which aims to contribute to a further optimized network management, control, scheduling, and allocation strategy.

The proposed parallel network system consists of an actual network and an artificial network. Based on the main idea of SDN, the artificial network can be constructed to implement corresponding computational experiments. Through the interactions between the actual network and the artificial network, a parallel network can not only obtain optimized route scheduling and data forwarding solutions as SDN achieves, but also guide and predict the actual network policies/status for achieving the global/local network optimization, such as network configuration, resource allocation, power control, channel allocation, and access control.

This article is organized as follows. In the next section, the basic concepts of parallel control and management and ACP theory are introduced. After that the architecture and operations of the parallel network system are presented. The application of the parallel network system in existing and future network systems is then given. Concluding remarks are provided in the final section.

Parallel Control and Management

The management and control of actual systems are largely offline, static, and supplementary via mathematical modeling and computational simulation. However, for complex systems, it is difficult to establish accurate models for evaluating and predicting their short-term actions. Therefore, the development trend is to explore the potential of artificial systems from offline to online, from static to dynamic, and from passive to proactive, which are precisely the features of the so-termed parallel system [8, 9].

Parallel System Method

The architecture of the parallel system mainly includes the actual system and the artificial system [10, 11]. The interactions between these two systems help to accomplish management and control of the actual system, experimentation and evaluation of its behaviors and decisions, and learning and training of operators and administration. The purpose of the parallel system is to connect the actual system and its artificial counterparts in various modes for different purposes. By comparing and analyzing the actual and artificial behaviors, future actions can be predicted, and the control and management strategies can be planned and modified.

Parallel system methods were originally proposed for the purpose of modeling, analysis, and control of complex systems. Generally, it consists of three steps:

- Modeling and representation using artificial societies
- Analysis and evaluation by computational experiments
- Control and management through parallel execution of actual and artificial systems

The ACP Theory

The complex systems considered in the ACP approach usually have two essential characteristics. The first is called inseparability, which means that with limited resources, the global behaviors of a complex system cannot be determined or explained by independent analysis of its individual components; instead, the system is regarded as a whole determination about how its parts behave. The second one is called unpredictability, which means that with limited resources, the global behaviors of a complex system cannot be determined or explained in advance on a large scope.

The ACP theory is the combination of artificial societies, computational experiments, and parallel execution:

$$\text{ACP} = \text{Artificial Societies} + \text{Computational Experiments} + \text{Parallel Execution}$$

Artificial Societies: The characteristics of artificial systems have offered many advantages for modeling complex systems. For example, first, artificial systems emphasize the importance of interactivity, interrelationship, and integration among complex systems; second, by using artificial systems in real, simulated, or mixed environments, this approach can generate complex interactions and behavior patterns [11, 12]. With these characteristics, especially the second one, artificial systems can adapt complex features of actual systems, and thus support various controllable and precise computational experiments, so as to quantitatively analyze and evaluate different behaviors as well as different influence factors.

Computational Experiments: The basic idea of computational experiments is to create artificial objects and to proactively generate diverse behaviors of experimental systems in a bottom-up fashion via interactions of artificial objects. Meanwhile, the influence of various factors on these behaviors must be taken into consideration when analyzing overall system behaviors. Besides, various concepts and methods of the experimental analysis and detection can be directly used to solve the corresponding problems in computational experiments. Furthermore, fast, parallel, and economic experiments will help those methods to be more large-scale, accurate, and comprehensive.

Parallel Execution: The key concept of parallel execution is to explore the potential of artificial systems from offline to online, from static to dynamic, and from passive to proactive, so as to make artificial systems play equivalent roles to actual systems. Various parallel systems are decided by the practical requirements and development progress of artificial systems. Parallel execution provides an effective mechanism to implement various solutions, as well as evaluate, validate, and improve their performance.

Parallel Network System

Real-world network systems exhibit two characteristics considered in the ACP approach (inseparability and unpredictability). Moreover, the main motivation behind employing the ACP approach in network systems is the lack of timeliness, flexibility, and effectiveness in the current network operation management systems. In this section, the current network status and the system architecture of a parallel network are successively given. As the main content, the concepts and methods of a parallel network system are proposed.

Current Network Status

In recent years, preliminary interest and discussions about the next generation network system have evolved into a full fledged conversation that has captured the attention and imagination of researchers and engineers around the world. Due to the annual wireless data explosion driven largely by smartphones, tablets, and

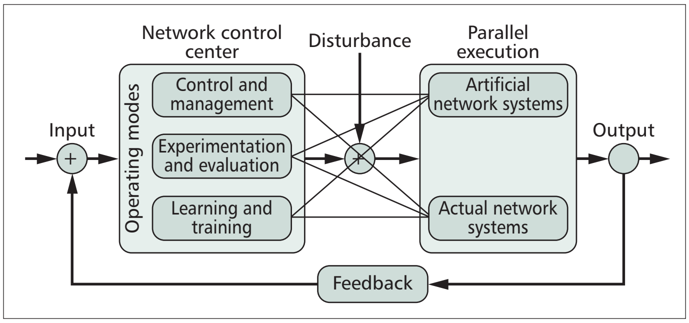

Figure 1. Framework of ACP-based parallel control and management for a network system.

video streaming, an incremental approach will not be able to meet network demands in the future [13, 14]. In addition to the huge volume of data, the number of devices and the data rates are also exponentially growing due to many new applications beyond personal communications. Furthermore, the increase of transmission rates results in plenty of various applications and service requirements, such as online finance, remote teaching, intelligent medical care, and intelligent transportation. In order to accommodate such a data and service explosion, traditional operators have to invest in more infrastructure. However, it would not only significantly increase the total cost but also complicate maintenance and coexistence with several different networks such as second generation (2G), 3G, and 4G. Besides, system upgrades would be even more challenging when new technologies such as 5G are introduced into current multi-network or heterogeneous environments.

Most network organizations have embraced the concept of cloud computing [15] and are using it comprehensively. However, if predictions regarding billions of devices and instant communications turn out to be true, even the most advanced and distributed cloud architectures would not be able to handle the demand of data and communications. Fog computing extends cloud computing and services to the edge of the network. Similar to cloud, fog provides data, compute, storage, and application services to end users. The distinguishing characteristics of fog computing are its proximity to end users, its dense geographical distribution, and its support for mobility. Services are hosted at the network edge or even end devices such as access points. By doing so, fog reduces service latency and improves quality of service (QoS), resulting in superior user experience.

System Architecture of a Parallel Network

In order to take full advantage of cloud/fog computing, SDN, and parallel systems, the concept of the parallel network is proposed here.

The application of the ACP approach in network systems will significantly enhance and improve the reliability and performance of existing network systems. In addition, it will provide an effective platform and an important solution to facilitate use of almost all the concepts and methods developed in the fields of artificial intelligence and computational intelligence, and thus insert true intelligence in the networking area. There are many other advantages of using the ACP approach in network systems. For example, cyberphysical systems, cloud/fog computing, and SDN are naturally embedded in this approach. Figure 1 presents the framework for ACP-based parallel control and management for network systems. In this network framework, the actual system and its artificial counterparts can be connected in various modes for different purposes. The interactions between actual and artificial network systems help to accomplish management and control of the actual system, experimentation and evaluation of behaviors and decision, and learning and training of operators and administrations. The purpose of the parallel system is to connect the actual system and its artificial counterparts in various modes for different purposes. By comparing and analyzing the actual and artificial behaviors, the future actions can be predicted, and the control and management strategies can be planned and modified.

System Framework: The key idea of a parallel network is the coordination of a global network system by interaction of an actual and an artificial network system. An artificial network sys-

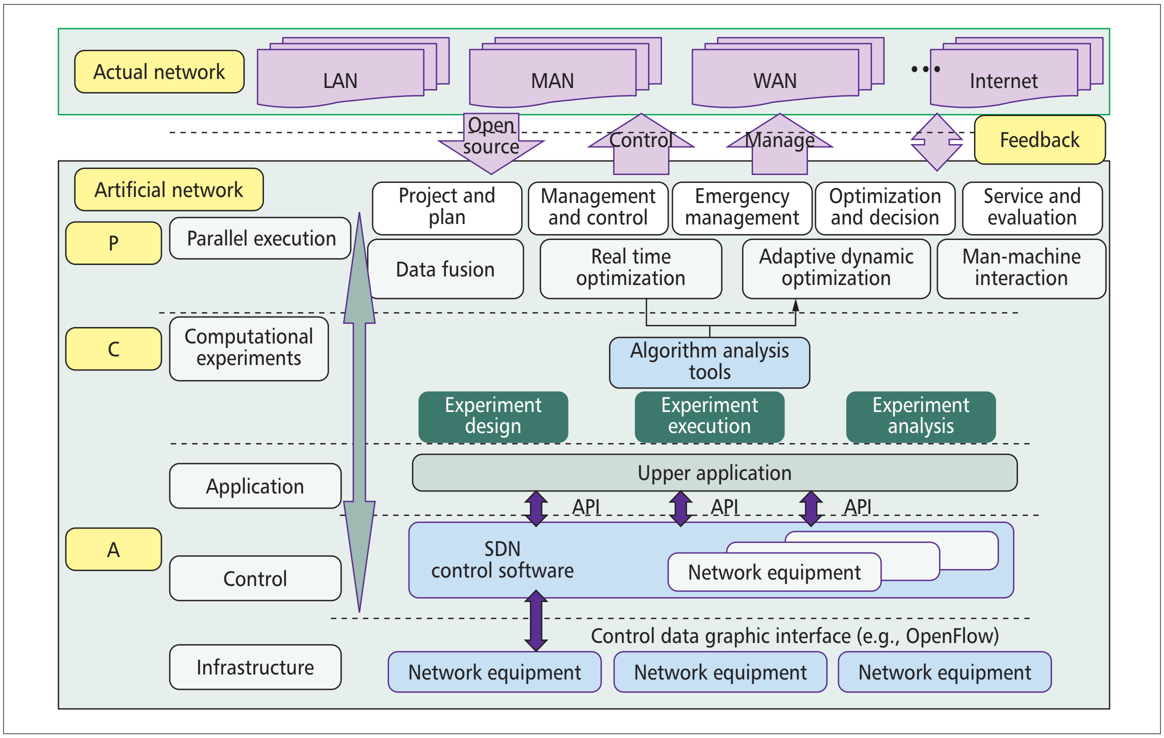

Figure 2. The framework of parallel network.

tem is considered as the basis of computational experiments; meanwhile, the optimization to network resources for the actual network system is effectively combined with the dynamic status of user demands. The framework of a parallel network is given in Fig. 2, where the controller provides centralized control and an open interface to implement a programmable intelligent control platform. Therefore, network administrators could easily define a control strategy based on network flow and service demand. These strategies can be applied to all kinds of network equipment, so as to achieve control of the whole network communication. By introducing the ACP theory to execute computational experiments and analysis, a parallel network will be able to improve network resources control and management, and provide optimized network solutions on a real-time basis, which will effectively address the changing demand for network users.

Artificial Network: Modeling of the actual network system and construction of its corresponding artificial network system are the foundation of a parallel network. By utilizing the main concepts of SDN, an artificial network system could be modeled as shown in Fig. 3.

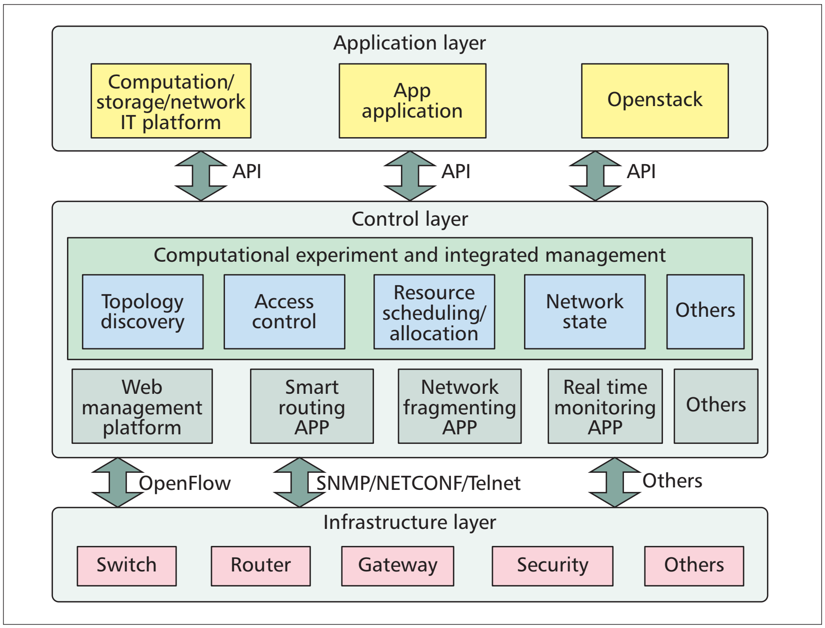

Figure 3. The framework of an artificial network.

In the artificial network architecture, the control and data planes are decoupled, and the underlying network infrastructure is abstracted from the applications. Consequently, unprecedented programmability, automation, and network control are obtained, which enables highly scalable and flexible networks to be built to meet the changing service demands.

By collecting the network state in the control layer, the artificial network system gives network managers the flexibility to configure, manage, secure, and optimize network resources via dynamic and automated methods. In addition, this architecture supports a set of application programming interfaces (APIs) that make it possible to implement general network services, including routing, multicast, security, access control, bandwidth management, traffic engineering, QoS, processor and storage optimization, energy usage, and all forms of policy management.

Computational Experiments: After modeling the artificial network, various characteristics and behaviors of the actual network can be analyzed by using the methods of computational experiments. The artificial network can be regarded as a controllable and repeatable system, where various experiments can be designed to introduce various uncertain factors, even those elements and events that are difficult to quantify in traditional ways. Experiments will be repeated and the statistics will be analyzed via systematic experiments and quantitative analysis of complex process systems.

Parallel Execution: Parallel execution between actual and artificial network systems, as demonstrated in Fig. 4, can be realized by using the computational experiment results. On one hand, various results of computational experiments would guide the actual network to achieve global optimization. On the other hand, the actual network data can be the feedback to the artificial network for its amendment and adjustment in order to further improve the current operating status of the actual and artificial systems. Different parallel execution systems can be developed for different objectives, including training, evaluation, control, management, optimization, and so on.

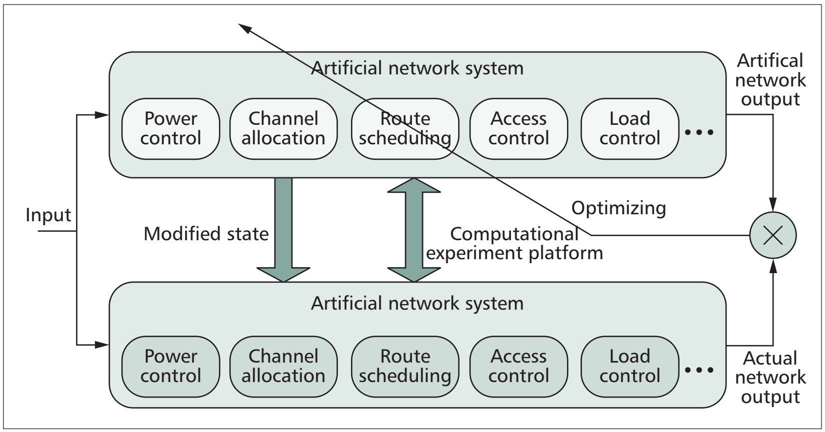

Figure 4. The framework of parallel execution.

There are typically more than one artificial network systems used in parallel network control and management. Different artificial network systems can be created for the purposes of historical network situations, normal and average performances, optimal and ideal operations, or worst-case scenarios for emergency management. Through interaction and parallel operations between an actual network system and its corresponding multiple artificial network systems, the effectiveness of different network strategies under various conditions and expectations can be evaluated and analyzed, both offline and online, and useful information can be obtained promptly and combined to generate and select control and management decisions.

Applications of a Parallel Network

Necessity for a Parallel Network

Currently, frequent network switching among different types of radio access technologies increases network load. The application of a parallel network will greatly improve the performance of the network system by coordinating, managing, and controlling the overall actual network system. The actual network system can dynamically arrange the network resources based on user requirements. It also can choose or switch the radio access technologies based on the actual network conditions, terminal abilities, and network configurations. With the

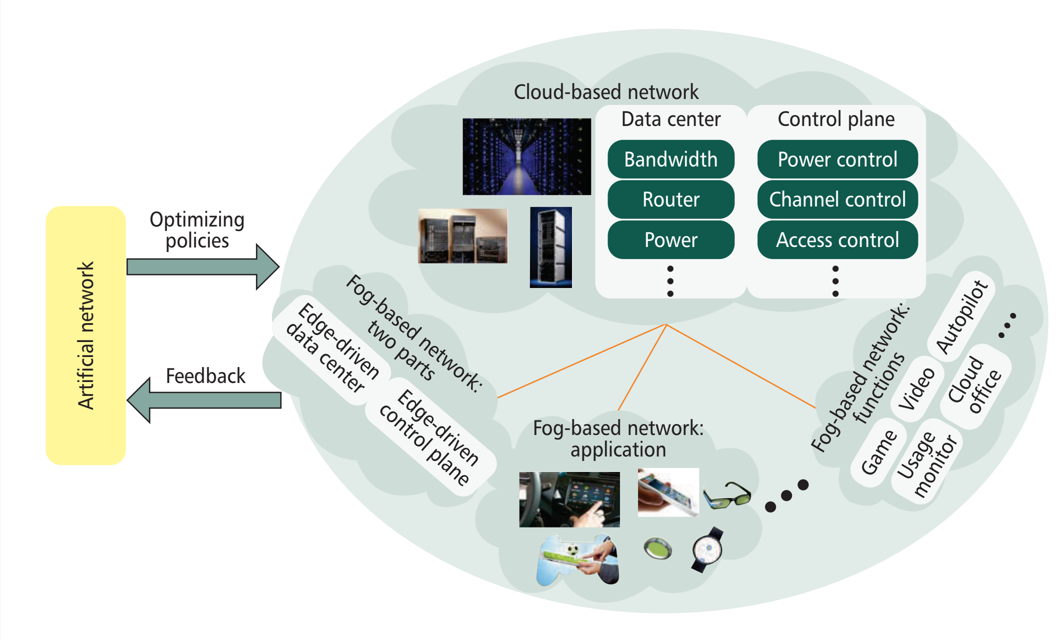

Figure 5. Real-time policy optimization for a global network system.

help of a parallel network, it is possible to improve the user experience, utilize network resources effectively, and reduce operational costs.

In addition, the parallel network system can provide optimized suggestions to construct wireless networks. Various issues will be considered, such as the signal transmission environment, distance, bandwidth, and power; thus, the actual constructed network can satisfy the requirements of network configuration.

The parallel network will be a global or local guide for all kinds of network circumstances, including intelligent buildings, mobile devices, wearable devices, and vehicular systems, and so on. According to the user demands, the parallel network will be able to provide a suite of flexible strategies to improve network status, utilize terminal capabilities, and optimize user settings and network configurations for the improvement of user experience and resource utilization efficiency, and to lower the operation cost.

Global Policy Real-Time Optimization

Network policies are sets of conditions, constraints, and settings that allow the network system to approach its optimal operating status. While the fog network conceptually extends the cloud network and leverages its underlying technologies, it spans broader geographic locations than a cloud network, and in a denser manner. Furthermore, fog devices are much more heterogeneous in nature, ranging from end-user devices and access points, to edge routers and switches. To accommodate the heterogeneity of cloud and fog networks, it is urgently essential to derive the corresponding policies between cloud and fog networks to support global network workload mobility and optimize different aspects of service mobility.

The cloud is commonly used to describe the diverse suites of hardware consisting of edge routers, switches, application delivery controllers, and servers, as well as the server-based applications, databases, and services that are hosted in the data center. Similarly, The fog is now being used to describe the edge of a network system. The proposed parallel network system aims to investigate the advantages of cloud and fog networks as shown in Fig. 5. Specifically, innovation in computing and storage offerings for data-intensive services is the interplay between cloud and fog networks. The fog platform supports real-time actionable analytics, processes and filters the data, and pushes to the cloud data that is global in geographical scope and time. By the interactions between actual and artificial network systems, a parallel network could provide methodologies, models, and algorithms to optimize the cost and performance through workload mobility between fog and cloud networks. Meanwhile, the feedback information and data from the global network would also help to adjust and optimize the artificial network system to further approach and effectively predict the behaviors of the actual network.

Local Action Real-Time Guidance

For a local or small network system as shown in Fig. 6, detailed network action guidance is expected from the proposed parallel network system. In the traditional data-centric network, services are provided by specific physical devices such as routers, switches, and firewalls. Each of these physical boxes is expensive and complex. Similar to server virtualization, a parallel network offers the capability of consolidating multiple network devices into a single physical piece of hardware. Thus, the network system simply moves from multiple dedicated physical devices to very few powerful servers and is constructed and operated in software; that is, network softwarization.

Traditionally, the control plane of networking has been proprietary, resulting in data-centric environments that are unable to respond effectively to the dynamically changing needs of today's network loads. By enabling network control via software, the parallel network gives users the ability to configure and reconfigure their networks to match the changing requirements of their workloads, without compromising user isolation and performance. The most remarkable characteristic of parallel networks for actual local networks is to achieve real-time guidance for network actions, such as route scheduling, power allocation, channel allocation, access control, and workload control. Meanwhile, similar to what is shown above, the artificial network system could obtain real-time adjustment and amendment based on the collected network information from the actual local network.

Concluding Remarks

In this article, we propose the fundamental framework of a parallel network based on the concept of ACP. The parallel network is expected to be a new generation of network system by means of "artificial network reflection based on big data," "computational experiments to carry out/predict the future," and "parallel execution to implement/create future network architecture." Unlike traditional process control and management systems, a parallel network system includes social and behavioral dimensions of operators and managers when evaluating the reliability and efficiency of production and safety regulations. Although a parallel network system still has a long way to go from theoretical concepts to practical implementation, we believe that the processing and analysis of a parallel network will become the foundation of cognitive science network very soon.

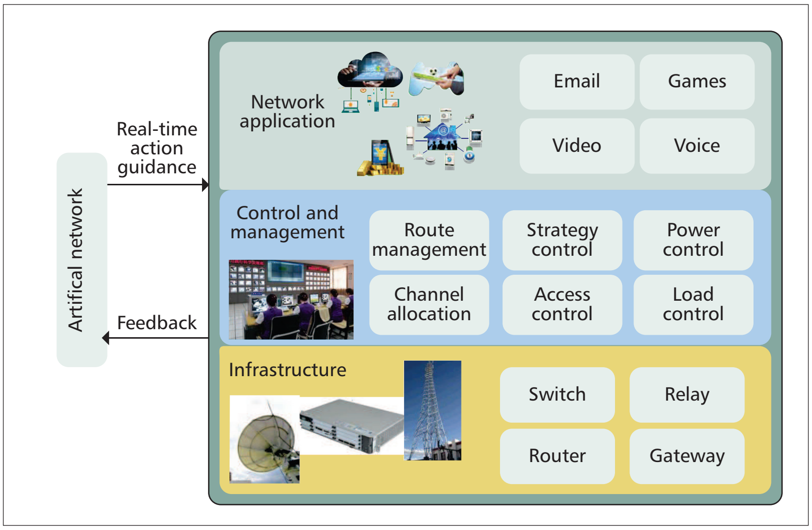

Figure 6. Real-time action guidance for local network systems.

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Biographies

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