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On the revolution of the information network development paradigm

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Abstract This paper summarizes the evolution logic, technical connotation, presupposition, applicable scope, and existing problems of information networks from the perspective of the development paradigm. This work aims to meet the requirements of symbiosis and coexistence, evolution and revolution, and integration of the function safety and network security of diversified networks and applications. Accordingly, we demonstrate the scientific necessity of the revolution of the information network development paradigm and propose the polymorphic network (PINet) paradigm that separates technical systems and the supporting environment. On this basis, we clarify the core idea, system form, and operation logic of the PINet paradigm and analyze the key technologies of the PINet paradigm in detail. Finally, we propose an engineering implementation scheme of the PINet paradigm, which explores possible methods and approaches to high-quality information networks at the development paradigm level.

Keywords information network development paradigm, separation of technical systems and supporting environment, polymorphic network (PINet)

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1 Introduction

The Structure of Scientific Revolutions, which was edited by Kuhn [1], an American philosopher of science, mentions that a paradigm is essentially a theoretical system and framework. Theories and laws in this framework are universal and serve as the coordinates to perform scientific research, establish scientific systems, and apply scientific ideas. Under the guidance of paradigms, pioneering scientists have made important achievements in various disciplines, reflecting the characteristics of different periods. In other words, paradigms are the world's outlooks and methodologies of the science and technology development stage and the methods of putting forward and solving problems.

The network development paradigm is the theoretical basis and practical standard of network technology innovation development. Hence, the application of the paradigm theory to the information network field is of great research value. However, thus far, the science and technology community and industry have not yet made an in-depth discussion on whether there is a paradigm in the development of network technology. Based on the scientific definition of a "paradigm", we attempt to summarize the thinking perspectives and methodologies in the development of an information network and point out three paradigms in the development history of network technology systems [2].

Paradigm I: services and network tightly bundled paradigm. The objective of this paradigm is to establish a private network for a certain type of business and provide professional and large-scale public services. Its methodology is based on the tight coupling between network and business and uses statistical multiplexing and network topology as the most important theoretical basis in the initial stage of network development. Its main deployment forms are representative scenarios, such as telephone networks [3] and radio and television networks [4]. If a new business needs to be built, building a private network with corresponding coverage is necessary.

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Paradigm II: integrated service digital network paradigm. The research focus of this paradigm is to establish an economical, efficient, and digital integrated service network for voice, data file, fax, real-time video, image data, and other services. The methodology is to divide all kinds of services into different categories and design a suitable network frame structure to achieve full coverage of a given business type according to the characteristics of the business between the source and the sink, such as whether there is a timing relationship, whether the rate is constant, and whether it is connection-oriented or connectionless. The most representative is the asynchronous transfer mode (ATM; also known as ATM network) [5].

Paradigm III: service and network separation paradigm. The objective of this paradigm is to provide multiservice convergence using the same network infrastructure. The methodology is to take an intelligent digital terminal as the object and adopt transmission control protocol/Internet protocol (TCP/IP) stacks [6] based on packet switching and best-effort forwarding to provide multimedia services based on the quality of experience (QoE), instead of guaranteeing a complex quality of service (QoS). A typical example of this methodology is our current Internet architecture. Owing to the ubiquitous application of computer technology, this paradigm enables the same network infrastructure to provide multi-business integration services by implementing virtualization technology. This technology realizes the relative separation between business function innovation and network architecture.

However, information networks have gradually become an important infrastructure closely related to national development and people's lives. New businesses have been emerging, such as mass content acquisition, high-definition video live broadcasting, and low-delay remote control. Under the guidance of the third paradigm, existing information networks are based on variable-length packet switching, best-effort transmission, shortest-path addressing, and TCP/IP protocols. The network function is single and rigid, the evolutionary repair of the network system makes the system engineering complexity out of control, and the generalized security crisis is highlighted [7]. As a result, the current information network faces many difficulties in responding to the needs of flexibility/scalability, differentiated/customized services, mobility support, global operation and maintenance management, and security and credibility from diversified applications, such as human-machine-things large-scale intelligent networking, all-time and space-time access, deterministic service performance, security performance quantifiable design and verification metrics, and network big data or distributed network computing [8].

With the advent of the era of human-machine-thing intelligent connection and in response to this era's requirements of symbiosis and coexistence, evolution and revolution, and function safety and network security of diversified networks and applications, we must innovate the development paradigm of information networks. Hence, to solve the defects of the existing Internet, such as the rigidity structure, single IP bearer, and difficulty in suppressing unknown threats, we plan to improve the functions, performance, efficiency, and security of networks from the perspective of network structure and explore a new network development paradigm in which the network technical system is separated from the supporting environment—the polymorphic network (PINet). The PINet can allow various network technical systems to dynamically load/unload or run on unified physical network element facilities in the form of network modalities. This characteristic can realize the coexistence and evolution development of multiple network technical systems in the same network environment, break through the current rigidity network architecture, greatly release the innovative vitality of the network technology system driven by emerging applications, and significantly lower the threshold for the application deployment and service provision of new networks.

The rest of this paper is organized as follows: Section 2 gives the overview of the PINet development paradigm. Section 3 describes the key technologies in the PINet. Section 4 gives the engineering implementation of the PINet development paradigm. Finally, Section 5 draws our conclusion.

2 Overview of the polymorphic network development paradigm

2.1 Separation of the technical system and supporting environment

Just as nature needs diversified species to complement and restrict one another to form a harmonious coexistence development pattern, diversified businesses need diversified network technology support. To solve the technical dilemma of the current development paradigm of the separation of a network and service, it is necessary to break through the single network bearing structure adopted by the existing paradigm, innovate the development paradigm of information network, and form a diversified network

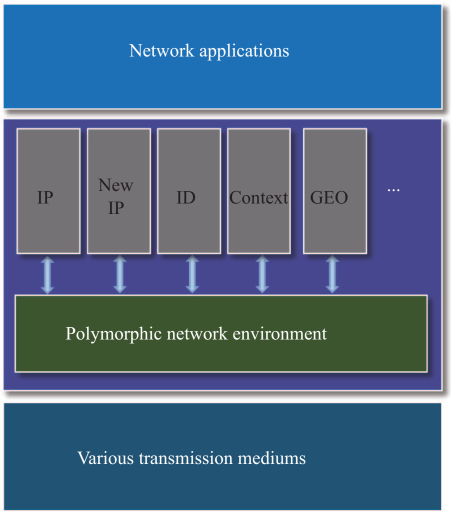

Figure 1 (Color online) Separation of technical system and supporting environment.

technical system closely related to business needs, and rely on diversified computing, storage, interconnection, transmission, and other resources to build a basic network infrastructure environment to support the coexistence and development of these diversified network technical systems.

This paper puts forward the development paradigm of separate network technical systems from the supporting environment, which dynamically loads and runs various existing or future network technical systems (e.g., business or service or management functions) in the filed definable network support environment [9, 10]. In this paradigm, different network modalities can run custom packet format, routing protocol, switching method, forwarding logic, service characteristics, operation and maintenance specifications, and security policies defined by the modalities so as to realize the symbiosis and independent evolution of multiple network modalities in the same technical physical environment (see Figure 1).

Based on the concept of multimodality in biology, this paper considers various network technical systems modalities, including a known telephone network, telegraph network, television network, satellite network, information network, mobile network, Internet of Things, integrated network of heaven and earth, and other emerging networks that may appear in the future [11]. Each network modality has its own technical architecture, protocol system, and scope of application, as well as its dependent network environment and corresponding user/management services or business functions, including corresponding service commitment or security and quality assurance [12].

We summarize the idea on the separation of network technical systems and the supporting environment and define it as the PINet development paradigm (the fourth paradigm). The core of this paradigm is to realize the separation of network technical systems and the supporting environment. Various network technical systems are dynamically loaded and run on the same physical network platform. Each network modality can run a custom message format, routing protocol, and switching method and support diverse forwarding logic. The PINet is mainly oriented to the diversified service requirements in the future and realizes the coexistence and evolution development of multiple modalities on the same physical network platform, providing a sufficient innovation space for network technical systems and network performance development.

The fourth paradigm is a methodology that aims to break the traditional network development paradigm—either the current rigid network architecture that can only adapt to the evolution or a new rigid architecture to perform the regime revolution. In fact, no single network technology architecture will always meet all current or future business needs. Although functional virtualization can realize almost all network functions in theory, the performance is far from the economic and technical quality of the desired functions. On the contrary, the PINet provides the possibility to realize the best match between business applications and technical systems so as to significantly reduce the cost of network resources, improve the quality of services, and ensure the robustness of services.

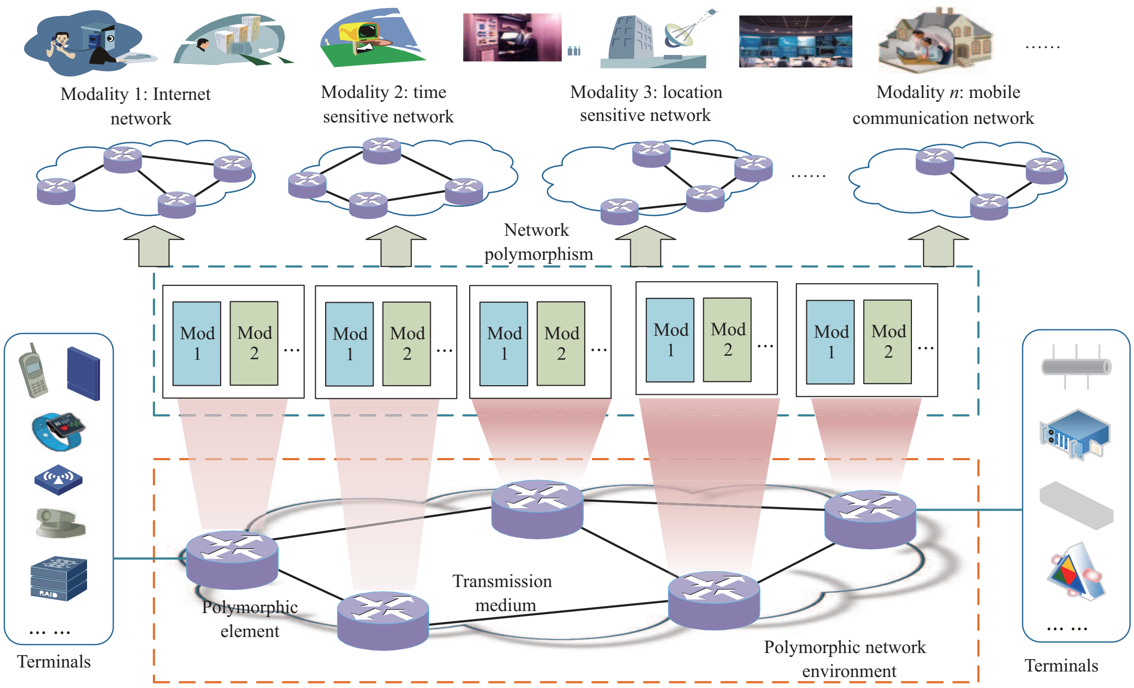

Figure 2 (Color online) The system form in PINet.

2.2 System form

The development paradigm of the PINet is not only limited to large-bandwidth network services from the beginning, but it also extends service scenarios to delay-sensitive networks, location-sensitive networks, and even power-sensitive networks [13], as shown in Figure 2. Its methodology is to use the technology of full-dimensional definability of network baseline resources to realize the symbiotic coexistence, evolution, and revolution development of multiple network modalities in the same basic physical environment. This basic physical environment can integrate diverse resources to form the basic capabilities required by various network modalities. We define this basic physical environment as the PINet environment (PINE), which is called the base of networks.

The PINet development paradigm can form special technical routes, such as routing/switching, connection, transport protocol, service attributes, management control, and security guarantee in this basic physical environment, and support the evolution or revolution development of industrial Internet and various types of existing or future networks, as well as the entire digital ecosystem. Hence, it realizes the revolution from a single network structure and service to the operation based on supporting multi-modal networks, which make the base of the network fundamentally meet the requirements of intelligent, diversified, secure, robust, and efficient services.

The scientific significance of a PINE lies in the discovery of chemical elements and their periodic table that can support various network baseline technologies. Accordingly, the compounds formed by these elements can support various network technical systems and related business functions and performance. On this basis, the development paradigm of the PINet adopts information fusion, cognitive computing, and collaborative computing and constructs the intelligent management and control loop of perceiving, decision-making, and adaptation through real-time sensing of services and resource status. Consequently, these functions realize an efficient adaptation of network modalities and upper-layer services.

2.3 Working logic

Guided by the goal of supporting the symbiosis and coexistence of diversified technical systems, the development paradigm of the PINet follows the design principles of the integration of underlying resources, symbiosis of multiple modalities, and customized service provision. As shown in Figure 3, we divide the network into the data layer, control layer, and service layer from the bottom to the top. These three layers implement hardware and software resource co-processing of storage, computing, and forwarding

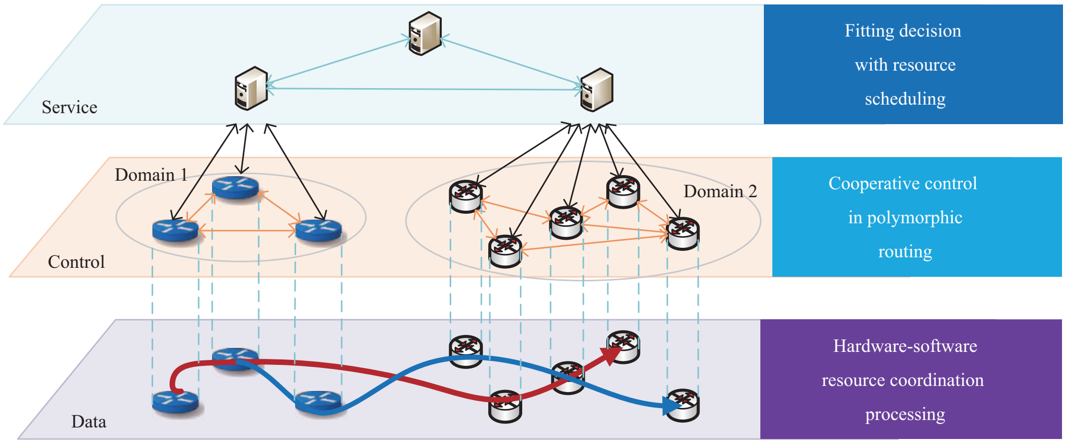

Figure 3 (Color online) Working logic in PINet.

integration, symbiosis and collaboration of network multimodal addressing, and network fitting decision of the service bearer and resource scheduling, respectively.

At the data layer, the PINet development paradigm implements the integrated collaborative processing of storage, computing, and forwarding and defines the network baseline in all dimensions with the help of a software definition hardware technology [14]. In this way, heterogeneous resources can flexibly organize and reconstruct network baseline capabilities on demand. That is, they can perform operations, such as table lookup forwarding, encryption and decryption, and packet caching, according to the processing logic defined by network modalities, and support resource allocation on demand for differentiated technical systems. Moreover, the data layer uniformly schedules, distinguishes, and combines resources under the coexistence of multiple network modalities, providing necessary and sufficient resource guarantees for each modality.

At the control layer, the PINet development paradigm implements the symbiosis and coordination of multimodal addressing routing. As a result, the message processing of each network modality can switch and cooperate with one another according to the actual demand, realizing the capability of providing differentiated network capability, omnidirectional space coverage, and omnidirectional scene coverage. The control layer unloads the same processing logic required by each modality protocol stack in different scenarios to the dedicated hardware forwarding module and realizes the other processing logic that varies with the scenarios through the customization of software switch instances. These functions fully embody the ideas of multi-domain collaboration and co-governance. In addition, the built-in resource configuration module dynamically coordinates the bottom processing resources, intelligently splits the business flow table of each independent modality, and uniformly implements the control of the upper business [15].

At the service layer, the PINet development paradigm implements network fitting decisions for service bearing and resource scheduling and realizes the adaptive bearing of network operation and function scheduling based on the fitting between service requirements and network service capabilities. In this process, the service layer first abstracts the user's network business requirements, plans user-initiated services in detail according to the basic service parameters and benefit expectations [16], allocates network traffic to the most appropriate network modality depending on the fitting relationship between businesses and services, and adopts dynamic service arrangement and adaptive service bearing mechanisms to form its intelligent network service strategy.

2.4 History of development paradigm

The following is an analysis and summary of the PINet and existing development paradigms in the Figure 4.

The first paradigm takes the telegraph network and telephone network as representative scenarios. Terminals are mainly non-intelligent analog devices in the early stage, and the control system generally uses hard-wired logic. By contrast, the latter is mostly controlled by stored programs. This paradigm uses simple network baseline technologies, such as addressing based on telephone/telegram numbers, common-channel or channel-associated signaling, and circuit or packet (space division or time slot or mixed) switching modes. The relevant theoretical system includes a network system based on the statistical

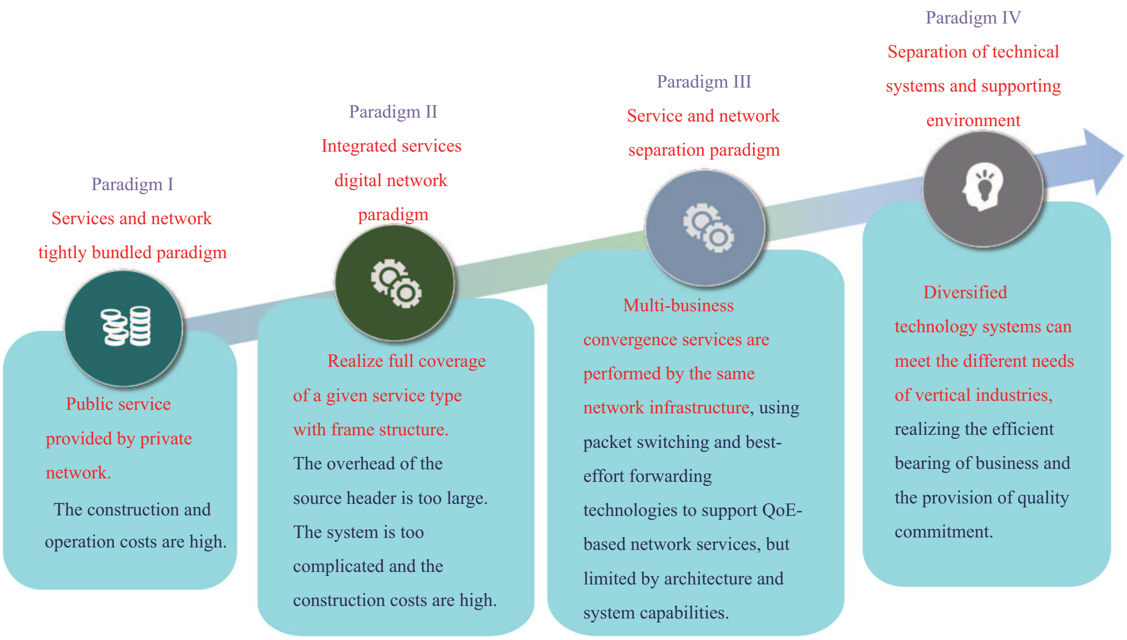

Figure 4 (Color online) Comparative analysis of information network development paradigms.

reuse theory and the evaluation criteria of quantifiable design and verifiable measurement. Accordingly, the service provides service level agreement (SLA) and QoS, and the service security and circuit utilization are high. However, the network paradigm exposed many defects-poor network scalability, weak network robustness, low efficiency in the use of transmission bandwidth, complex business management, and maintenance scheduling. Moreover, new services often require expensive private networks.

The second paradigm still insists on the idea of a tight coupling between networks and businesses and proposes the asynchronous transfer mode (ATM) architecture. In this network, a fixed-length (48/53 bytes) cell is used as the basic switching unit, and services are divided into multimedia service forms with/without QoS constraint supported by a fixed-length packet switching mode. The full coverage of given service types is realized through a specially designed frame structure. The ATM establishes an integrated comprehensive network for voice, data, fax, real-time video, image data, and other major transmission services to reduce the cost of network construction, business development, and operation management. This is the main difference between the second and first paradigms in terms of methodology. However, the design standard of a special switching system is too complicated, which brings the disadvantages of high construction cost and low operation management efficiency. The development dilemma of the second paradigm is that the scalability of networks and services is greatly constrained when the demand grows beyond the given four business categories.

The third paradigm realizes the separation of network and services. Under the premise of the ubiquitous application of computer technology, the same network infrastructure provides multi-business integration services with virtualization technology, and business function innovation is relatively separated from the network architecture. Undoubtedly, the most representative achievement under the guidance of this paradigm is the computer communication network of the TCP/IP system. The computer network supports the multimedia form service based on the QoE through indefinite packet switching and best-effort forwarding. The network only undertakes the abstract message forwarding function, which fully embodies the design principle of simple network, intelligent terminal. The workflow of TCP/IP protocol stacks also draws lessons from the design experience of computer software architecture. That is, different functional modules are organized in a strict hierarchical structure from top to bottom, and protocols at each level achieve downward compatibility and invocation through encapsulated interfaces. The IP layer provides the communication address identification function, and almost all network traffic converges to this thin waist, realizing the unified bearing of multiple services based on virtualization technology.

The fourth paradigm is based on the separation of technical systems and supporting environment. This paradigm breaks through the dualistic dilemma of evolving on a single system or replacing another system with one system, and creates a system that can allow a variety of network technologies and related businesses to coexist, evolve and transform in an inclusive manner, which transforms the development of the information network from the search for a better single network system to the creation of polymorphic development of the ecological track. The PINet supports dynamic load and operation of the required network technical systems in the form of network modalities, and implements network system logic according to the baseline technologies such as software and hardware configuration, packet format, routing protocol, forwarding logic, service characteristics, and management mode. This fourth paradigm creates an integrated network supporting environment with symbiotic coexistence, dynamic concurrency, evolution and revolution integration through filed definable network baseline technology, which can not only guarantee the self-sustaining development of various services and network technical systems, but also realize the intelligent, efficient and secure integrated deployment and management of diversified networks, which has a filed definable technical physical environment and ecology independent of specific network architecture and related business.

3 Key technologies in the polymorphic network

As a demand-oriented diversified network paradigm, the PINet realizes the transformation from a single network structure to a service-based full-dimensional definable network structure. Hence, it fundamentally satisfies the network demands for intelligence, diversification, individuation, high security, high robustness, and high performance and supports the evolution or revolution development of the Internet and future networks. The core of the PINet is the coexistence and coordinated development of diverse network modalities in a full-dimensional definable network support environment. A network technology system is a modality and each network modality has its own technical architecture, protocol system, and scope of application. The network support environment supports the integrated collaborative processing of storage, computing, and forwarding resources and realizes the flexible organization and on-demand scheduling of heterogeneous resources by the filed definable network baseline (FDNB) technology. In a PINE, various APP-style network modalities coexist on a ground-style PINet platform and share heterogeneous network resources formed by the full-dimensional definable construction technology. Thus, they can achieve the coexistence development, independent evolutionary, and revolutionary development of multiple technological systems in the same network infrastructure.

3.1 Filed definable network baseline

As the diversity of the earth's ecosphere can be attributed to the combination of elements on the periodic table, the diversity of network technical systems can also be expressed by PINet baseline (PNB) technologies. As shown in Figure 5, the PNB involves the following: (1) IP identification [17], geographic location identification [18], content identification [19], and identity identification and other possible route or addressing methods; (2) circuit/packet, time/space division, fixed-length/indeterminate length, data block exchange, and other switching modes; (3) heterogeneous storage computing and forwarding collaborative resource scheduling; (4) common/along signaling or routing, content/semantics control mode; and (5) intelligent management and integration of function safety and network security.

The FDNB is the basis of the PINet development paradigm that realizes the separation of the technical system and supporting environment. On the one hand, it breaks the rigid implementation framework of traditional network baselines using software-defined hardware, standardized network function, and hot-plug interface. On the other hand, by establishing the network baseline function that can be defined and arranged flexibly, it realizes an open, flexible, and general architecture that can be defined in all dimensions for various network modality baseline services. The core of the FDNB is to construct reconfigurable and programmable underlying data processing logic, which can take advantage of the development of microelectronics wafer/sub-wafer packaging technology and the super-scale resource reconfigurable system effect of the software-defined hardware technology [20]. It will sink the definition of the network function to the control layer, data layer, and even physical layer and realize the definition of software/hardware, protocol, interface, chip, and other aspects of the base network of the open architecture. That is, the field definable functional platform supports the dynamic loading and evolution of all modalities and the reliable isolation between network modalities. The flexible organization of the base network provides platform support for the reliable operation of PINet technical systems by redefining network baseline elements and automatically arranging services to flexibly adapt to the constantly developing needs.

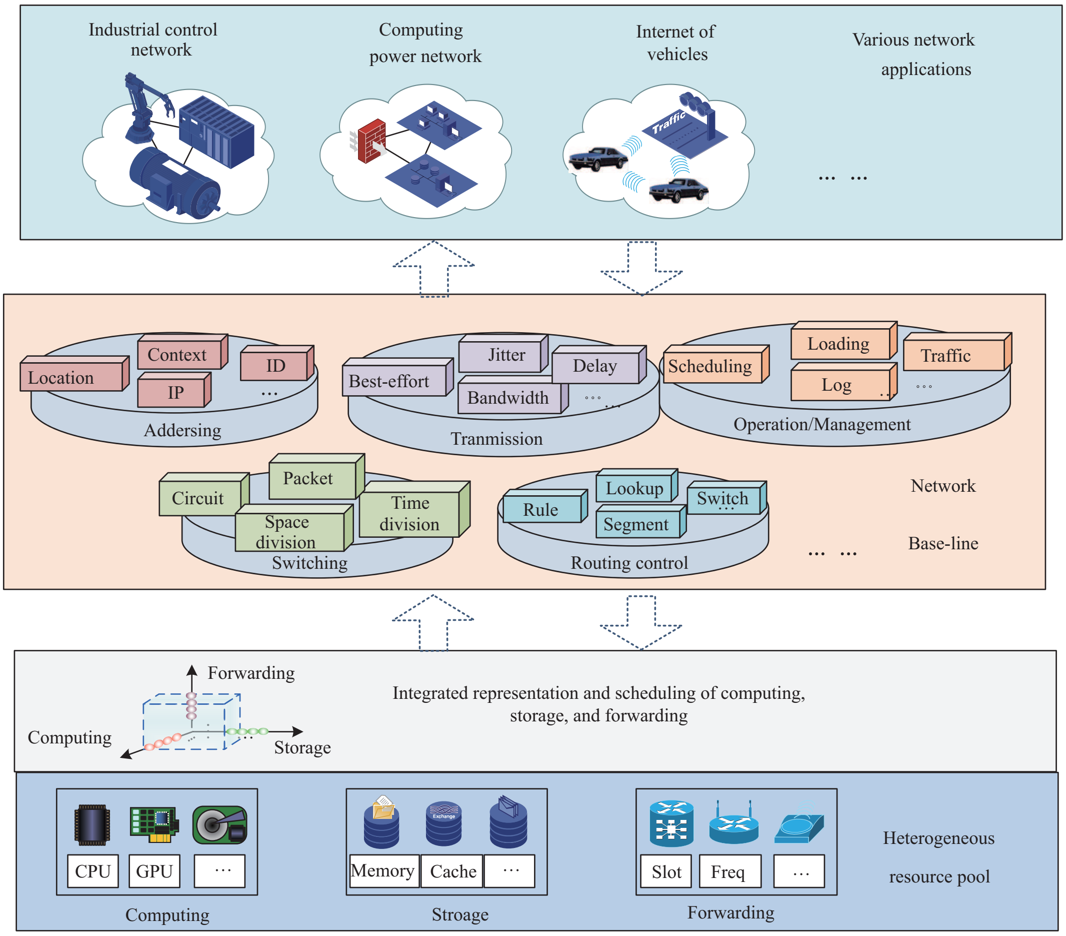

Figure 5 (Color online) Filed definable network technical systems.

Through standardized plug-and-play interfaces, the FDNB technology can build physical network element facilities that support the symbiotic operation of multiple network modalities and provide hardware and software support at the technical implementation level for addressing methods, message formats, routing protocols, signaling methods, computing/storing/forwarding mechanisms, switching methods, scheduling strategies, security mechanisms, service quality, and maintenance management, defined by multiple network modalities. It provides intelligent dynamic allocation, management, and guarantee of hardware and software resources in the network environment and supports the independent deployment and operation of multiple network modalities and related applications on the facilities.

3.2 Integrated complier for heterogeneous storage computing and forwarding resources

One of the core features of the development paradigm of PINet is the separation of network technical systems (i.e., applications) from the physical environment (i.e., platform). At this point, diversified network applications compile heterogeneous and differentiated software and hardware resources at the bottom through open and standard interfaces and construct various network technical systems on a unified physical platform environment. To support various network modalities, the base contains heterogeneous resources, including computing, storage, and forwarding resources. These resources are packaged in different styles to be provided to the upper layer. Some are various hardware configuration interfaces, whereas some are software implementation application programming interfaces (APIs), such as P4 [21]. When deploying various modalities, users can write their own modality programs, which can be compiled by the compiler for the configuration of various hardware and software resources to support the realization of the modalities.

Therefore, the integrated compilation system for storage, computing, and forwarding resources is the entrance and foundation of the realization of the PINet development paradigm. The combination of the open programmable hardware structure and the compilation environment of software and hardware

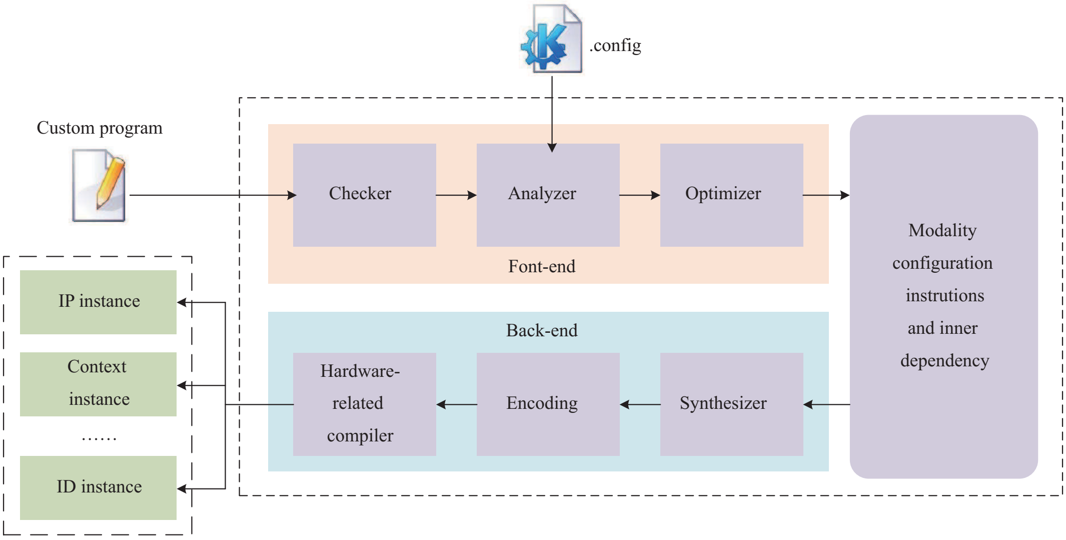

Figure 6 (Color online) Integrated compilation for heterogeneous resources.

collaboration can realize flexible and definable data plane processing functions, fully release the maximum potential of software and hardware collaboration, and then meet the requirements of different business capabilities in different scenarios.

As shown in Figure 6, the PINet compiler exists in the form of a composite development suite with a complete set of workflows to assist network administrators in efficiently defining and configuring network environments. From the perspective of the programming input, the PINet compiler provides rich semantics to flexibly meet the network functions required by the upper layer. With the pre-parser checking the programming language, the current network topology information and corresponding resource configuration are also inputted to the analysis module and optimization module of the front-end compiler. The compiler generates modality configuration instructions and functional dependency constraints by considering the functional arrangement of each network modality and the constraints of storage and forwarding resources of the underlying computing through the built-in optimization algorithm. Then, the back-end compiler receives context-aware modality configuration instructions and generates and loads configuration files for forwarding devices of different principles and forms. Finally, the PINet compiler implements a complete mapping of custom network flow processing logic to multiple underlying execution units.

3.3 Diversified identification access and modality coexistence

Under the development paradigm of the PINet, the information network integrates and abstracts various and changeable network service capabilities in practical applications and establishes polymorphic identification space, including IP identification, content identification, identity identification, and geospatial identification. Moreover, it supports the mixed access and intelligent collaboration of the above-mentioned heterogeneous identifiers. At the same time, the PINE can flexibly bear the application requirements according to the service characteristics of different routes, which adopts matching-mapping and unified management mechanism of the identification space. Through the dynamic perception of user and service requirements, it can select intelligently and schedule collaboratively heterogeneous network resources to realize the modality switching of the autonomous intelligent network identification space between upper-layer services. This functionality can meet the diversified service needs of users on demand, provide diversified network support efficiently, and simultaneously take into account the improvement and evolution of existing networks.

From the perspective of satisfying the business requirements, diversified identification access and modality coexistence are constructed based on the business characteristics requirements of diversified applications and the dynamic behavior of networks, which keeps the mechanism with multiple carrying capacities and can present polymorphic characteristics, such as function, security, and service quality support diversification. For a group of flows with the same requirements, the PINE carries them by providing specific routing patterns that meet their capability requirements. In this way, the entire network infrastructure can realize the coexistence of multiple modalities for different types of business flows. After the service path of each modality is established, its delivery capability continues to be monitored by a cognitive function. If the application requirements cannot be met or the constraints of the route adjustment are met, then a new round of service path calculation is performed.

In the above process, the PINE uses unified management and invocation interfaces to abstract the identification space into a network resource, respectively construct the operation logic corresponding to the network modalities, and clarify the similarity of the support of different services by each identification space. Based on the supporting capacity of modality space for network services, the modality space is stratified and classified, and diversified identification access and modality coexistence are performed according to the matching and mapping rules among modality spaces. In the process, according to the commonality of each identification space and the implied progressive relationship between identification categories, the network to high-level identification (e.g., content identification) can be replaced by a linear combination of low-level identification (e.g., domain identification, host identification). As a result, the compatibility and scalability of the network are improved. At the same time, it can intelligently and cooperatively schedule a variety of heterogeneous identification space and its network resources to meet the diversified service needs of users on demand and efficiently by implementing the arbitrary selection of an identification space through the matching and mapping of each identification space or the identification hybrid mechanism through the linearly combined part of the identification space.

3.4 Endogenous security construction

Due to the rapid expansion of network scale and the huge complexity of various network elements, the network is often subjected to various unknown threats or disturbances, such as link/node failure and system backdoor/vulnerability, resulting in performance degradation or even function loss. Security attributes must be embedded in the PINE, which can not only suppress random disturbances, such as node or link failures, but also prevent the influence of deliberate disturbances, such as system backdoors and vulnerabilities, to solve the problem of base functions and network security in an integrated manner [22].

The endogenous security construction of PINE is derived from the mimicry construction technology inspired by the biological world. By introducing a dynamic heterogeneous redundancy structure into the network, the unknown-unknown security threat is transformed into the known-unknown reliability event, and the negative feedback mechanism based on the iterative decision is adopted to deal with the uncertain failure disturbance in the system. Based on the idea of dynamic heterogeneous redundancy and negative feedback control, in this work, an endogenous security construction scheme of the PINet element (PNE) is designed. Multimodal ruling and the multidimensional dynamic reconstruction negative feedback control mechanism are implemented on the pipeline structure of the PNE. This method enables the corresponding functional equivalent of data processing to represent great uncertainties and enables the defense scene of the target object to have convergent dynamics, randomness, and diversification. At the same time, the collaborative approaches among heterogeneous pipelines are strictly isolated. In turn, this action can maximize the suppression effect of the polymorphic decision on the dark function in the non-cooperative mode of the dynamic heterogeneous environment or the function of the point-to-surface combination defense independent of attacker information and characteristics and high tolerance of software and hardware differential-mode failure and random failure, as shown in Figure 7.

In the scheme presented above, the parser distributes input requests to multiple heterogeneous data processing pipelines with equivalent functions according to the negative feedback controller instructions. The heterogeneous pipeline set of functional equivalence provides a reconfigurable heterogeneous executor that can work normally and process input requests independently. It should also generate output vectors satisfying given semantics and syntax in large probabilities. According to the decision parameters or decision strategy generated by the algorithm, the polymorphic adjudicator determines the consistency of the polymorphic output vector content and forms the output response sequence. Once the inconsistency is found, the negative feedback controller is activated. After the negative feedback controller is activated, according to the control algorithm generated by the control parameters, the controller will decide whether to send the instruction to the input agent to replace/migrate the abnormal executor or instruct the abnormal executor to perform online/offline cleaning and recovery operations (including triggering other background processing functions) or perform combination operations, such as component-based reorganization, reconstruction, and reconfiguration under the condition of functional equivalence.

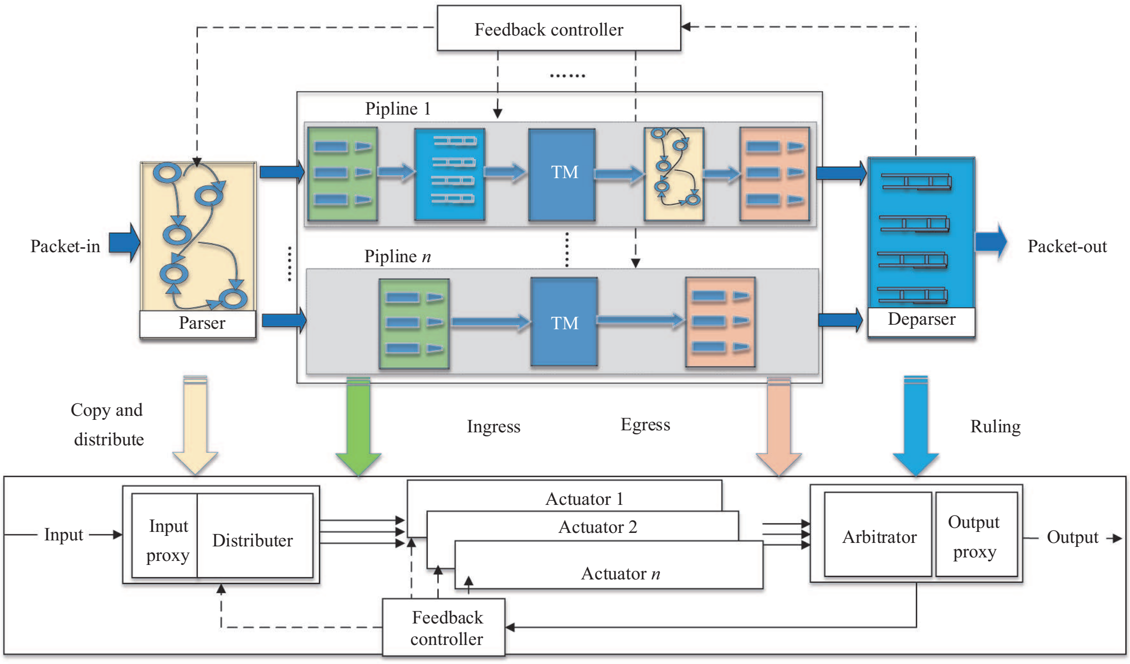

Figure 7 (Color online) An endogenous security construction scheme for network elements.

4 Engineering implementation of the polymorphic network development paradigm

4.1 Typical instance

The development paradigm of the PINet can be realized using different engineering implementation means in different historical periods, such as centralized/distributed control, wireless/wired communication, hierarchical network management system, and even cloud platform network.

Combined with the current engineering capability level of the industry, this paper presents an engineering implementation case of a PINet paradigm, as shown in Figure 8. The scheme is composed of a data layer, control layer, and modality layer. The data layer is made up of PNEs, which are used to construct network data paths supporting the symbiotic coexistence of various modalities and realize table lookup forwarding, calculation/storage, and other processing of various modalities. The control layer runs the modality control system. Through the network modality control interface, it performs modality configuration and operation control on the PNE equipment of the data layer, such as forwarding table configuration and modality message format configuration. The modality layer consists of various network modalities running in the form of applications or plug-ins, which perform corresponding functions, such as network identity assignment, routing protocol interaction, and forwarding table generation. Each modality is configured in the publish/subscribe messaging method through the network morph programming interface.

This solution designs a unified management interface that can sense and analyze multiple application requirements to obtain and analyze application requirements. Then, combined with the principle and operation mode of each network modality, the corresponding network modality work logic is constructed, as shown in Figure 9. Therefore, the project implementation adopts the control and data separation structure, in which the control functions of each modality, such as route calculation and identification management, are run on the modality control system. It can perform data parsing, identity mapping, intelligent decision-making, identity switching, and other related operations and realize resource registration, demand awareness, service modality awareness, and other functions of different network modalities by calling the management and control interfaces provided by various modality applications. The function of modality data processing and forwarding is completed by PNEs. The PINE of storage, calculation, and forwarding is built through the interconnection among network elements. At this time, the modality control system achieves platform management, horizontal expansion, distributed storage, and other functions and provides the upper application a unified call way through different levels of abstraction.

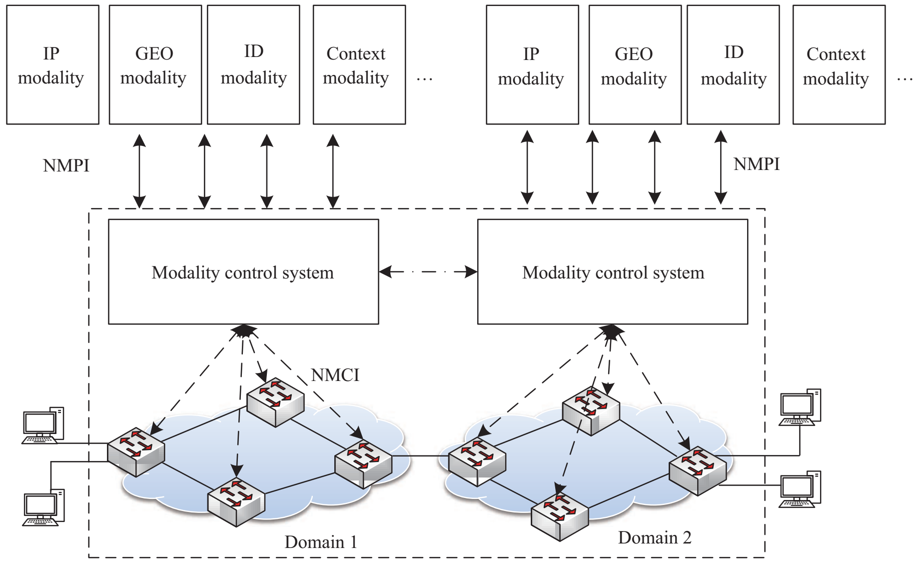

Figure 8 (Color online) A typical implementation for PINet.

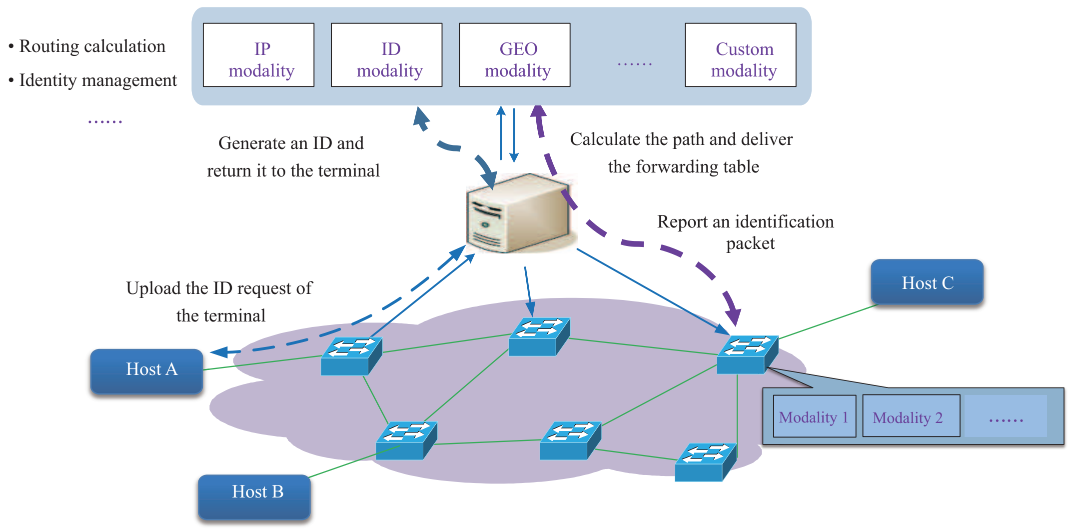

Figure 9 (Color online) Modality processing mechanism.

Moreover, it realizes the corresponding network modalities and various modality applications by adopting the integrated compilation technology of heterogeneous resources.

Each modality identification management is still completed by the modality itself, and the identity management function should be deployed in the modality system, mainly including the identity registration system, identity mapping system, and identity authentication system. The identification registration system dynamically allocates all kinds of identifiers to hosts and adds fingerprint information to identifiers using the password mechanism. The identity mapping system establishes the mapping relationship between different identities of the same host. The identity authentication system authenticates hosts and assigns secret keys to the identity registration system.

4.2 Networking test and verification

At present, National Key R&D Project of China—PolymorphIc Intelligent Network Core Technology and Principle Platform has completed the network test, in which the network architecture consists of one backbone network and six access domains. The backbone network consists of four nodes with a link bandwidth of 100 Gbps. Each access domain is composed of network elements/controllers and various fixed/mobile terminals. The test network topology is shown in Figure 10.

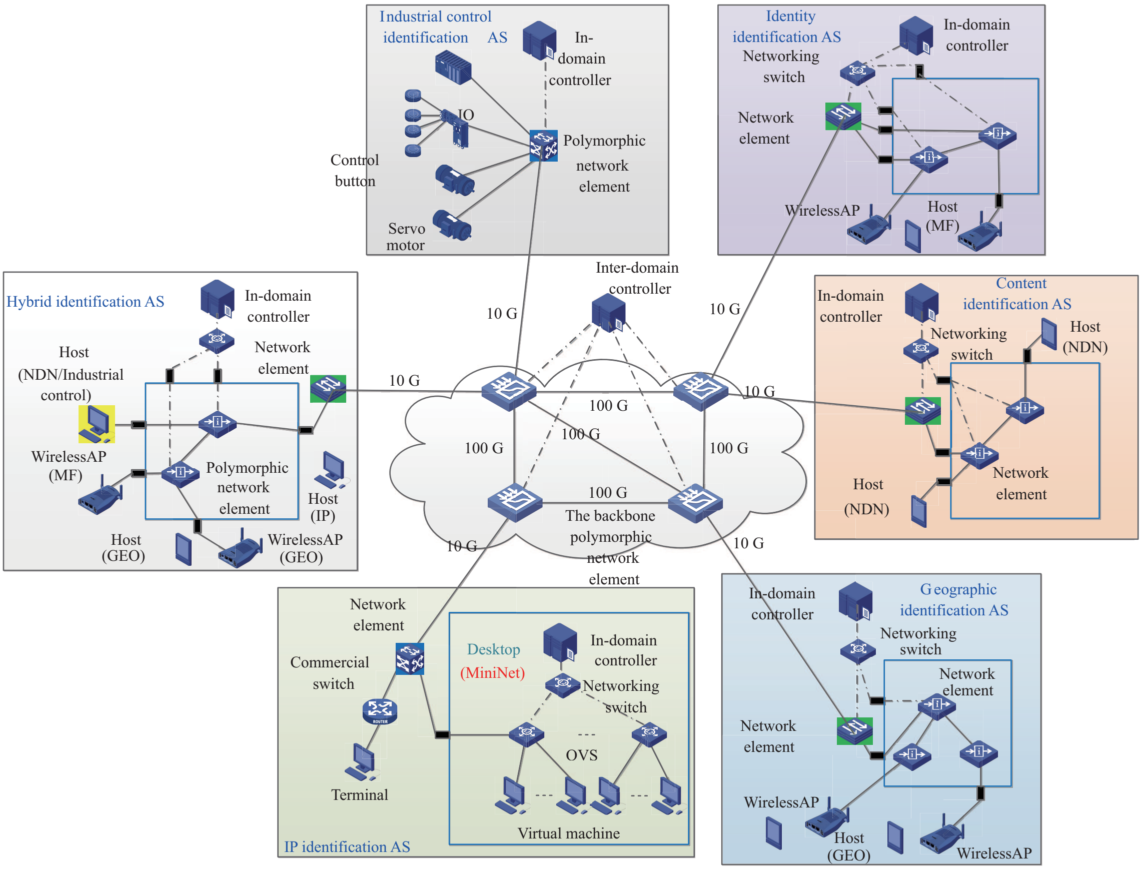

Figure 10 (Color online) Experimental topology with the platform of PINet.

The platform supports the definition and addition of network modalities using software programming and realizes the flexible expansion and dynamic management of network modalities through loading, running, and unloading on demand. It also supports the coexistence and symbiosis of the network modalities of different technical systems and realizes the common network bearing and operation of five different network modalities, including geographic identification network modality, content identification network modality, identity identification network modality, industrial control identification network modality, and IP identification network modality. It dynamically configures the processing logic of the network data plane and control plane using software programming and supports the flexible parsing of new network protocols, programmable routing and forwarding, and network caching. This parsing has the functions of device connection and network topology discovery and statistics and analysis of the traffic classification of backbone networks according to different modalities.

In terms of modality development and application, the platform has completed the following typical experiments.

(1) Realized the direct addressing and routing of packets based on location information and carried out a precise push and information acquisition of packets within the specified area.

(2) Implemented addressing and routing of packets based on file name directly; supported network retrieval of content files, network connectivity test, message transfer, network file transfer, and other functions; and supported pushing content files to the edge network where users live through customized messages according to user interest requests.

(3) Realized addressing and routing of message based on identity identification; provided the dynamic access of mobile terminals; maintained the connection state of end-to-end data transmission before and after the terminal mobile switch access network; and supported message transmission and file continuation under the dynamic access of mobile terminals.

(4) Realized addressing and forwarding of messages based on industrial control equipment ID directly and supported programmable forwarding function based on Power Link, servo motor control inside the factory, and remote control outside the factory.

(5) Compatible with typical service functions, such as the interconnection between virtual and real networks and terminals, and web server access based on existing IP identifiers and realized IP autonomous domain web services and other applications.

5 Conclusion

This paper summarizes the evolution logic of information networks from the aspect of development paradigm and demonstrates the internal logic of the revolution of the information network development paradigm in the new era. We propose the PINet paradigm, which separates technical systems from the supporting environment and clarifies the core idea, system form, and operation logic of the development paradigm of the PINet. By summarizing four development paradigms of the information network, we analyze the core supporting technologies for realizing the PINet paradigm in detail and demonstrate its engineering implementation. The PINet explores possible methods and approaches to solve the problem of the high-quality development of information networks and provides guidance for the development paradigm to cope with the symbiosis and coexistence of diversified networks and applications, and the co-development of function safety and network security at its level.

Guided by the PINet development paradigm, constructing a new generation of information and communication infrastructure, which separates network technical systems from the supporting environment, can greatly reduce the threshold of application and market deployment of innovation network technical systems. Moreover, it can make the jungle law of the survival of the fittest become the only criterion determining innovation network technical systems and market application ecology. Thus, it provides a new generation of information network infrastructure support for the development of digital societies.

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