IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received December 25, 2019, accepted January 13, 2020, date of publication January 24, 2020, date of current version February 6, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.2969208*

# A Survey on Intent-Driven Networks

**LEI PANG[1], CHUNGANG YANG[1], (Senior Member, IEEE), DANYANG CHEN[1], YANBO SONG[1], AND MOHSEN GUIZANI[2], (Fellow, IEEE)**
[1]State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an 710071 China
[2]Computer Engineering Department, University of Idaho, Moscow, ID, USA

Corresponding author: Chungang Yang (chgyang2010@163.com)

This work was supported in part by the National Science Foundation of China (61871454); by the open research fund of National Mobile Communications Research Laboratory, Southeast University (No. 2019D10); by the Fundamental Research Funds for the Central Universities (JB190119); by the China Electronics Technology Group Corporation (CETC) Key Laboratory of Data Link Technology (CLDL-20182308); by the National Science Foundation of China under Grants 61671062.

**ABSTRACT** Software defined network and network function visualization enhance the network flexibility and management agility, which increase network fragility and complexity. However, the vast majority of network parameters are manually configured, which makes the configuration failures still inevitable. Future networks should be self-configuring, self-managing, and self-optimizing. Intent-driven network (IDN) is a self-driving network that uses decoupling network control logic and closed-loop orchestration techniques to automate application intents. At present, a unified definition of IDN has not yet been presented, and the research background and current status of IDN are not clear. Considering the emerging applications and research of IDN, in this article, we survey existing technologies, clarify definitions, and summarize features for IDN. Specifically, we discuss the basic architecture and key technologies of IDN. In addition, diversity gains and challenges are analyzed briefly. Finally, some future work is highlighted and wider applications of IDN are provided for further research.

**INDEX TERMS** Future Internet architecture, intent-driven network, software defined network.

## I. INTRODUCTION

The network is becoming ubiquitous, shared, and intelligent with the rapid development of the wired, wireless, cloud-based networks, and the Internet of things (IoT). Meanwhile, companies are increasingly turning to digital business strategies to quickly respond to market developments. However, the self-organizing forwarding mode of conventional networks cannot accurately schedule routing, such as in data center networks, packet transport networks, and wide area networks. Virtualizing resources for easy pooling and calculation, as well as rapid configuration and release, is critical to the effective management of modern data centers.

Network function virtualization (NFV) is a networking paradigm, which abstracts network capabilities that allow software running on standardized computation nodes to install, control, and operate these functions for better flexibility and resiliency. The emergence of the software defined network (SDN) makes the network more flexible and efficient to generate network policies independently and dynamically [1]. SDN separates the data plane and control plane of the traditional network into two functional modules and uses a centralized controller to manage various networks. This programmable architecture makes it easier to drive network innovation and development. The joint use of SDN and NFV has become the main strategy for achieving low-cost and efficient operation of network construction. However, there are still some technical challenges, some of which are:

- High complexity and security issues: The high flexibility of the software often means the high complexity of the program. Under the SDN architecture, the system needs to maintain multiple logical networks simultaneously while applications share resources while their functions do not affect each other. The core controller of the SDN network may have security problems, such as overload, single point failure, and vulnerability to network attacks.
- Separation of service and network: The future networks not only support conventional communication services but also provide backward cooperation for a large number of emerging industries. The trend of service is gradually shifting from core applications based on existing technologies to new technologies and applications in the vertical industries. However, existing networks use a single network function to support multiple application

The associate editor coordinating the review of this manuscript and approving it for publication was Yue Zhang.

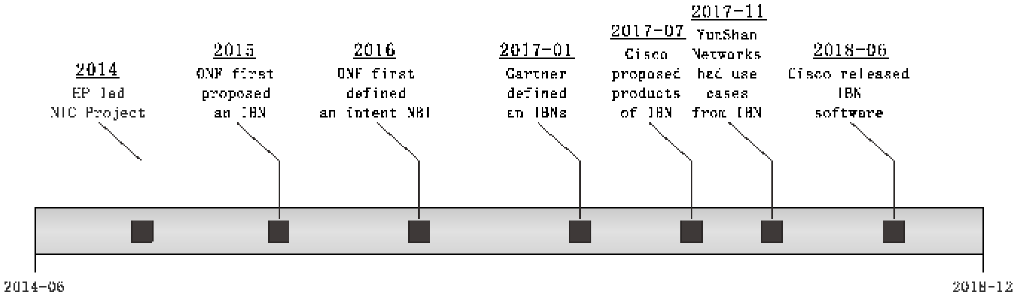


**FIGURE 1.** Roadmap of IDN development.

services, which is difficult to provide a customized network. The separation of application service and network cannot realize the timely network delivery, thereby deteriorating quality of service and quality of experience [2].

- Manual and error-prone network configuration: Commercial networking products are with over thousands of parameters, which are implemented using manual operations, including conflict and consistency analysis. However, configuration failures are still inevitable and the expense of configuring network precisely are high. Therefore, achieving self-management of network and automatic configuration are still quite challenging.

Driven by technology and demand, intent-driven networks (IDN) emerged and changed the network architecture and technology, which may affect the network development in the near future [3]. An IDN is an intelligent network, which can automatically convert, verify, deploy, configure, and optimize itself to achieve target network state according to the intent of the operators, and can automatically solve abnormal events to ensure the network reliability. IDN provides a full-life cycle management for network elements under the condition of collecting network status. Conventional networks rely on humans to input specific execution commands, different from which, driven by intent, humans do not have to directly input policy commands, just input the desired business intent, i.e., *I want the network to reach a certain situation* or *I hope to get a quality service*. Network administrators do not pay attention to the network details or implementation techniques, just express their requirements. IDN can automatically translate the intents and complete the subsequent operations. The network then verifies in real time whether the actual network status matches the network status expected by the business intent. The contributions of this article are as follows:

- To understand the background of IDN, we survey the current research status of IDN in different fields and clarify the definition of IDN.
- To make clear of the operating mechanism of IDN, we discuss key technologies and the basic architecture of IDN.
- To explore the application areas of IDN, some of its challenges and possible applications in the future.

The rest of the article is organized as follows. The origin and development of IDN are presented in Section II. In Section III, we discuss the concept of IDN and the key technologies. Meanwhile, diversity gains and challenges are analyzed briefly. The basic architecture of IDN is proposed in Section IV. In Section V, we highlight several future perspectives for further research. Finally, conclusions are drawn in Section VI.

## II. ORIGIN AND DEVELOPMENT OF IDN

The earliest mention of IDN can be traced back to February 2015. David Lenrow, the chairman of the open network foundation northbound interface working group, published a draft which states the basic idea of IDN [4]. Subsequently, Open Networking Foundation (ONF) released the white paper “Intent NBI-Definition and Principles” in October 2016, which is the first document describing intent-based northbound interfaces (NBIs). This document describes the Intent NBI paradigm, its utility and properties, and its essential implementation structure [5]. Meanwhile, communities and organizations are working on how to deepen IDN applications in terms of translation mechanism.

The important event time points for IDN are shown in Fig. 1. In 2016, some Silicon Valley startups have launched some IDN products and have received more than 10 million dollars of start-up funds. Gartner released a report in early 2017 which defined the intent-based networking system (IBNs) and predicted that IBNs is the next big thing in the networking arena. Similarly, in the middle of 2017, the major players in online communities had launched intent-based products and use cases, and introduced “Intuitive Network”, “Automated Driving Network”, and other derivative concepts. At present, researchers from standardization organizations, open source communities, industry, and academia are actively studying the mechanisms and applications of IDN.

### *A. STANDARDS DEVELOPING ORGANIZATIONS*

At present, the Internet Engineering Task Force (IETF) and European Telecommunications Standards Institute (ETSI) organizations have conducted research on IDN. ETSI ISG working group defines a system called Experiential Networked Intelligence (ENI), an innovative, policy-based, and

**TABLE 1.** Current states of the IETF working group in IDN.

| Object | Concept | Working Group | Document Status |
|---|---|---|---|
| ANIMA | Autonomic Control Plane (ACP) | IETF-ANIMA | Draft |
| ANIMA | Generic Autonomic Signaling Protocol (GRASP) | IETF-ANIMA | Draft |
| ANIMA | Reference Model for Autonomic Networking | IETF-ANIMA | Draft |
| ANIMA | Information Distribution in Autonomic Networking | IETF-ANIMA | Draft |
| ANIMA | Autonomic Slice Networking | IETF-ANIMA | Draft |
| ANIMA | Using an ACP for Stable Connectivity of Network OAM | IETF-ANIMA | RFC 8368 |
| Autonomic Networking | Definitions and Design Goals | IRTF-NMRG | RFC 7575 |
| Autonomic Networking | General Gap Analysis | IRTF-NMRG | RFC 7576 |
| Autonomic Networking | Use Case for Distributed Detection of SLA Violations | IRTF-NMRG | RFC 8316 |
| Autonomic Networking | Intelligent Reinforcement-learning-based Network Management | IRTF-NMRG | Draft |

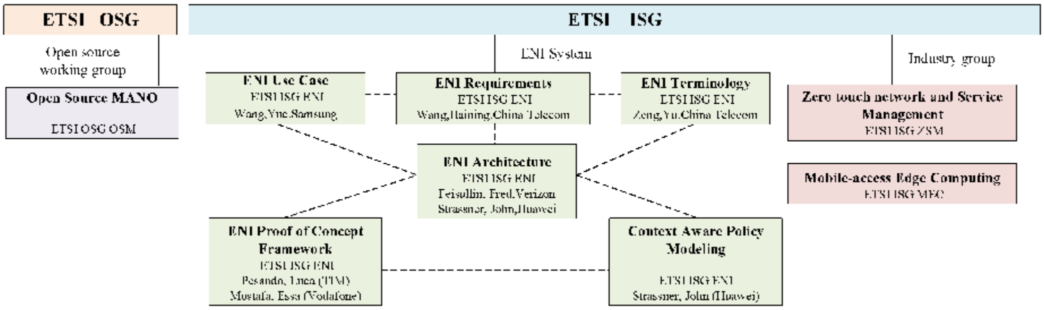


**FIGURE 2.** Different ETSI working groups on IDN.

**TABLE 2.** Current states of intent API in open source communities.

| Project | Intent Components | Characteristics |
|---|---|---|
| OpenStack | GBP for OpenStack | Specify relationships between different levels of applications, easy to extend |
| OpenStack | Congress | Describe service requests in a high-level common language |
| OpenDayLight | GBP for OpenDayLight | Apply the strategy to the lowest device |
| OpenDayLight | NIC | Generic abstract strategy syntax |
| OpenDayLight | NEMO | Visually describe the need for resources and operational logic |
| ONAP | OOF | Build various types of policy constraints |

model-driven functional entity [6]. ENI can understand the configuration and take actions according to context changes. In addition to the ENI system, ETSI also studies open source management and orchestration, focusing on edge computing for service management and mobile access to support ENI systems. Working on existing systems, the ENI system is not a completely independent system. Moreover, in order to avoid changing the existing systems, the interface between the ENI system and the existing system is consistent. As shown in Fig. 2, different ETSI working groups have different research directions of IDN.

IETF is working on automated network management and autonomic networking integrated model and approach (ANIMA), which aims to improve network management efficiency. A key to automated network management is the YANG data modeling language used to model configuration and state data manipulated by the Network Configuration Protocol (NETCONF) and RESTCONF that were developed within the IETF. At the same time, network operation, administration, and maintenance (OAM) have been further developed with the help of autonomic network research. Table 1 is a summary of the current status of the IETF working group in IDN. In addition to exploring the architecture and technology of the ENI system, ETSI is actively exploring zero touch network and service management.

### B. OPEN SOURCE COMMUNITIES

SDN is an implementation mode of IDN, or a typical architecture for implementing IDN; however, the implementation of IDN is not limited to this. At present, the open source communities has two research contents: the design of SDN controller driven by the intent engine and the intent NBI.

Considering performance, scalability, reliability, and manageability of SDN controllers with intent components, the relatively mature developments are Open Network Operating System (ONOS) and OpenDayLight. ONOS has a component called Intent Framework [7]. A network abstraction module of OpenDayLight is called Intent Component, which simplifies the interaction between the application and the controller. Intent Component abstracts the network object and element capabilities from the perspective of requirements [8].

Different from ODL and ONOS, OpenStack is an important application of SDN controller. As shown in Table 2, the components of OpenStack related to the NBI are

Neutron-based GBP [9] and Congress components. OpenDayLight hopes to provide an open NBI and use YANG data modeling language to model services and data. The purpose of Network Intent Composition (NIC) is to provide a generalized abstract strategy grammar that allows users to easily describe their intents [10]. Network Model (NEMO) is a new intent NBI language introduced by Huawei, which allows applications to use an intent-based policy to create a virtual network consisting of nodes with policy control flows [11].

As the latest open source project that invests on IDN, ONAP (Open Network Automation Platform) guarantees end-to-end business by providing global and large-scale orchestration capabilities between physical and virtual network devices. ONAP improves business agility by providing a common, open, interoperable northbound REST interface and supporting YANG (Yet Another Next Generation) and TOSCA (Topology Orchestration Specification for Cloud Applications) data models. ONAP provides general functions for building specific behaviors (e.g., data acquisition, closed-loop control, meta-data process creation, policy/ process distribution, etc.). Since November 2017, ONAP has released four versions, including the Amsterdam version, the Beijing version, the Casablanca version, and the Dublin version. In the Casablanca version, ONAP introduced new SDN business scenarios and platform capabilities. AT&T and France Electric will definitely use the Casablanca version for deployment testing [12].

At present, the above research pays more attention to the methodological design of intent translation instead of the full-life cycle management of network element. In addition, intent NBI simplifies the network management and new service establishment, which is an important research direction.

### C. INDUSTRIAL PRODUCTS

Several companies have developed the IDN and its products. The digital network architecture center developed by Cisco is an IDN management platform, which combined with Catalyst 9000 series campus switches to provide automation for campuses [13]. Apstra introduced an IDN operating system, AOS, to facilitate the closed-loop construction and operation in IDN [14]. Huawei announced its intent-driven smart network solution at the 2018 World Mobile Communications Conference, which used to build a predictable and self-healing system between users and applications. In addition, startups such as Anuta Networks, Forward Networks, and YunShan networks also worked to promote intent networks from the perspective of automatic network configuration, orchestration levels, and autopilot.

Although the products and directions of these companies are different, they are the same in three respects. First, their products are all oriented to the management side, which means that users can serve as network administrators. Second, their purpose is to liberate manual operations and make the network management more intelligent and convenient. Third, the main technologies include telemetry, artificial intelligence, and automated deployment. Additionally, it can be seen that IDN is required in the scenario of large-scale networks and high time-varying networks.

### D. ACADEMIC RESEARCH

The concept of IDN has recently attracted increasing attention from academia.

As a means of service description, the intent is to specify the network requirements abstractly and can be converted to advanced policies for network execution. The appearance of intent makes the northbound interface more accurate to describe the network requirements. The authors in [15] proposed novel intent-based modeling for abstracting network services, which specifies network requirements as network policies. Under a virtualized network, the intent is described as a tenant requirement specification at the management and configuration level [16]. The current research focuses on the northbound interface based on intent, enabling the service-oriented network architecture [17], [18], the operator core network [19], and the service function chain [20]. In particular, the authors in [21], [22] proposed the service description framework: iNDIRA, which constructs semantic graphs through natural language processing to understand, interact, and create the required network services.

As a new concept in the field of network automation, the use of IDN enhances the flexibility and stainability of network deployment. The authors in [23] designed reference models in communication network automation systems to support specific communication network service deployments. The intent in [24] is translated into a set of configurations that build the required service chain while meeting the specified QoS and security. An intent-based automation architecture was proposed in [25] to provide security services in multi-layer IP networks, Ethernet, and optical networks. From an industrial perspective, the architecture of the intent-driven automation network, components, and use cases were discussed in [26] while another architecture of IDN named OSDF was studied in [27]. An SDN resource management application consisting of an intent-driven framework: Chopin was proposed in [28] to enable automated resource management. As a concrete implementation on OpenFlow switches, p4 has been initially adopted as a data plane programming language for deploying end-to-end intent [29]. The user intents can be incorporated into the construction process of the automation networks. A resource negotiation scheme between the user and the network was proposed in [30] to provide an application-aware connection service.

There are already some technical studies on the various aspects of intent translation and deployment. The definitions and linkages of intents, strategies, and configurations in the network were proposed in [31]. The authors mainly study the intent translation mechanism under the issue of reactive configuration updates. The authors in [32] used Lumi to construct an intent refinement process that transforms natural language into network strategies. Other translation methods are also being adopted, such as primitive verb composition [33] and sequence-to-sequence learning model [34]. Also, the intent

**TABLE 3.** The state of the art of IDN in academia.

| Field | Object | Characteristics | Reference |
|---|---|---|---|
| Intent Northbound | Virtualized network interface | Abstract network service | [15] |
| Intent Northbound | Virtualized network interface | Characterizing tenant requirements specifications | [16] |
| Intent Northbound | Service oriented interface | Service-oriented network architecture | [17] |
| Intent Northbound | Service oriented interface | Service-oriented network architecture | [18] |
| Intent Northbound | Carrier service interface | Carrier-oriented network | [19] |
| Intent Northbound | Service orchestration interface | Network dynamic service chain | [20] |
| Intent Northbound | Service description framework | Intent representation based on semantic graph | [21] |
| Intent Northbound | Service description framework | Intent representation based on semantic graph | [22] |
| Intent Controller | Automated reference model | Communication network service deployment | [23] |
| Intent Controller | Service chain construction | QoS and safety requirements | [24] |
| Intent Controller | Automated network architecture | Cross-domain multi-layer network | [25] |
| Intent Controller | Intent components and use case | Industrial perspective | [26] |
| Intent Controller | Intent-based network architecture | Intent deployment process | [27] |
| Intent Controller | Intent management framework | Resource management application | [28] |
| Intent Controller | Data plane programming | End-to-end intent deployment | [29] |
| Intent Controller | Resource negotiation scheme | Guiding role of user intent | [30] |
| Intent Flow | Intent translation mechanism | Reactive configuration update | [31] |
| Intent Flow | Intent refinement | Lumi tools | [32] |
| Intent Flow | Intent refinement | Verb primitive composition | [33] |
| Intent Flow | Intent refinement | Sequence-to-sequence learning model | [34] |
| Intent Flow | Intent disambiguation | Logical consistency problem | [35] |
| Intent Flow | Group policy construction | Graph-based strategy representation | [36] |
| Intent Flow | Multi-domain intent decomposition | Graph-based intent representation | [37] |
| Intent Flow | Multi-intent compilation | Intent monitor and reroute service | [38] |
| Intent Applications | 5G | Northbound interface access control | [39] |
| Intent Applications | 5G | Backhaul interface | [40] |
| Intent Applications | 5G | Network slicing | [41] |
| Intent Applications | 5G | Dynamic service descriptor | [42] |
| Intent Applications | IoT | Cross-domain end-to-end service management | [43] |
| Intent Applications | IoT | Cross-domain end-to-end service management | [44] |
| Intent Applications | Cloud network | service deployment | [45] |
| Intent Applications | Cloud network | service abstraction | [46] |

solver was designed in [35] to handle the logical consistency problem of multiple intents. As an effective description method, graph-based policy description and multi-domain intent decomposition were adopted in [36], [37]. In particular, the intent monitor and reroute service (IMR) was used in [38] to extend the ONOS Intent Framework so that it can compile multiple intents simultaneously and deploy routes.

From the perspective of application fields, the exploration of IDN has involved in conventional wired/wireless networks, cloud networks, IoT, and the 5th generation mobile communication technology (5G). In 5G networks, intent-based northbound interfaces [39], backhaul interfaces [40], network slicing [41], and service orchestration [42] have become major research directions. In the field of IoT, the authors in [43], [44] designed an intent-based northbound interface to enable cross-domain end-to-end service management. In the cloud networks, the characterization, mapping, and configuration issues of intent are further discussed in [45], [46].

As shown in Table 3, the current approach to intent modeling presents a trend toward structuring, functionalization, and domain specificity. Intent deployment at the northbound interface presents a trend toward non-standardization, software defined, and componentization. In network automation, the deployment of IDN is often related to semantic understanding, data processing, rule mapping, policy generation, and closed-loop feedback. IDN has enabled the network and users to construct an information path. In the process of intent translation and deployment, there are challenges such as semantic refinement, ambiguity elimination, policy contradiction, and multi-domain distribution.

### *E. CURRENT STATUS OF IDN*

For subsections A, B, C, and D, the current status and necessary of this article are as follows.

- So far, a unified and clear definition of IDN has not yet been formed.
- The enabling techniques of IDN are still in the exploration stage.
- The basic components and core architecture of IDN are based on different development logic and present different functional characteristics.
- The industry has not yet explored and applied other areas for IDN.

## III. INTENT-DRIVEN NETWORKS

### *A. FORMAL DEFINITION OF IDN*

Intents are closely related to two other terms, namely, Policy and Configuration. Intents have the ability to express freely, with the highest level of abstraction, whether it is feasible or not. A policy is a rule that describes a feasible intent in a concrete way. The configuration is to extract the necessary information of the current network environment from the policy and create specific format update information on the physical or virtual network device [31]. Intents can be declarative or imperative. Therefore, the northbound interface language can be divided into imperative languages and declarative languages (including logical, interactive, functional languages, etc.).

Different research institutions and organizations have various definitions of IDN.

- **Gartner—IBNs:** Analyst Gartner released a report to define an IBNs in early 2017. A complete IBN provides four capabilities:
  - Translation and Validation
  - Automated Implementation
  - Awareness of Network State
  - Assurance and Dynamic Optimization [47]
- **Cisco—IBN:** IBN bridges the gap between business and IT. It captures business intent and continuously aligns the end-to-end network with that intent. Intent can apply to application service levels, security policies, compliance, operational processes, and other business needs. Intent-based networking captures and translates business intent so that it can be applied across the network. The network continuously monitors and adjusts to ensure alignment. That's achieved through a closed-loop system that includes Translation, Activation, and Assurance [48].
- **Huawei—IDN:** On February 26, 2018, at the 2018 World Mobile Congress, Huawei officially released its version of IDN. IDN is a network that can run itself based on the intent of a business strategy. The core of the IDN digital world is the Network Cloud Engine (NCE). The NCE consists of four engines of intent, automation, analysis, and intelligence. IDN can actively identify user intent and realize end-to-end automatic configuration of the network [49].

The descriptions of the above mentioned networks with business intents are different; however they all construct an information channel between the control model and the actual environment, to accurately control the output of the network system. In this process, intent has become a bridge between the network data and the application services. In this perspective, IBN is no difference from IDN. In this article, we describe these definitions as IDN. The formal definitions of Intent and IDN are as follows.

*Definition 1:* Intent is a declarative way of describing the state of the system. It abstracts the objects and capabilities of the network from the perspective of requirements and can be translated into an advanced policy.

*Definition 2:* IDN can automatically convert, verify, deploy, configure, and optimize by itself to achieve target network state according to the intent of the operators, and can automatically solve abnormal events to ensure the network reliability. IDN can be a programmable and customizable automation network, which can realize representation of application intent, global awareness of network status, and closed-loop optimization. Details are given as follows.

- Representation of application intent: Applications can tell the network its intent, either explicitly or implicitly. Regardless of which approach is used, the network needs to understand the intent of the application and translate it into a specific expression.
- Global awareness of network status: Applications need to control and adjust network configurations to meet the application goals based on the network state. Therefore, the perception of the network status is indispensable. By means of telemetry and machine learning, visual operation and maintenance as well as intelligent decision making can be realized ultimately.
- Closed-loop optimization: According to the feedback of the network status, the gap between network configuration and application intent is inferred. The closed-loop system adjustment is continuously performed to enhance the learning mode to adjust the network configuration and finally satisfy the business intent. In the process above, the full-life cycle management of network elements is automatically running.

### B. ENABLING IDN TECHNOLOGIES

- Intent representation: A network intent refining method was proposed in [34]. The intent is collected through an intelligent voice robot interface, and a neural network learning model is used to extract the user intent expressed in natural language. In the process of intent refining, the Nile language is used to turn intents into network strategies. The intent refining system introduces a feedback mechanism, which effectively improves the accuracy of intent recognition, but does not check the consistency of the network intent before the network policy is issued. A system for automatically generating ACL update plans based on the advanced intent of network operatorsąłJinjing was proposed in [50]. Jinjing allows operators to express their update intent (such as ACL migration and flow control) in a declarative language called LAI, and Jinjing automatically synthesizes ACL update plans that meet their intents. Jinjing modeled the ACL configuration formally and designed an intent primitive to ensure the accuracy of the system operation. However, the system can only be used for the ACL update plan and designed for the WAN. It has not been applied to other networks. The goal of intent representation is to represent the natural language that describes the network requirements or tasks as a design of rules which can be recognized by the network. Intent representation includes the definition rules of intent primitives, natural language processing algorithms, and intent verification. Intent primitives are defined as five tuples: <domain, attribute, object, operation, result>. Domain: Identify the scope of service, and formalize the functional Domain of Object, Operation, Attribute. Attribute: Describing the specific characteristics of a field. Objects: Customer Facing Node (CFN), Connection and Service Flow for Administrators. Operations: Describing the user's expected behavior, which can be expressed in the pattern of Conditions, Actions, and

**TABLE 4. The architectural components of different IDN frameworks.**

| Framework | Key architectural components | Reference |
|---|---|---|
| INDIRA | Intent Parser, Intent Renderer | [21][22] |
| ACINO | Intent Framework | [25] |
| IBN | Intent Parser, Optimization and Decision maker | [26] |
| OSDF | Policy Storage, Policy Conflicts Detector, Policy Parser | [27] |
| Chopin | Coordinated path selection, Optimization | [28] |
| Intent Refinement System | Extractor, Translator, Deployer | [34] |
| ICSM | Parser, Composer, Calculator | [46] |

Constraints. Result: Describing the state users want to achieve and can be expressed by clauses of "expecting to reach a certain state" or "avoiding reaching a certain state".

- Closed-loop verification: The intent-based control loop is used in [51] to guarantee the QoS of video services. The proposed method uses IBN to define advanced network behaviors to reconfigure the network for service needs dynamically. Based on the network, this method routes video traffic and successfully improves QoS. IDN aims to maintain the state of enforcement in the network through their own intents. IDN uses the network verification method to generate reliability configuration parameters. Such a process requires closed-loop feedback. A closed-loop feedback control compares the deviation between system behavior (output) and expected behavior and eliminates deviations to achieve the desired system performance. Application intents are expressed as a series of operational network element level configuration, which adapts to the current network state. The network status is reported to the controller by the telemetry device and interpreted as an understandable topology/measurement. The above two processes maintain real-time closed-loop verification to generate reliable network configuration.
- Network telemetry: Packet-Optical In-band Network Telemetry (POINT) was proposed in [52] to provide a general abstraction for optical networks. POINT creates a unified telemetry data plane, instead of focusing solely on a specific architectural point in the network. POINT collects telemetry data in an optical network in a programmable manner and builds links between data packets and optical network telemetry data. The network telemetry is introduced to make devices actively push state information, which realizes end-to-end network traffic visualization in real time. It can solve problems that cannot be observed by conventional network monitoring methods, such as delay, forwarding paths, caching, and packet loss. Through further data analysis, a digital model can be established to provide a holistic solution and necessary technical support for refined network operation and maintenance.

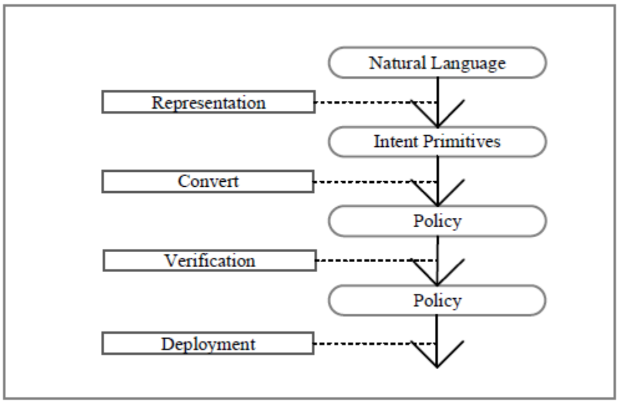
### C. DIVERSITY GAINS OF IDN

IDN makes the future network flexible, reconfigurable, convergent, open, programmable, flexible, and customizable, and promotes the development of the network from manual operation to intelligent operation. The gains are long-term and diverse.

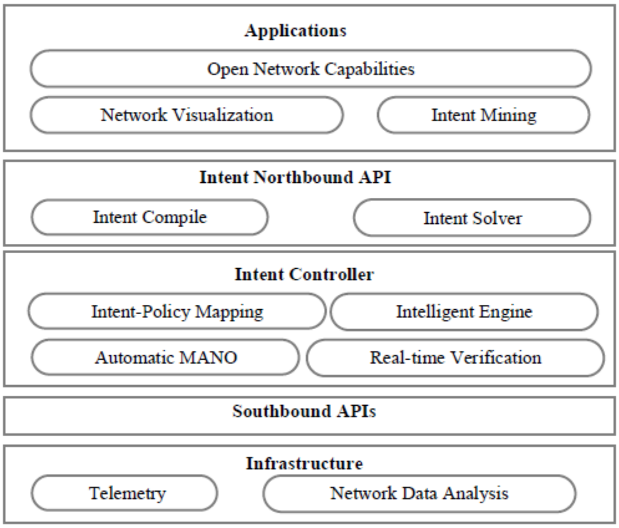
- High compatibility and network resource utilization: There is no need to rely on various interfaces of different devices and vendors at the physical network layer. In terms of operation and maintenance, IDN can solve the network management problem in heterogeneous environments and enable users to complete unified control with policy-based media.
- Static parameters dimension reduction and dynamic network optimization: IDN can reduce manual work, automate and simplify parameter configuration, and improve the reliability of network service. The problem can be quickly and accurately located in the case of network downtime or network failure. Moreover, network self-optimization and self-recovery can be realized.
- Benefiting different roles in the network: For network administrators, they can pay more attention to network services rather than specific micro configuration, which makes network delivery closer to service. For the ultimate users, the network can adapt to different services and provide better quality of experiment. For network service providers, the network configuration and maintenance work is more concise and labour saving.

## IV. IDN ARCHITECTURE

As shown in Table 4, different research groups have different concepts and design solutions for the IDN architecture. INDIRA can translate the intent language into RDF graphs through intent parsing and rendering components, and finally into network commands. The input of the rendering component is the user configuration and topology details [21], [22]. ACINO focuses on network orchestration. Intents issued by client applications are submitted via REST NBI. The orchestrator completes routing requests, compilation, mapping, and orchestration through an intent framework, and finally deploys network equipment using a southbound protocol [25]. Another IBN framework from an industrial perspective was proposed in [26]. Intents are translated and implemented with the support of Intent Processor, Optimization and Decision Maker, State Observer, and Data Store modules. Similar to [26], the OSDF framework implements high-level network policies into a device executable language through the Policy Storage Module, Policy Conflicts Detection Module, and Policy Parser Module [27].



(a) Intent Flow



(b) Basic Architecture of IDN

**FIGURE 3.** **Intent flow and basic architecture of IDN.**

Chopin is an intent-driven SDN resource management application [28]. First, Chopin pre-processes the intent of the application offline, and selects a subset of paths that can meet the application requirements; then, it balances the requirements of each path through online optimization. The ICSM framework takes cloud service intent as input and outputs it in YAML format [46]. ICSM is composed of service requester, resource composer, and parameter calculator.

In short, as shown in Fig. 3(a), in terms of execution actions, IDN mainly includes intent representation, convert, verification, and deployment; in terms of the transformation of intent form, the intent flow of ‘‘natural language, intent primitive, executable strategy, reliable configuration’’ is formed. In terms of hierarchical relationship, combining the latest practices of ODL and ONOS, IDN mainly includes service application layer, northbound interface, intent enabling layer, southbound interface (SBI), and infrastructure layer, as shown in Fig. 3(b). Although SDN is a typical implementation architecture for IDN, the implementation of IDN is not limited to this.

- The business application layer generates commercial intent, including different services in different scenarios. Commercial intent can be generated directly or indirectly. Direct intent refers to the network management intent-oriented to the management plane, which can be directly expressed through the application layer. The indirect intent emphasizes the intent of each user. Such intent is usually contained in the operation of the software in the mobile device. The business application layer programs the underlying device through the programming interface provided by the intent enabling layer, which abstracts the capability of the network element. Moreover, this layer provides management interfaces to achieve diversity business innovation.
- The intent enabling layer is the core of intent, with management control and policy-making capabilities. The layer parses and checks the intent flow that is translated through the intent northbound interface. The application intents are processed into a regularized intent request that can be executed by the current network. The specific resource in the network is obtained through the mapping algorithm of the intent and the resource. This layer adopts an intent-based management and orchestration system to achieve unified scheduling of resources. And the closed-loop arrangement is introduced into life-cycle management of the network elements. With the help of intelligent engine, it completes functions such as data collection, data storage, data processing, model training, and parameter adjustment, which provide a priori experience for strategy formulation. Meanwhile, closed-loop verification guarantees the reliability of the output network configuration parameters.
- The infrastructure layer includes various physical device entities. It also deploys a large number of network data collection tools to provide the necessary parameters for feedback information and policy configuration.
- The NBI is a module for translation intent which connects the business application layer and the intent enabling layer. Intent compile and intent solver implement intent representation and consistency checking. The SBI is based on virtualization technique and is connected to various network element devices. It is mainly used as an interaction between the infrastructure layer and the intent enabling layer. Additionally, various computing resources and communication resources are virtualized.

## V. TYPICAL CHALLENGES AND WIDER APPLICATIONS

### A. CHALLENGES OF IDN

IDN improves the automation of networks and the abstraction of complex problems. However, IDN also faces some technical challenges and industry dilemmas. The challenges of IDN are as follows:

- Fine and real-time access to network information: Data traffic is not the whole state of the network. The CPU, memory, network congestion information, and event log

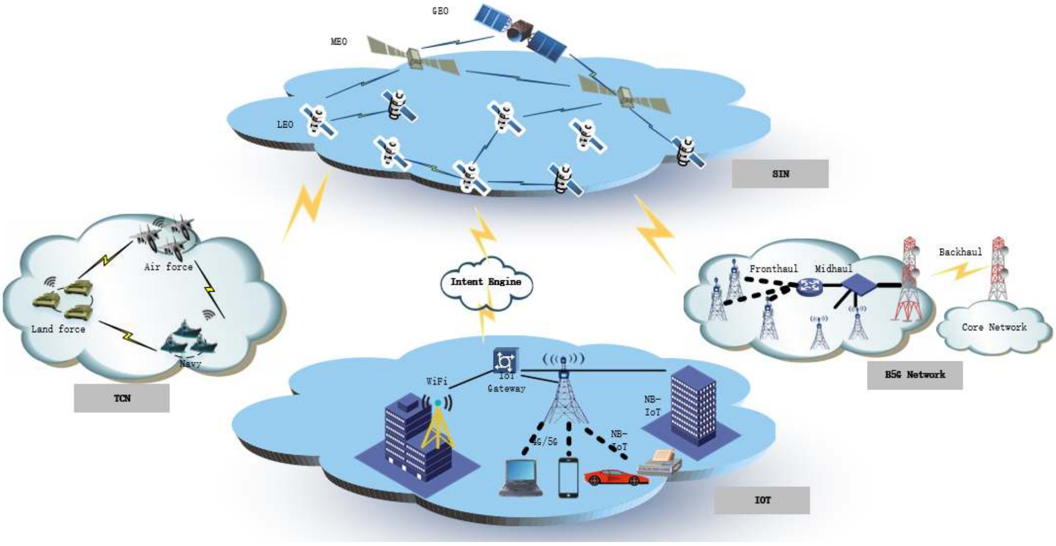


**FIGURE 4.** Different application scenarios of IDN.

information of the network device also need to be transmitted in real time. IDN needs to build a digital network platform with comprehensive and detailed network status information.

- Continuous closed-loop verification and automated deployment: During the closed-loop verification process, a large number of logical verification problems occur, including redundancy, correlation, generalization, and overlap. The above problems can cause errors or unnecessary delays in the verification process. In addition, network automation deployments face changes in the entire network, which requires the network to have a complete architecture to support the reusability of the configuration.
- Challenges from industry and standards: Due to the fact that all major equipment manufacturers are independently developing equipment suitable for their IDN solutions, the industry has not yet formed a complete supply and demand industrial chain. Meanwhile, during the operation of the system, each component and device relies heavily on API, and the current unified standard has not been formed. However, this is an area where conflicts of profits exist. Currently, vendors have private APIs, and the barriers established to isolate support for other IDN components will greatly inhibit the development of IDN.

### B. WIDER APPLICATIONS OF IDN

As a portable and promising technology, IDN will play an active role in various application scenarios in the future, including beyond 5G Network, space information network (SIN), IoT, and tactical communication network (TCN). As shown in Fig. 4.

- Beyond 5G Network:
  - **Network intelligence**: The goal of network intelligence is to realize closed-loop autonomy and self-healing networks, which greatly improve the efficiency of network operation and maintenance. From a business perspective, it is necessary to implement closed-loop autonomy of network services (covering end-to-end slicing, bearer networks, cloud infrastructure), such as self-configuration of slices, self-optimization; from a local functional perspective, in some scenarios which require intelligence, It is necessary to realize self-loop of network functions, such as self-healing of network functions.
  - **Customized service guarantee**: The service requirements above indicate that 5G networks need to be more flexible to support business needs in different environments. 5G networks need a more flexible architecture, which not only can be quickly deployed and changed, but also provide efficient and flexible management capabilities to respond quickly and adjust to different industry requirements in the future. IDN can be applied to the access network, core network and backhaul network with its unique control advantages, giving a customized service guarantee for the 5G application scenarios.
- Space Information Network:
  - **Simplify SIN management**: The space information network is a network system that acquires, transmits and processes spatial information in real time by using space platforms (high, medium and low orbiting satellites, stratospheric balloons and spacecraft, etc.) to ensure ocean navigation, emergency rescue, navigation and position, major applications such as air transportation, aerospace measurement and control. However, due to the diverse types of SIN nodes and large differences in capabilities, as well as the close relationship between business intents and network systems,

the network has closed and rigid defects. With the rapid growth of various tasks and the emergence of its new types, SIN architecture needs to be adaptively and dynamically reconstructed. Using the method of IDN, through the intent mining, the task intent can be discovered and the network intent is obtained through the intent extraction and characterization. The intent is transformed into the corresponding strategy and finally, the task and strategy matches well so that the accuracy and robustness of SIN strategy matching can be improved.

  - **Intent-driven multi-task collaboration**: Intent mining can unearth the intent of the task and obtain the network intent through intent translation. Using the collaborative framework, find the satellites that meet the above network intents, perform task division, and clarify the task division of each satellite. Then establish a connection with the ground station through cooperative communication, and clearly define the task and status in real time. Finally, download the observation data to the ground station. The resource management of SIN will be more efficient through accurate translation of task intent.

- IoT:
  - **Open Intent NBI**: In the IoT platform, in order to better provide an end-to-end service chain across multiple domains, it is necessary to implement unified management and orchestration functions of the network. The core is to define an open, vendor-independent, interoperable northbound interface (NBI), which should be abstracted from the data planes and control planes associated with a particular domain.
  - **Security**: The security of IoT devices must be considered. All participants in the IoT ecosystem need the security of equipments, data, and solutions. Meanwhile, to keep the situation within the manageable range, the participants also need to be able to recover from cyber attacks, even if the security fails. And all of those mentioned need to be done automatically without human intervention. IDN adopts an automated method to ensure the security of the IOT ecosystem. It can not only define a policy that all physical devices must be in the security domain, but it can accurately locate the objects attacked by the network and complete data analysis in real time as well.
- Tactical Communication Network:
  - **Tactical intent translation and understanding**: Intent identification is an important basis for determining the next operational action. The structured language brought by IDN can form an abstract description based on the battlefield situation, comprehensive analysis of target combat missions, operational plans, and operational objectives.
  - **Intent-driven TCN (ID-TCN)**: ID-TCN is based on military application intent, which can realize shared perception, efficient command, precision strike, and robust self-supporting operations. ID-TCN consists of machine combat units, individual combat units, battlefield decision units, and battlefield situation analysis units. ID-TCN accelerates network response and softens the rigid structure of the network. The establishing of ID-TCN is of great significance to the military command and military combat capability.

## VI. CONCLUSION

As a promising network technology, intent-driven network (IDN) gets extensive attention from open source communities and industry. However, a unified and clear definition of IDN has not yet been formed and the enabling techniques of IDN are still in the further exploration stage. In this article, we summarize the research status and development trends of IDN, and clarify the IDN architecture while giving its formal definition. IDN also faces serious challenges such as the continuous closed-loop verification and automated deployment. We have identified some of those challenges for future research in this area. Accordingly, it is necessary to carry out related research in various fields on IDN.

## REFERENCES

[1] C. Prakash, "PGA: Using graphs to express and automatically reconcile network policies," in *Proc. ACM Conf. Special Interest Group Data Commun.*, New York, NY, USA, 2015, pp. 29–42.
[2] M. Chen, Y. Hao, S. Mao, D. Wu, and Y. Zhou, "User intent-oriented video QoE with emotion detection networking," in *Proc. IEEE Global Commun. Conf. GLOBECOM)*, Washington, DC, USA, Dec. 2016, pp. 1–6.
[3] Veriflow. (2018). *Intent-Based Networking: Top 10 Questions and Answers*. [Online]. Available: https://www.veriflow.net/intent-based-networking/
[4] *Intent: Don't Tell Me What to Do!* Accessed: 2015. [Online]. Available: https://www.sdxcentral.com/articles/contributed/
[5] Open Networking Foundation. *Intent NBI: Definition and Principles*. Accessed: 2016. [Online]. Available: https://www.opennetworking.org/software-defined-standards/archives/
[6] ETSI ISG. (2017). *Improved Operator Experience Through Experiential Networked Intelligence (ENI)*. [Online]. Available: https://www.etsi.org/technologies/experiential-networked-intelligence
[7] Open Network Operating System. *ONOS Intent Framework*. Accessed: 2017. [Online]. Available: https://wiki.onosproject.org/display/ONOS/Intent+Framework
[8] OpenDayLight. *The OpenDaylight Project*. Accessed: 2017. [Online]. Available: https://www.opendaylight.org/
[9] OpenStack. *OpenStack Group Based Policy*. Accessed: 2017. [Online]. Available: https://wiki.openstack.org/wiki/GroupBasedPolicy
[10] OpenDayLight. *OpenDayLight Network Intent Composition*. Accessed: 2015. [Online]. Available: https://wiki.opendaylight.org/view/NetworkIntentCompositionUseCases
[11] *NeMo: An Applications Interface to Intent Based Networks*. Accessed: 2016. [Online]. Available: http://nemo-project.net
[12] Open Network Automation Platform. *ONAP Architecture Overview*. Accessed: 2018. [Online]. Available: https://www.onap.org/
[13] Cisco. *Cisco Digital Network Architecture*. Accessed: 2018. [Online]. Available: https://www.cisco.com/c/zh_cn/solutions/enterprise-networks/index.html
[14] Apstra. *Apstra Operating System*. Accessed: 2018. [Online]. Available: https://www.apstra.com/
[15] R. Cohen, "An intent-based approach for network virtualization," in *Proc. IFIP/IEEE Int. Symp. Integr. Netw. Manage. (IM)*, Ghent, Belgium, 2013, pp. 42–50.

[16] Y. Han, J. Li, D. Hoang, J. Yoo, and J. W. Hong, "An intentbased network virtualization platform for SDN," in *Proc. Int. Conf. Netw. Service Manage. (CNSM)*, Montreal, QC, USA, Oct. 2016, pp. 353–358.

[17] M. Pham and D. B. Hoang, "SDN applications—The intent-based Northbound Interface realisation for extended applications," in *Proc. IEEE NetSoft Conf. Workshops (NetSoft)*, Seoul, South Korea, Jun. 2016, pp. 372–377.

[18] F. Paganelli, F. Paradiso, M. Gherardelli, and G. Galletti, "Network service description model for VNF orchestration leveraging intent-based SDN interfaces," in *Proc. IEEE Conf. Netw. Softwarization (NetSoft)*, Bologna, Italy, Jun. 2017, pp. 1–5.

[19] P. Sköldström, S. Junique, A. Ghafoor, A. Marsico, and D. Siracusa, "DISMI—An intent interface for application-centric transport network services," in *Proc. Int. Conf. Transparent Opt. Netw. (ICTON)*, Girona, Spain, Jul. 2017, pp. 1–4.

[20] F. Callegati, W. Cerroni, C. Contoli, and F. Foresta, "Performance of intent-based virtualized network infrastructure management," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, May 2017, pp. 1–6.

[21] M. Kiran, E. Pouyoul, A. Mercian, B. Tierney, C. Guok, and I. Monga, "Enabling intent to configure scientific networks for high performance demands," *Future Gener. Comput. Syst.*, vol. 79, pp. 205–214, Feb. 2018.

[22] A. Mercian, M. Kiran, E. Pouyoul, B. Tierney, and I. Monga, "INDIRA: 'Application intent' network assistant to configure SDN-based high performance scientific networks," in *Proc. Opt. Fiber Commun. Conf. Exhib. (OFC)*, Los Angeles, CA, USA, 2017, pp. 1–3.

[23] D. Schulz, "Intent-based automation networks: Toward a common reference model for the self-orchestration of industrial intranets," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Florence, Italy, Oct. 2016, pp. 4657–4664.

[24] E. J. Scheid, C. C. Machado, M. F. Franco, R. L. dos Santos, R. P. Pitscher, A. E. Schaefer-Filho, and L. Z. Granville, "INSpIRE: Integrated NFV-based intent reinement environment," in *Proc. IFIP/IEEE Symp. Integr. Netw. Service Manage. (IM)*, May 2017, pp. 186–194.

[25] T. Szyrkowiec, "Automatic intent-based secure service creation through a multilayer SDN network orchestration," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 10, no. 4, pp. 289–297, Apr. 2018.

[26] B. T. Saha, D. Tandur, L. Haab, and L. Podleski, "Intent-based networks: An industrial perspective," in *Proc. 1st Int. Workshop Future Ind. Commun. Netw. (FICN)*, 2018, pp. 35–40.

[27] D. Comer and A. Rastegatnia, "OSDF: An intent-based software defined network programming framework," in *Proc. IEEE 43rd Conf. Local Comput. Netw. (LCN)*, Chicago, IL, USA, Oct. 2018, pp. 527–535.

[28] V. Heorhiadi, S. Chandrasekaran, M. K. Reiter, and V. Sekar, "Intent-driven composition of resource-management SDN applications," in *Proc. 14th Int. Conf. Emerg. Netw. Exp. Technol. (CoNEXT)*, 2018, pp. 86–97.

[29] B. Lewis, L. Fawcett, M. Broadbent, and N. Race, "Using P4 to enable scalable intents in software defined networks," in *Proc. IEEE 26th Int. Conf. Netw. Protocols (ICNP)*, Cambridge, Sep. 2018, pp. 442–443.

[30] A. Marsico, "An interactive intent-based negotiation scheme for application-centric networks," in *Proc. IEEE Conf. Netw. Softwarization (NetSoft)*, Bologna, Italy, Jul. 2017, pp. 1–2.

[31] Y. Tsuzaki and Y. Okabe, "Reactive configuration updating for Intent-Based Networking," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Da Nang, Vietnam, 2017, pp. 97–102.

[32] A. S. Jacobs, "Deploying natural language intents with Lumi," in *Proc. SIGCOMM Posters Demos ACM Conf. Posters Demos (SIGCOMM)*, Beijing, China, 2019, pp. 82–84.

[33] Y. Elkhatib, G. Coulson, and G. Tyson, "Charting an intent driven network," in *Proc. Int. Conf. Netw. Service Manage. (CNSM)*, Tokyo, Japan, Nov. 2017, pp. 1–5.

[34] A. S. Jacobs, "Refining network intents for self-driving networks," in *Proc. Afternoon Workshop Self-Driving Netw. (SelfDN)*, Budapest, Hungary, Jan. 2018, pp. 15–21.

[35] H. Zhang, Y. Wang, X. Qi, W. Xu, T. Peng, and S. Liu, "Demo abstract: An intent solver for enabling intent-based SDN," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Atlanta, GA, USA, May 2017, pp. 968–969.

[36] A. Abhashkumar, J. Kang, S. Banerjee, A. Akella, Y. Zhang, and W. F. Wu, "Supporting diverse dynamic intent-based policies using Janus," in *Proc. 13th Int. Conf. Emerg. Netw. Exp. Technol. (CoNEXT)*, Incheon, South Korea, 2017, pp. 296–309.

[37] S. Arezoumand, K. Dzeparoska, H. Bannazadeh, and A. Leon-Garcia, "MD-IDN: Multi-domain intent-driven networking in software-defined infrastructures," in *Proc. Int. Conf. Netw. Service Manage. (CNSM)*, Tokyo, Japan, 2017, pp. 1–7.

[38] D. Sanvito, D. Moro, M. Gullì, I. Filippini, A. Capone, and A. Campanella, "Enabling external routing logic in ONOS with intent monitor and reroute service," in *Proc. IEEE Conf. Netw. Softwarization Workshops (NetSoft)*, Montreal, QC, Canada, Jun. 2018, pp. 332–334.

[39] R. A. Addad, D. L. C. Dutra, M. Bagaa, T. Taleb, H. Flinck, and M. Namane, "Benchmarking the ONOS intent interfaces to ease 5G service management," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Abu Dhabi, United Arab Emirates, Dec. 2018, pp. 1–6.

[40] T. Subramanya, R. Riggio, and T. Rasheed, "Intent-based mobile backhauling for 5G networks," in *Proc. Int. Conf. Netw. Service Manage. (CNSM)*, Montreal, QC, Canada, 2016, pp. 348–352.

[41] F. Aklamanu, S. Randriamasy, E. Renault, I. Latif, and A. Hebbar, "Intent-based real-time 5G cloud service provisioning," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Abu Dhabi, United Arab Emirates, Dec. 2018, pp. 1–6.

[42] M. Odini and A. Krichel, "Intent based modelling key to 5G & ZSM," in *Proc. IEEE Softwarization*, 2018, pp. 1–6.

[43] W. Cerroni, "Intent-based management and orchestration of heterogeneous openflow/IoT SDN domains," in *Proc. IEEE Conf. Netw. Softwarization (NetSoft)*, Bologna, Italy, Jul. 2017, pp. 1–9.

[44] W. Cerroni, "Intent-based service management for heterogeneous software-defined infrastructure domains," in *Proc. IEEE NetSoft Special Issue: Softwarization Sustaining Hyper-Connected World: En Route to 5G*, 2018, vol. 29, no. 1, pp. 1–22.

[45] J. Kang, J. Lee, V. Nagendra, and S. Banerjee, "LMS: Label management service for intent-driven cloud management," in *Proc. IFIP/IEEE Symp. Integr. Netw. Service Manage. (IM)*, Lisbon, Portugal, May 2017, pp. 177–185.

[46] W. Chao and S. Horiuchi, "Intent-based cloud service management," in *Proc. 21st Conf. Innov. Clouds, Internet Netw. Workshops (ICIN)*, Paris, France, Feb. 2018, pp. 1–5.

[47] Gartner. *Innovation Insight: Intent-Based Networking Systems*. Accessed: 2017. [Online]. Available: https://www.gartner.com/doc/3599617/innovation-insight-intentbased-networking-systems

[48] Cisco. *Intent-Based Networking*. Accessed: 2018. [Online]. Available: https://www.cisco.com/c/en/us/solutions/intent-based-networking.html

[49] Huawei. *IDN Maximize Your Business Value*. Accessed: 2018. [Online]. Available: https://developer.huawei.com/ict/en/site-idn

[50] B. Tian, X. Zhang, and E. Zhai, "Safely and automatically updating in-network ACL configurations with intent language," in *Proc. ACM Special Interest Group Data Commun.*, 2019, pp. 214–226.

[51] N. F. S. de Sousa, N. Islam, D. A. L. Perez, and C. E. Rothenberg, "Policy-driven network traffic rerouting through intent-based control loops," in *Proc. Brazilian Symp. Comput. Netw. Distrib. Syst. (SBRC)*, 2019, pp. 1–15.

[52] M. Anand, R. Subrahmaniam, and R. Valiveti, "POINT: An intent-driven framework for integrated packet-optical in-band network telemetry," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–6.

**LEI PANG** received the bachelor's degree in communication engineering from Xidian University, Xi'an, China, in 2018, where he is currently pursuing the master's degree in electronic and communication engineering. He is also with the GUIDE Research Team, under the guidance of Dr. C. Yang. His research interests include intent-driven networks (IDN) and wireless software defined networks (SDN).

**CHUNGANG YANG** (Senior Member, IEEE) received the bachelor's and Ph.D. degrees from Xidian University, Xi'an, China, in 2006 and 2011, respectively. From September 2010 and March 2011, he held the visiting scholar position at the Department of Electrical and Computer Engineering, Michigan Technological University. From March 2015 and March 2016, he held the visiting scholar position at the Department of Electrical and Computer Engineering, University of Houston. He is currently a Full Professor with Xidian University, where he leads the Research Team of Game, Utility, Intelligent computing Design for Emerging communications (GUIDE). He has edited two books: *Game Theory Framework Applied to Wireless Communication Networks* (IGI Global, 2016), and *Interference Mitigation and Energy Management in 5G Heterogeneous Cellular Networks* (IGI Global, 2017). His research interests are information communication network theory architecture protocol technology based on game theory, utility learning, and artificial intelligence, including artificial intelligence B5G 6G communication networks, intent-driven networks, air-space-ground of integrated information communication networks, ad hoc networks, and cognitive heterogeneous networks.

**DANYANG CHEN** received the bachelor's degree in communication engineering from Xidian University, Xi'an, China, in 2017, where she is currently pursuing the master's degree in electronic and communication engineering. She is also with the GUIDE Research Team, under the guidance of Dr. C. Yang. Her research interests include intent-driven networks (IDN) and space information networks.

**YANBO SONG** received the bachelor's degree in communication engineering from Xidian University, Xi'an, China, in 2017, where he is currently pursuing the Ph.D. degree in electronic and communication engineering. He is also with the GUIDE Research Team, under the guidance of Dr. C. Yang. His research interest includes wireless intent-driven networks (IDN).

**MOHSEN GUIZANI** (Fellow, IEEE) received the B.S. (Hons.) and M.S. degrees in electrical engineering and the M.S. and Ph.D. degrees in computer engineering from Syracuse University, Syracuse, NY, USA, in 1984, 1986, 1987, and 1990, respectively. He has served as the Associate Vice President of Graduate Studies, Qatar University, the Chair of the Computer Science Department, Western Michigan University, and the Chair of the Computer Science Department, University of West Florida. He has also served in academic positions at the University of Missouri–Kansas City, the University of Colorado–Boulder, Syracuse University, and Kuwait University. He is currently a Professor and the ECE Department Chair of the University of Idaho, Moscow, ID, USA. He is the author of nine books and more than 500 publications in refereed journals and conferences. His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grids. He is a Senior Member of ACM. He has also served as a member, the Chair, and the General Chair of a number of international conferences. He received the teaching award multiple times from different institutions as well as the Best Research Award from three institutions. He also received the 2017 IEEE ComSoc Recognition Award for his contribution to Wireless Communications. He was the Chair of the IEEE Communications Society Wireless Technical Committee and the Chair of the TAOS Technical Committee. He is also the Editor-in-Chief of the IEEE NETWORK. He has serves on the editorial boards of several international technical journals and the Founder and the Editor-in-Chief of *Wireless Communications and Mobile Computing Journal* (Wiley). He guest edited a number of special issues in the IEEE journals and magazines. He served as the IEEE Computer Society Distinguished Speaker, from 2003 to 2005.

• • •