TITLE

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A Survey of Intelligent Network Slicing Management for Industrial IoT: Integrated Approaches for Smart Transportation, Smart Energy, and Smart Factory

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***Abstract*—Network slicing has been widely agreed as a promising technique to accommodate diverse services for the Industrial Internet of Things (IIoT). Smart transportation, smart energy, and smart factory/manufacturing are the three key services to form the backbone of IIoT. Network slicing management is of paramount importance in the face of IIoT services with diversified requirements. It is important to have a comprehensive survey on intelligent network slicing management to provide guidance for future research in this field. In this paper, we provide a thorough investigation and analysis of network slicing management in its general use cases as well as specific IIoT services including smart transportation, smart energy and smart factory, and highlight the advantages and drawbacks across many existing works/surveys and this current survey in terms of a set of important criteria. In addition, we present an architecture for intelligent network slicing management for IIoT focusing on the above three IIoT services. For each service, we provide a detailed analysis of the application requirements and network slicing architecture, as well as the associated enabling technologies. Further, we present a deep understanding of network slicing orchestration and management for each service, in terms of orchestration architecture, AI-assisted management and operation, edge computing empowered network slicing, reliability, and security. For the presented architecture for intelligent network slicing management and its application in each IIoT service, we identify the corresponding key challenges and open issues that can guide future research. To facilitate the understanding of the implementation, we provide a case study of the intelligent network slicing management for integrated smart transportation, smart energy, and smart factory.**

Some lessons learnt include: 1) For smart transportation, it is necessary to explicitly identify service function chains (SFCs) for specific applications along with the orchestration of underlying VNFs/PNFs for supporting such SFCs; 2) For smart energy, it is crucial to guarantee both ultra-low latency and extremely high reliability; 3) For smart factory, resource management across heterogeneous network domains is of paramount importance. We hope that this survey is useful for both researchers and engineers on the innovation and deployment of intelligent network slicing management for IIoT.

***Index Terms*—Network slicing, Autonomous vehicle, Smart energy, Smart factory, Orchestration and management.**

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I. Introduction

The Industrial Internet of Things (IIoT) is one of the key enablers for the digital transformation of traditional industries towards Industry 4.0 [1]. IIoT services have diversified requirements due to the nature of their applications. Smart transportation, smart energy, and smart factory/manufacturing are typical applications of IIoT services and have formed the backbone of IIoT though they also affect each other. Take smart manufacturing as an example. As shown in Fig. 1, the manufacturing industry consists of smart factory, distribution center, and logistics. The realization of smart factory heavily depends on both smart energy and smart transportation. For example, robot arms in a production line require a highly-reliable electricity supply. Meanwhile, autonomous vehicles are expected to be widely adopted in smart transportation to foster the future logistics. However, these diverse IIoT services also pose critical requirements on the communications/networking infrastructure of IIoT [1].

Network slicing has emerged as a promising paradigm to accommodate diverse IIoT services [2]. It enables multiple independent logical networks running on the same physical network infrastructure. Network slicing is essentially a slice of physical infrastructure that contains resources of multiple IIoT network domains. Each slice is thus an isolated End-to-End (E2E) network tailored to meet the requirements of the accommodated IIoT service, e.g., quality-of-service (QoS), reliability, and security. According to the application demands, a slice can be dynamically created or torn up [3], scaled up or down with more or fewer resources [4], and reconfigured by adding or removing network functions [5]. This can in turn maximize the efficiency of utility and reusability of the resources in the physical IIoT infrastructure.

To realize network slicing management for IIoT, a full slice lifecycle management needs to be maintained, where the

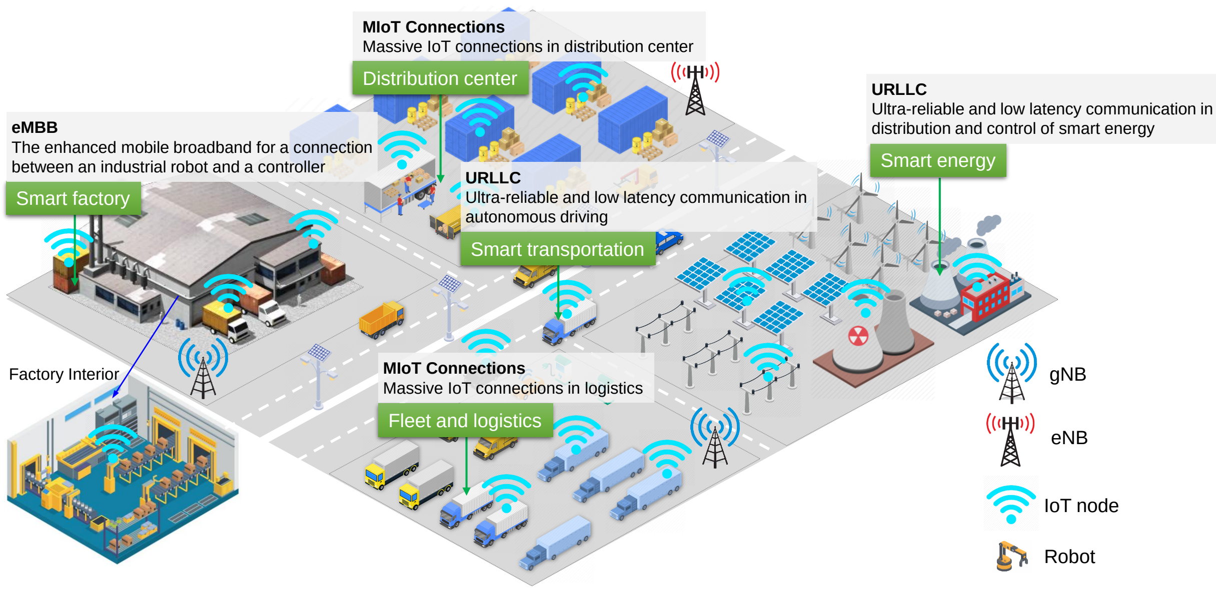

Fig. 1. Critical requirements of IIoT applications

requirements of an IIoT service shall be identified first. The slice can then be created accordingly based on the specific IIoT service needs. After that, the allocation of physical network resources to the slice shall be carried out. Then, the allocated resources shall be adjusted according to the changing service requirements. This is also known as resource reallocation to the slice. Meanwhile, adding and/or removing network functions, as well as relocating network functions, may be considered according to the IIoT service demands. Numerous works [2], [3], [5] have been conducted to tackle the challenges and address the issues at different phases of the network slicing management. The use of Artificial Intelligence (AI) for intelligent network slicing management has been a hot research topic in recent years and has been considered in different phases [4].

The concept of network slicing management has been discussed in several standard organizations, including the Next Generation Mobile Networks (NGMN) – 5G white paper version 1.0[1], the Network Functions Virtualization Industry Specification Group of European Telecommunications Standards Institute (ETSI ISG NFV) – NFV Release 3 "Report on network slicing support with ETSI NFV architecture framework"[2], the Open Networking Foundation (ONF) – TR-526 "Applying SDN architecture to 5G slicing"[3], the Internet Engineering Task Force (IETF) – Internet-Draft "Network slice for 5G and its characteristics"[4], the International Telecommunication Union (ITU) Study Group 13[5], and 3GPP. Network slicing was first formally, but lightly, discussed in 3GPP Release 15[6]. In this technical report, three types of predefined slices were mentioned, including enhanced mobile broadband (eMBB), ultra-reliable and low latency communication (URLLC) and massive Internet of Things (MIoT), and a dedicated network function was introduced for slices handling - the network slice selection function (NSSF). Consider Fig. 1 again, in which URLLC is highly expected for distribution and control of smart energy while logistics needs to fulfill MIoT connections from various sensors and RFID tags in a warehouse and a fleet of vehicles. In addition, these three predefined slices allow inter-operator operations. The concept of network slicing was then discussed with more details in 3GPP Release 16 (completed in June 2020).

[1]https://www.ngmn.org/wp-content/uploads/160113_NGMN_Network_Slicing_v1_0.pdf

[2]https://www.etsi.org/deliver/etsi_gr/NFV-EVE/001_099/012/03.01.01_60/gr_NFV-EVE012v030101p.pdf

[3]https://opennetworking.org/wp-content/uploads/2014/10/Applying_SDN_Architecture_to_5G_Slicing_TR-526.pdf

[4]https://tools.ietf.org/html/draft-rokui-5g-ietf-network-slice-00

[5]https://www.itu.int/en/ITU-T/about/groups/Pages/sg13.aspx

[6]https://www.3gpp.org/release-15

A. Motivation

Several surveys on network slicing and/or network slicing management have been reported in the current literature. Most of them are carried out for the enabling technologies of network slicing, e.g., network hypervisors [6], virtual machines & containers [7], Software Defined Networking (SDN) [8], Network Functions Virtualization (NFV) [3], and edge/cloud/fog computing [9]. Some of them focus on the investigation of industry initiatives, standardization efforts, open-source projects, and proof-of-concept products [10]–[13]. It is worth noting that network slicing ought to be created and managed based on the specific application requirements. Although some surveys have discussed the application requirements for network slicing, they only touch this from a high-level point of view, e.g., the three use cases of 5G – eMBB, URLLC, and mMTC [14]–[19]. There are few surveys on network slicing management for concrete application scenarios, especially IIoT service applications. We present a detailed comparison of this paper with other existing surveys in Section II-I.

B. Scope and Main Contributions

Although it has been termed for a while, network slicing is mainly proposed for enhancing service deployment and network performance for communication services, e.g. 5G. IIoT services will become the killer applications for 5G and B5G. It is of paramount importance to consider the detailed requirements of specific IIoT applications, e.g., autonomous vehicles and smart factory, so that the required knowledge of performing network slicing in the specific application domains can be acquired. The obtained knowledge would be crucial for both engineers and researchers in the process of creating/studying network slices to accommodate specific IIoT applications.

To bridge the important gap of network slicing survey works, this survey paper carries out a comprehensive investigation of network slicing management from the perspectives of key IIoT applications, including smart transportation, smart energy, and smart factory. The main contributions of this survey paper are summarized as follows:

- This survey provides a thorough investigation and analysis of network slicing management according to a set of criteria including enabling technologies, slicing architecture, resource orchestration and management, proof-of-concept products, standardization progress, and the general use cases. We also highlight the difference between this survey paper and existing survey works on network slicing management.
- An architecture of intelligent network slicing management for IIoT applications including smart transportation, smart energy and smart factory is presented.
- The above three IIoT applications are thoroughly investigated in order to have a deeper understanding of network slicing management, in terms of IIoT application requirements, network slicing architecture, network slice orchestration and management, the key research challenges and open issues, as well as the discussion, remarks, and lesson learned.
- For network slicing orchestration and management, the network slice orchestration architecture for each IIoT application is studied, along with the AI-assisted management and operation works. Given the importance of mobile edge computing (MEC) for IIoT applications, the MEC-empowered network slicing solutions are investigated. In addition, the relevant important reliability and security studies for network slicing are researched.
- For the research challenges and open issues, new challenges of IIoT applications are discussed, including cross-domain slicing, performance issues, new business models, and the corresponding deployment issues.
- For each application, a list of important questions regarding the creation and maintenance of network slicing are discussed, including computational complexity, resource availability, the available datesets that can be used for the AI related research of network slicing management, performance evaluation and benchmarks, and the future research directions.
- We provide a case study of the intelligent network slicing management for integrated smart transportation, smart energy, and smart factory.

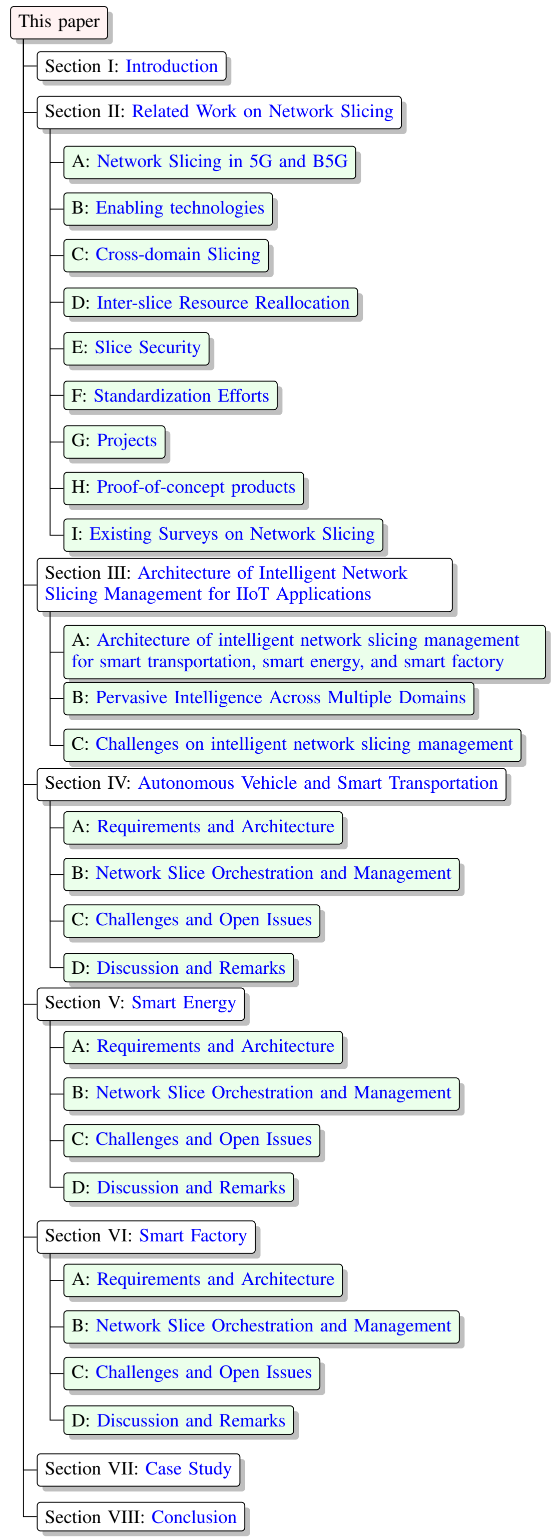

Fig. 2. The structure of this paper.

The rest of this paper is organized as follows. Section II introduces network slicing in 5G and B5G, presents the enabling technologies, and summarizes the recent standardization efforts, projects and proof-of-concepts, as well as existing

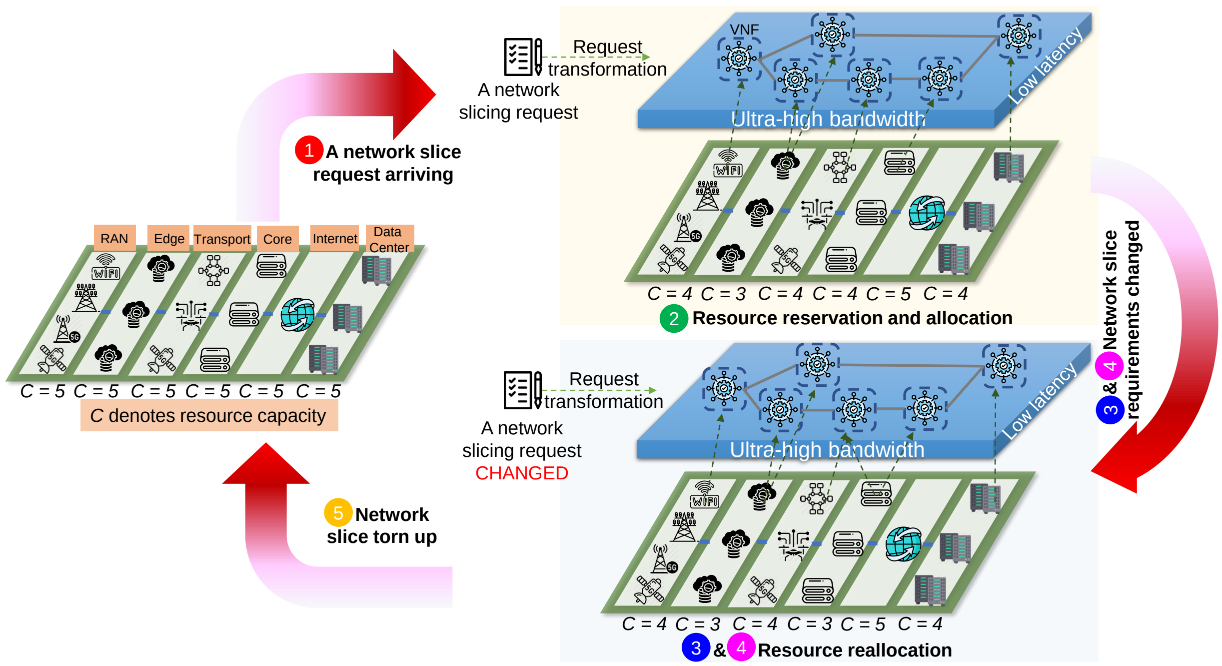

Fig. 3. The typical lifecycle of a network slice.

survey works of network slicing. Section III presents an architecture of intelligent network slicing management for IIoT applications including smart transportation, smart energy, and smart factory. Sections IV – VI carry out the survey of network slicing for smart transportation, smart energy, and smart factory, respectively. Section VII gives a case study of the intelligent network slicing management for integrated smart transportation, smart energy, and smart factory. Finally, Section VIII concludes this paper. Fig. 2 shows the structure of this paper.

II. Related Work on Network Slicing

A. Network Slicing in 5G and B5G

Network slicing is essentially a slice of physical infrastructure resources that can be used to build a logical virtual network [2]. In this way, a physical infrastructure can support multiple network slices, each of which can accommodate a specific service. Fig. 3 depicts a typical lifecycle of a slice with the following working principles:

1) Once a network slice request is received, the required Virtual Network Functions (VNFs) and how they should be connected to form a logical network are worked out;
2) The resources that are required to build the logical network, need to be reserved in the physical network infrastructure and allocated to the logical network;
3) With the changes of application needs in terms of required resources, dynamic scaling up and scaling down of the allocated resources are carried out;
4) With the changes of application demands in terms of the required VNFs or the connection between VNFs, adding and/or removing or relocating VNFs are performed;
5) Once the service finishes its lifecycle, the slice that was built to accommodate the service is torn up and the allocated resources are released.

In order to achieve the above lifecycle of a slice, network slicing needs to possess the following abilities:

- *Template translation*. For each network slicing request, a network slicing template is generated first and then translated to the logical network of a slice.
- *On-demand creation*. According to the description in the template, a slice can be instantiated with the allocation of necessary resources to ensure service level agreement (SLA).
- *Dynamic reconfiguration* Due to the changing service requirements and SLAs, the allocated resources can be dynamically rescheduled, and the pre-installed VNFs can be dynamically added, removed and reallocated.
- *Third party management*. Several roles possess the full or partial ownership of a slice. The *slice owner* is the requester of a slice. The *network operator* provides the required resources to build the slice. The *tenant* rents the slice and runs a service over the slice. Network slicing should allow these third parties to manage and use slices.

Automation and *isolation* are the two main principles to ensure the efficiency of network slicing lifecycle and the performance and security of each slice.

- Automation. Many AI-powered solutions have been developed to enhance the automation of template translation [20], on-demand creation [3], dynamic reconfiguration [4], [21] and third party management [22]–[24]. In practical, for dynamic reconfiguration, existing solutions mainly aim to maximize the resource utilization of a physical infrastructure while minimizing the violation of SLA requirements [4].

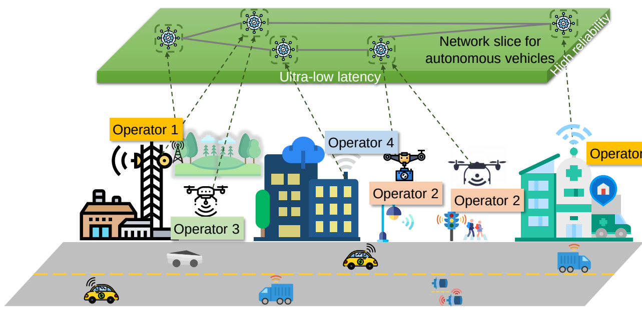

Fig. 4. A cross-domain slice of edge computing for autonomous vehicles.

- Isolation. Virtualization technologies have been developed to ensure the resource isolation in a shared resource infrastructure [25], [26]. Although they are widely used in 5G network slicing, the performance of isolation is still a hot research topic and is being researched and improved [27]. Isolation can also be achieved through using different physical resources [28] or access control mechanisms [29], [30].

In 5G network slicing, according to the business needs, a network slice could be a slice of radio access network (RAN) resources only, a slice of core network resources only, or a slice of resources spanning RAN, core network, and transport networks. In the scenario of multiple network operators, network slicing could span multiple network domains, also known as cross-domain slicing. In other words, it is a slice of network resources belonging to different network operators. Network slicing at the edge is a typical example of cross-domain slicing, as network operators are sharing their infrastructure resources at the edge to increase the coverage of edge service at a low cost. Fig. 4 illustrates a cross-domain slice of edge computing for autonomous vehicles. In the actual implementation, a specific service can run with a single slice or multiple slices, according to the service needs. Fig. 5 depicts two services, a voice service and a medical service, where the voice service runs with a specific slice that is orchestrated based on the requirement of voice services, and the medical service runs with three slices for voice communication, remote control, and medical video transmission, respectively. In addition, a network slice could traverse diverse network connectivity technologies. This is usually the case of supporting the communication between different entities e.g., factories.

B. Enabling technologies

In this section, we will discuss the enabling technologies of network slicing from the application's point of view, including NFV, SDN, virtualization, and containerization, as well as edge/cloud computing. We also investigate the existing network slicing survey works and summarize their coverage of these enabling technologies.

1) Network Functions Virtualization: NFV is a way of virtualizing network functions, such as routers and firewalls, that were traditionally run on proprietary hardware devices [31], [32]. It is one of the key enabling technologies of

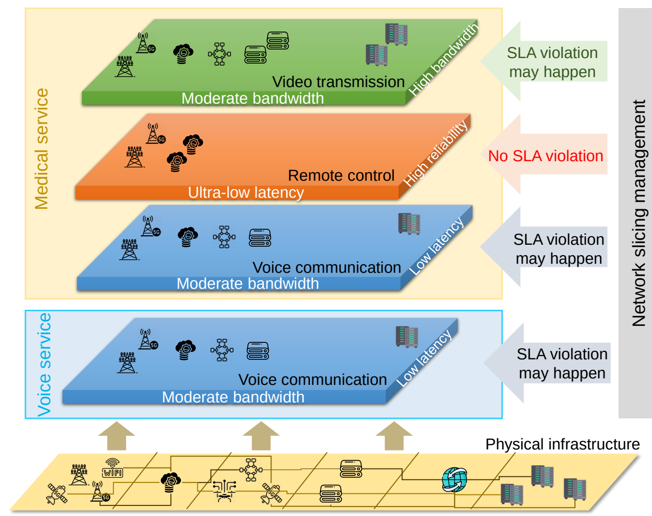

Fig. 5. Network slicing for a voice service and a medical service, with different strategies for network slicing management.

network slicing. There are three key components of the NFV architecture, namely VNF, NFV Infrastructure (NFVI) and Management and Orchestration (MANO) [12], [33], [34]. VNF is the software form of network functions deployed on virtual environments. NFVI is the infrastructure resources of NFV including computing, networking, and storage, upon which VNFs will be deployed. MANO is the component that is responsible for the lifecycle management of VNFs, the resource management of NFVI, as well as VNF and NFVI orchestration and the lifecycle management of deployed services.

With NFV, the required functionalities of a slice request can be readily fulfilled by deploying the VNFs on virtual machines (VMs) or containers of standard servers. The deployed VNFs can be further chained through SDN by virtue of MANO. The chained VNFs form a service function chain that provides the dedicated service to end users. In the event of adding/removing/reallocating functions in a slice due to service requirements, the VNFs as multiple pieces of software can be easily installed or uninstalled on the server, or migrated between servers; this is managed by the MANO. The lifecycle management of the chained service is also maintained by the MANO. NFV can provide the flexibility and elasticity of network slicing for service deployment in virtual environments [35]–[37].

2) Software Defined Networking: SDN decouples the control plane from the data plane of a network [38]–[41]. The control plane is realized through a logically centralized controller that can directly program the underlying devices in the data plane through an open northbound interface, e.g., OpenFlow [42], [43], POF [44], [45] and P4 [46]. The controller is essentially an intelligent brain of the network that has a global view of the network and can work out the suitable network control and management strategies based on network big data analytics and data mining. Such strategies can be implemented through the programmability introduced by SDN. The SDN architecture is basically composed of three layers: the application layer, the control layer, and the infrastructure layer [40]. In particular, the application layer hosts all network applications and functions, e.g., firewalls and load balancing. The control layer is essentially the controller of the SDN architecture. The infrastructure layer contains the physical network devices, e.g., routers and switches. In addition to the southbound interface between the control layer and the infrastructure layer, the communication between the application layer and the control layer is carried out via the northbound interface, e.g., RESTful API [47], [48].

To facilitate the application of SDN in the network slicing management, the network slicing can be considered as a service of the network, termed as network slicing-as-a-service [20], [49], [50]. This service can then be hosted in the application layer of SDN. The network slices can be managed through the strategies worked out by the controller, e.g., managing the slices belonging to the same context using the similar strategy as depicted in Fig. 5. In addition, as a possible application under this network slicing-as-a-service, the deployed VNFs in the physical infrastructure can be connected through the strategy of SDN controller to meet the logical network slicing requirement.

3) Virtualization & Containerization: Both virtualization and containerization technologies can provide a way for a server to host multiple VNFs in virtual environments [51]–[54]. Virtualization allows multiple VMs to run simultaneously on the hardware of a single physical server, where each VM has its own operating system, binaries and libraries [55], [56]. A hypervisor [57], [58], a software or firmware, is used to create an abstraction layer over the hardware of a server, and it is used to create VMs and enable multiple VMs to run alongside each other and share the same physical server resources. Each VM is usually many gigabytes in size, and it usually takes minutes to start a VM. Similarly, containerization allows multiple containers to run simultaneously on the hardware of a single physical server (or a VM), where a container does not have its own operating system and all containers share the operating system, and also binaries and libraries, of the hosting physical server [59]–[61]. Containers are therefore more lightweight in comparison with VMs. A container is usually megabytes in size, and it usually takes seconds to start a container.

A simple difference between VMs and containers is that VMs virtualize the hardware of a physical server, while containers virtualize the operating system of a physical server. Both VMs and containers have been widely used to accommodate VNFs in virtual environments. Containers are more popular in recent years due to their lightweight nature, especially in the mobility scenarios where it is quicker to reallocate a VNF between physical servers [62], [63].

4) Edge and Cloud Computing: Edge and cloud computing provides the computing and storage capability that can be used in various aspects of network slicing. For example, it can be used by MANO for calculating the strategies of NFV management and orchestration, and it can also be used in the SDN controller for helping with the computation of AI-powered solutions for network slicing management. In addition, it can be used inside a slice to provide computing capability for the accommodated service. In comparison with cloud computing, edge computing brings the computing capability in close proximity to where it is needed. This can significantly reduce the transmission delay between the computing facilities and the users/applications, and it is in favour of delay-sensitive applications. Edge computing can also provide privacy protection of data computation to some extent, since the computation is carried out locally [64]–[66]. Due to the limited computing and storage capability at the network edge, edge computing is usually in collaboration with cloud computing, also known as edge-cloud orchestration [67], to carry out the required computing tasks of network slicing.

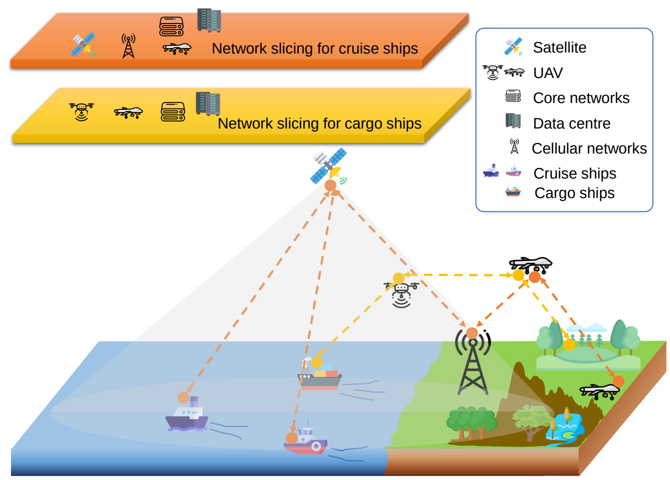

Fig. 6. A typical case for space-air-ground-sea communication.

C. Cross-domain Slicing

A network slice may contain the resources from network domains belonging to different network operators [68]–[70]. A typical example is edge computing as shown in Fig. 4. Due to the high expenditure of a wide coverage of edge computing, network operators are more inclined to collaborate with each other in a federated manner to increase the edge computing coverage at a lower cost. To have adequate edge computing resources for a certain service, a network slice at the 5G RAN may cross different network domains. Another typical example of cross-domain slicing is the inter-factory communication, where the network in each factory may have its own operator and the communication network between factories usually belongs to a third network operator. Recently, the space-air-ground-sea mobile network has been widely discussed as a typical use case for B5G/6G (see Fig. 6). Under this type of networks, a network slice may require the resources from the devices at different networks, i.e., satellites at the space network, unmanned aerial vehicles (UAV) at the air network, cellular towers at the ground mobile network, and autonomous surface/underwater vehicles at the sea mobile network.

Different from network slicing in a single network domain, cross-domain slicing encounters the following difficulties:

- Different network domains have different control and management strategies. It is important to understand the strategies of different network domains in a proper

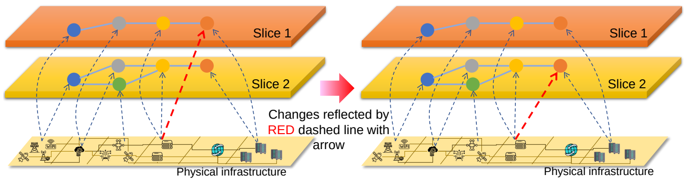

Fig. 7. Inter-slice resource allocation.

way, so that the seamless control of the E2E network slice can be performed. This could be done through a communication protocol between network domains.
- Different network domains use different network connectivity technologies. Some connectivity technologies have QoS mechanisms (e.g., time sensitive networking, 5G RAN, and 5G core networks), while some legacy technologies do not have (e.g., IEEE 802.11 and IEEE 802.15.4). It is important to have appropriate solutions in place to ensure the E2E QoS of network slicing, so that the SLA of the accommodated services can be guaranteed.
- Different network domains adopt different security and privacy considerations. When sharing information (e.g., control and management strategies) between network domains, required information of ensuring the seamless control of the E2E network slice may not be available. It is important to have a robust E2E slice management and control solution that can tolerate the missing information.

D. Inter-slice Resource Reallocation

Recall that a physical network infrastructure can support multiple network slices which share the physical network resources including computing, storage, and networking resources. From network operators' point of view, a slice needs to be allocated adequate resources to guarantee SLA of the service. In practice, network operators expect to maximize the resource utilization of the physical infrastructure while minimizing the violation of service SLA. In this way, their revenue can be maximized. In order to achieve this, the resources allocated to one slice (say Slice 1) may need to be reallocated to another (say Slice 2), since Slice 1 underutilizes the allocated resources and Slice 2 demands more resources. From applications' point of view, a slice needs to ensure the application's QoS requirements, so the resource reallocation needs to ensure the QoS of the service that a slice is accommodating is not affected.

Fig. 7 depicts a typical example of inter-slice resource reallocation, where the underutilized resources of Slice 1 can be reallocated to Slice 2 in case of its increasing resource demands or used to accept a new slice. In this case, the revenue of network operators can be increased.

E. Slice Security

As a network slice has to be exposed to different roles and entities, network slicing encounters security issues in the following aspects:

- A network slice may be managed and maintained by a number of roles including slice owners (who request the slice), tenants (who actually use the slice to run services), and network operators (who provide resources to support the slice). The control ability for different roles needs to be defined properly.
- Multiple network slices share the physical infrastructure resources through various virtualization technologies. Although in principle resources belonging to different slices should be isolated, some existing virtualization technologies reduce the virtualization overhead at the cost of violating the VM isolation like paravirtualization virtualized network I/O schemes [71].
- Network functions are in the software form of VNFs which are more vulnerable than its hardware form. Additional efforts e.g. redundancy might be needed to ensure the reliability of network slicing.
- Cross-domain resource allocation brings additional security issues to the E2E network slicing. Extra overheads must be needed in terms of management and control to address the corresponding security issues.

F. Standardization Efforts

Many standardization efforts are made to the 5G network and the enabling technologies of network slicing including SDN and NFV. The standard organizations include ETSI, NGMN, ONF, IETF, 3GPP, ITU, Metro Ethernet Forum (MEF), TeleManagement Forum (TM Forum), and Organization for the Advancement of Structured Information Standards (OASIS). In recent years, network slicing and softwarization are explicitly discussed in their technical reports. Table I summarizes the related network slicing standards, and the corresponding working groups of these standardization bodies, along with the outcomes of the standardization.

ETSI focuses on the standardization of NFV and Multi-access Edge Computing (MEC) and their application in network slicing. ONF is the first standard organization to apply SDN in network slicing and is currently focusing on SDN-related standards. 3GPP develops protocols for mobile telecommunications, where ETSI is part of its seven organizational partners. Network slicing starts to be included from 3GPP Release 15. NGMN develops the standards for the 5G E2E architecture framework where network slicing is part of it. IETF involves the specification of various aspects of 5G network slicing and network slice management. Recent works include 5G E2E network slicing for transport networks and packet network slices using segment routing. The IMT-2020 of ITU-T is to support diverse service requirements with E2E network slicing. Recent works include network slice orchestration and management for providing network services to 3rd party and framework for the support of network slicing. ITU-T Focus Group on Technologies for Network 2030 develops the Network 2030 architecture framework, where network slicing is part of it.

TABLE I
THE STANDARDS OF NETWORK SLICING

Standardization body	Working group/Project	Outcome (Group Report/Technical Report)	Release date
ETSI	Multi-access Edge Computing (MEC) Industry Specification Group (ISG)	Support for network slicing	2019-11
	Multi-access Edge Computing (MEC) Industry Specification Group (ISG)	Support for network slicing	2019-11
	Network Functions Virtualisation (NFV) ISG	NFV Resiliency for the support of network slicing	2019-06
	Next Generation Protocols (NGP) ISG	E2E network slicing reference framework and information model	2018-09
	NFV ISG	Network slicing support with ETSI NFV architecture framework	2017-12
NGMN	P1-Requirements and Architecture Project	5G End-to-End Architecture Framework v4.31	2020-11
	End-to-End Architecture Framework Project	5G End-to-End Architecture Framework v3	2019-08
	5G Network Management & Orchestration (NWMO) Project	5G Network and Service Management including Orchestration	2019-03
ONF	Technical Recommendations	Applying SDN Architecture to 5G Slicing	2016-04
IETF	Individual (Internet-Draft)	IETF Network Slice for 5G and its characteristics	2020-11
	TEAS (Internet-Draft)	Definition of IETF Network Slices	2020-10
	Network Working Group (Internet-Draft)	5G End-to-end Network Slice Mapping from the view of Transport Network	2020-02
	TEAS (Internet-Draft)	Packet Network Slicing using Segment Routing	2019-11
	Individual (Internet-Draft)	5G Transport Slice Connectivity Interface	2019-07
	Network Working Group (Internet-Draft)	Network Slicing Architecture	2017-06
	Network Working Group (Internet-Draft)	Network Slicing - 3GPP Use Case	2017-04
3GPP	Technical Report	Release 15	2019-10
	Technical Report	Release 16	2020-07
ITU	ITU-T Focus Group on Technologies for Network 2030	Network 2030 Architecture Framework	2020-06
	ITU-T SERIES Y	Network slice orchestration and management for providing network services to 3rd party in the IMT-2020 network	2019-12
	ITU-T SERIES Y	Framework for the support of network slicing in the IMT-2020 network	2018-12

TABLE II
THE PROJECTS OF NETWORK SLICING

The project	Key contributions	Applications considered	Award date
5G-Transformer	Transport slice creation in the order of minutes, multi-domain orchestration of transport networking and computing resources, and integrated fronthaul and backhaul networks	Transportation	2017-06
E2ENS	A commercially viable E2E network slicing ecosystem, multi-vendor, multi-domain, multi-operator contexts, and integrated RAN and core network slicing ecosystems	A selection of market-ready, operator sponsored use cases	N/A
SLICENET	E2E cognitive network slicing and slice management, and virtualized multi-domain and multi-tenant 5G networks	e-health, smart grid, and street lighting	2017-06
CORRELATION	Aim to study service-level traffic patterns, traffic correlation among different services, and improve service-level traffic prediction	N/A	2020-02
5G-Encode	Aim to develop a private 5G network, propose new business models with the adoption of 5G technologies, such as network slicing, within IIoT environment.	Manufacturing industry	Early 2020
5Genesis	Unifying diverse 5G resources across five interoperable E2E platforms, to support verticals over an E2E sliced network	N/A	2018-07

G. Projects

Most of existing projects are dedicated to the enabling technologies of network slicing, including SDN and NFV. Since 2015, some typical projects include VITAL[7] (adopting SDN and NFV in the integration of terrestrial and satellite networks), SONATA[8] (adopting SDN and NFV for flexible network programmability and optimization of software network deployment), and 5GEx[9] (adopting SDN and NFV for E2E network and service elements to mix in multi-vendor, heterogeneous technology and resource environments). In recent years, more projects dedicated for network slicing are developed, including 5G-Transformer[10], E2ENS[11], SLICENET[12],

[7] https://cordis.europa.eu/project/id/644843
[8] https://www.sonata-nfv.eu
[9] https://cordis.europa.eu/project/id/671636
[10] http://5g-transformer.eu
[11] https://telecominfraproject.com/e2ens/
[12] https://cordis.europa.eu/project/id/761913

TABLE III
THE PROOFS-OF-CONCEPT OF NETWORK SLICING

The proof-of-concept	Application areas	Key demonstration	Demo date
GSMA network slicing PoC	Power grid	Demonstrate the created network slice is able to meet the requirements of power grid applications, in terms of bandwidth, delay, reliability, isolation requirements, and number of connections	2020-02
ETSI GANA model in 5G network slicing PoC	Smart insurance IoT use case	Exhibit hybrid SON Mappings to the ETSI GANA Model while ensuring E2E Autonomic (Closed-Loop) Service for 5G Network Slices by Cross-Domain Federated GANA Knowledge Planes	2018-10
		Implement both GANA Knowledge Planes and ONAP for fulfilling requirements of ETSI GANA Standard by using ONAP Components	2019-02
		Demonstrate Programmable Traffic Monitoring Fabrics to empower On-Demand Monitoring and Feeding of Knowledge into the ETSI GANA Knowledge Plane for assuring 5G Network Slices automatically; and Orchestrated Service Monitoring in NFV/Clouds	2019-01
		Exploit ETSI GANA as Multi-Layer AI Framework for Implementing AI Models for Autonomic Management & Control (AMC) of Networks and Services; and Intent-Based Networking (IBN) via GANA Knowledge Planes (KPs)	2019-09
		Evaluate AI Models and Cognitive Decision Elements of ETSI GANA Model via a Generic Test Framework for Testing GANA Multi-Layer automatically & their AI Algorithms for Closed-Loop Network Automation	2020-03
		Use Generic Framework for Multi-Domain Federated ETSI GANA Knowledge Planes (KPs) for E2E Closed-Loop Security Management & Control for 5G Slices	2020-06
Cisco's PoC for KDDI 5G standalone network	N/A	Build a 5G standalone network for KDDI with network slicing features	2020-02
SLICENET's PoC	N/A	Slice management for an E2E network slice across multiple administrative domains; fault prediction on network slices by virtue of machine learning mechanisms; automatic policy based actions implementation to guarantee the E2E slice availability	2019-07
UK's 5G network slicing PoC	Smart tourism	Test the network slicing capabilities of 5G in a visitor attraction setting (The Roman Baths); video and images make up the Virtual Reality (VR) experience to transport the user through time	2019-03
	Concert	Using network slicing to support a product that allows many users to experience the same VR reality at the same time	N/A

CORRELATION[13], 5G-Encode[14], and 5Genesis[15]. Table II summarizes the scope and key contributions of the typical network slicing projects.

H. Proof-of-concept products

With the advancement of network slicing technologies in both academia and industry, several Proof-of-Concept (PoC) products have been developed and demonstrated in a range of application areas. Typical examples include: GSMA network slicing PoC for power grid[16], ETSI GANA (Generic Autonomic Networking Architecture) model in 5G network slicing[17] that includes six proof-of-concept from 2018 to 2020, Cisco's PoC for KDDI 5G standalone network with network slicing features[18], SLICENET project's PoC on predictive fault management of E2E multi-domain network slicing[19], and UK's 5G network slicing PoC[20] that includes mobile virtual reality and heritage, a network slicing for an urban setting, 3D motion tracking, and 4K 360 degree content. Table III summarizes the key technologies and application areas of typical network slicing PoC products.

I. Existing Surveys on Network Slicing

The technologies of network slicing have been well developed, according to the investigation on its various aspects in Sections II-B and II-H. In this section, we summarize the key contributions of existing network slicing survey works and present the gap of survey works in the current literature. Table IV summarizes the key contributions of existing survey works in terms of the important aspects of network slicing.

Most surveys only investigate the general use cases of network slicing without explicitly discussing the details for specific application scenarios. The works in [75], [80] mentioned several specific application scenarios, and the works in [81], [82] focused on inter-slice mobility management in 5G. For example, Saraiva de Sousa et al. [75] included next-generation mobile communication networks, transportation networks, data centers, and IoT. Campolo et al. [80] focused on vehicle-to-everything services. Addad et al. [82] investigated drone traffic control, autonomous vehicles, and rapidly changing video streaming. However, these works [75], [80], [82] only discussed the advantage of network slicing and its enabling technologies at a high level. In contrast, our survey focuses on the detailed application and analysis of network slicing in

[13]https://news.cision.com/ranplan-wireless/i/5g-network-slicing-optimisatoin-graphic-correlation,c2762185
[14]https://www.5g-encode.com
[15]https://5genesis.eu
[16]https://www.gsma.com/futurenetworks/wp-content/uploads/2020/02/Network-Slicing-Proof-of-Concept_Power-Grid_CMCC_Huawei_CSG_GSMA_Apr20.pdf
[17]https://intwiki.etsi.org/index.php?title=Accepted_PoC_proposals
[18]https://newsroom.cisco.com/press-release-content?type=webcontent&articleId=2056982
[19]https://slicenet.eu/slicenet-poc-contributions/
[20]https://www.westofengland-ca.gov.uk/infrastructure/5g-smart-tourism/5g-use-cases/

TABLE IV
THE KEY CONTRIBUTIONS OF EXISTING SURVEY WORKS OF NETWORK SLICING

The survey works of network slicing	Enabling technologies	Architectures	Orchestration and management	PoCs	Standard-izations	General use cases	Specific applications
Barakabitze et al. [72]	✓	✓	✓	✓	✓	✓	✗
Laghrissi et al. [7]	✓	✗	✗	✗	✗	✗	✗
Guerzoni et al. [73]	✓	✓	✓	✗	✓	✓	✗
Lin et al. [74]	✓	✗	✓	✗	✗	✓	✗
Saraiva de Sousa et al. [75]	✓	✓	✓	✗	✓	✓	✓
Afolabi et al. [76]	✓	✓	✓	✗	✓	✓	✗
Ordonez-Lucena et al. [17]	✓	✓	✓	✗	✓	✓	✗
Taleb et al. [77]	✓	✓	✓	✗	✓	✓	✗
Su et al. [78]	✓	✓	✓	✗	✗	✗	✗
Richart et al. [26]	✓	✗	✓	✗	✗	✗	✗
Vassilaras et al. [79]	✓	✓	✓	✗	✗	✓	✗
Campolo et al. [80]	✓	✓	✓	✗	✓	✓	✓
Kaloxylos et al. [11]	✓	✓	✓	✗	✓	✓	✗
Sajjad et al. [81]	✓	✓	✓	✗	✓	✓	✗
Addad et al. [82]	✓	✓	✗	✗	✓	✓	✓
Our work	✓	✓	✓	✓	✓	✓	✓

three typical and important emerging applications in 5G and B5G, in terms of application requirements, network slicing architecture, network slice orchestration and management, the corresponding research challenges and open issues. The network slice orchestration architecture for each application is studied, along with the AI-assisted management and operation works. For each application, a list of important questions regarding the creation and maintenance of network slicing is discussed, including computational complexity, resource availability, the available datesets that can be used for the AI-related research of network slicing, performance evaluation, benchmarks, and the future research directions.

III. Architecture of Intelligent Network Slicing Management for IIoT Applications

This section introduces an architecture of intelligent network slicing management for three key IIoT services: smart transportation, smart energy, and smart factory. We first present the overall architecture of intelligent network slicing management in Section III-A. We next present pervasive intelligence across multiple domains in Section III-B and discuss challenges of intelligent network slicing management in Section III-C.

A. Architecture of intelligent network slicing management for smart transportation, smart energy, and smart factory

The provision of intelligent network slicing management services can foster three key IIoT applications: smart transportation, smart energy, and smart factory. Fig. 8 presents an architecture of intelligent network slicing management for offering solutions to smart transportation, smart energy, and smart factory. This architecture consists of a cross-domain network infrastructure, network slices, and intelligent network slicing services. As depicted in Fig. 8, a cross-domain network infrastructure is composed of various terminals, radio access networks, transportation networks (deployed with edge devices), core networks, and cloud/storage services. In this architecture, intelligent network slicing management plays an important role in connecting the underlying cross-domain network infrastructure and providing users with multiple network slices for IIoT.

Intelligent network slicing management services essentially contain the following key components: 1) operation support system (OSS)/business support system (BSS), 2) VNF pool, 3) MANO, 4) slice templates, 5) slicing orchestrator, 6) SDN, 7) big data, and 8) AI algorithms. Serving a middleware between the underlying network slices and the tenants, OSS/BSS provides the tenants with detailed slice descriptions, which can be further used to design slices after tailoring existing slice templates. The underlying hardware resources can be virtualized through computing virtualization and network virtualization so as to offer VMs, containers and VNF pools. Each slice (e.g., smart energy slice) can be constructed and implemented by either underlying hardware resources or virtualized computing/network-related resources. For simplification of implementing network slices, tenants often offer slice templates, which can be further tailored to meet different requirements. After decoupling the control plane from the data plane, SDN technologies can enable various network slicing services as mentioned in Section II.

It is worth mentioning that both big data and AI algorithms play a crucial role in endowing intelligence across multiple domains for the entire IIoT. In particular, big data analytics on IIoT data can help to extract valuable information from massive IIoT data collected across different domains, such as transportation systems, power grids, and factories. These

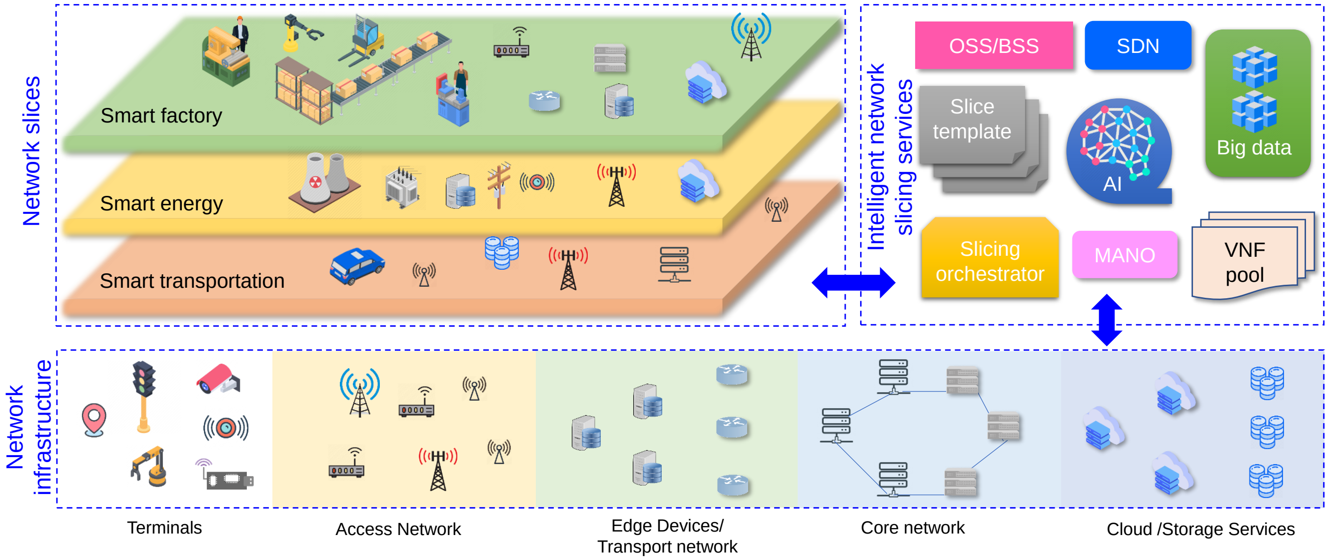

Fig. 8. Architecture of intelligent network slicing management for smart transportation, smart energy, and smart factory

IIoT data can be further analyzed by data analytics tools so as to capture user demands, behaviours, and machine/device states (e.g., faults or malfunctions). To this end, the recent advances in AI algorithms, especially for machine learning (ML) and deep learning (DL) algorithms bring opportunities in data analytics [83]. In addition to ML/DL schemes in data analytics, the recent advent in deep reinforcement learning (DRL) [84] and distributed federated learning [85] also further endow IIoT with the pervasive intelligence across multiple domains.

B. Pervasive Intelligence Across Multiple Domains

It is a necessity to achieve a pervasive intelligence across multiple domains for IIoT applications. This pervasive intelligence should be deployed from IIoT devices to nearby edge nodes as well as remote cloud servers [86]. Take DL algorithms as an example. Despite the advances of DL algorithms in extracting valuable information from IIoT data, they often have stringent requirements on computing resources. As a result, computational-intensive DL tasks have often offloaded to remote cloud servers. However, remote clouds may not be able to meet the critical latency requirements. Thus, some latency-sensitive tasks need to be executed at nearby edge nodes or IIoT devices. Consequently, a collaboration between IIoT devices, edge nodes, and remote clouds becomes an inevitable trend to fully realize pervasive intelligence [87].

It is worth noting that collaborative schemes for the device-edge-cloud computing paradigm need to address the cross-multi-domain issues. For example, caching/storage services in smart transportation are also necessary especially for infotainment applications while different services providers may offer caching or streaming services at either edge nodes or cloud servers. These services providers may be located at different domains. Thus, the collaborative schemes for IIoT devices, edge nodes, and cloud servers need to explicitly address these issues, like subscribing or signing different SLAs with different services providers. We will further discuss these issues in the coming sections with respect to smart transportation, smart energy, and smart factory.

C. Challenges on intelligent network slicing management

Although intelligent network slicing management is promising to offer intelligent IIoT services to further support smart transportation, smart energy, and smart factory, it also poses several research challenges. We summarize these challenges from the following perspectives.

- *Diversity of critical requirements* of different IIoT applications. The heterogeneity of IIoT applications leads to the diverse requirements on network slicing management. Take smart transportation as an example. Driving/transportation safety applications may have high requirements on communication latency. However, vehicular infotainment services may be latency-tolerant while having high requirements on data rate. Consider the emerging applications like autonomous driving, which may have critical requirements on both latency and data rate. The complex requirements of diverse applications may lead to the difficulty in designing network slice templates and managing different virtual/physical resources.
- *Complexity in cross-domain slicing management*. Another challenge of intelligent network slicing management lies in the complexity of slicing management across different domains. Take smart energy as an example, in which a network slice dedicated for a smart energy application (e.g., meter-reading service) may be involved with multiple sectors such as grid operators, business customers, residential customers, and payment services. It is necessary to properly handle service function chains across different domains though the cross-domain slicing management is very complex.
- *Difficulty in obtaining IIoT datasets*. Although IIoT generates massive data, the heterogeneous IIoT data may

contain noises, errors, and redundant information. Meanwhile, due to the privacy and security concerns, these IIoT data may not be always publicly available for researchers for the further analysis. All these factors lead to the difficulty in obtaining well-processed IIoT datasets, especially for smart energy and smart factory.

In the next sections, we will further elaborate on the detailed analysis of three key IIoT services from the aspects of application requirements, network slicing architecture, enabling technologies, AI-assisted orchestration, MEC-empowered slicing, and open issues.

IV. Autonomous Vehicle and Smart Transportation

This section presents an overview of network slicing solutions to autonomous vehicles and smart transportation. We start from critical requirements of smart transportation and then present the network-slicing architecture to address these requirements. We next present network slice orchestration and discuss challenges as well as open issues. Finally, we give an analysis on other issues such as computational complexity and performance benchmarks.

A. Requirements and Architecture

There are growing interests in autonomous vehicles and smart transportation from both industry and academia. Many research efforts have been concentrated on improving vehicular communications and establishing intelligent transportation systems (ITS), both of which play a crucial role in fostering smart transportation. In particular, vehicular communications mainly address communications and networking issues in a vehicle-to-everything (V2X) manner [80], [88]. In particular, V2X communications mainly include vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and the vehicle-to-network (V2N). Consequently, diverse elements in vehicular communications are interconnected with the transportation infrastructure, thereby underpinning ITS and other vehicular applications. However, diverse vehicular applications also have different service requirements on underlying vehicular communications and networks. In the following, we first present use cases in smart transportation. We then analyze the critical requirements of these use cases.

1) Use cases of network slicing in smart transportation: V2X communications are enabling a diversity of vehicular applications. We mainly consider four typical use cases and analyze their critical requirements. As shown in Fig. 9, there are four use cases in smart transportation: (i) localization and navigation, (ii) driving/transportation safety, (iii) autonomous driving, (iv) infotainment services. In the following, we further elaborate on them.

Localization and navigation. In a smart transportation system, vehicles, pedestrians, and various sensors can collect context-aware sensory data. However, both precise location information and strictly synchronized timestamps are often required for the data providers [89]. For example, a navigation system should be timely updated with an accurate position (i.e., coordinates) of a road under construction as well as the

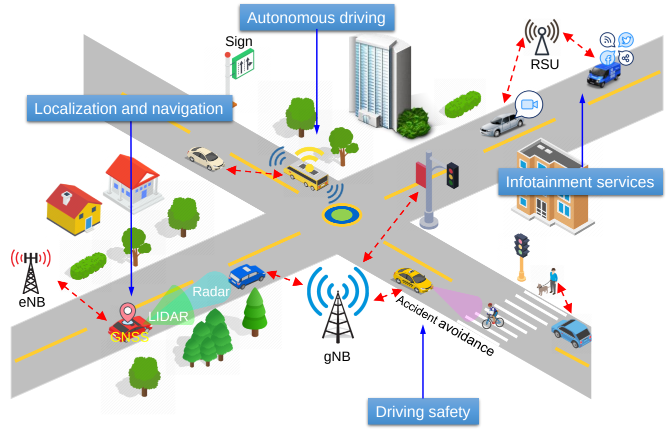

Fig. 9. Application scenarios in smart transportation.

traffic-congestion period, so that drivers can avoid such a road when driving. As one of the main localization methods, the Global Navigation Satellite System (GNSS) can reach 1 cm localization accuracy with extra hardware requirement or the localization accuracy within 1 m without additional hardware devices [90]. In addition to GNSS, other devices, such as radar, light detection and ranging (LIDAR), and Infrared (IR) cameras have also been adopted to assist navigation. For example, radar can detect moving objects (such as vehicles and pedestrians) and analyze their distance, direction, and speed, while IR cameras can detect hot objects, especially for pedestrians. Such technologies can enhance the localization and navigation system to support other applications such as autonomous driving.

Driving/transportation safety. It is reported that traffic accidents have caused lots of casualties and fatalities every year. Thus, transportation safety has been a crucial issue in smart transportation. Sending safety warnings to vehicles can inform drivers beforehand so as to avoid collisions [91]. During this process, real-time and reliable V2X communications can guarantee the timely delivery of warning messages. For example, a vehicle witnessing the rear-end collision can send warning messages to other vehicles driving towards the collision place. In this case, the timeliness of message delivery becomes crucial to the early warning.

Autonomous driving. With the rapid development of diverse information and communications technologies (ICT) and vehicle mechanical technologies, autonomous vehicles have experienced a fast evolution [92]. Autonomous vehicles are expected to alleviate the burden of human drivers and reduce the traffic congestion by precisely controlling vehicles and intelligently scheduling/planning routes. Autonomous driving is essentially involved with a wide spectrum of technologies, including vehicle mechanics, navigation, adaptive cruise control, machine vision, and vehicle automation. V2X communications play a critical role in autonomous driving, since autonomous vehicles need to connect with the transportation infrastructure to exchange information (e.g., navigation information, map, localization, traffic status, etc.).

Infotainment services. Vehicular manufacturers have recently integrated LED display, touchscreen, Dolby audio

TABLE V
CRITICAL REQUIREMENTS OF TYPICAL USE CASES OF SMART TRANSPORTATION

Requirements / Use cases	Communications			Data storage/cache	Computing	Security
	Latency	**Data rate**	**Reliability**			
Localization and navigation	10 ms ∼ 100 ms	1 Mb/s	low to high	★★	★★	low to high
Driving/transportation safety	50 ms ∼ 100 ms	1 Mb/s	99.9%	★	★	high
Autonomous driving	1 ms	10 Mb/s	close to 100%	★★★	★★★★★	high
Infotainment services	up to 100 ms	15 Mb/s	fair	★★★★★	★★★★	low to medium

Requirement level: from the lowest (★) to the highest (★★★★★)

systems into vehicles to achieve in-car entertainment. In-vehicle infotainment services include high definition (HD) video streaming, music streaming, social media accessing, Web browsing, and game playing [93]. The proliferation of autonomous vehicles in the future will further foster the popularity of infotainment services in vehicles. However, the emerging in-vehicle infotainment services also raise critical requirements on V2X communications, e.g., the high data rate for HD video streaming.

2) Critical requirements: As discussed above, vehicular applications in smart transportation have different communication requirements in terms of latency, data rate, and reliability. Meanwhile, these applications also have critical requirements on data storage (cache), computing, and security. Table V summarizes the critical requirements for the four typical use cases in smart transportation.

Firstly, there are a diversity of localization and navigation services with varied latency requirements [94]. For example, the localization of a vehicle for repairing and maintenance purposes may be latency-tolerant, while it is latency-critical for localization for autonomous vehicles [95]. In general, localization and navigation services also have the low data rate requirement. Similarly, they have diverse reliability requirements for different scenarios. Moreover, localization and navigation services have less critical data storage and computing requirements. Although most localization and navigation services have low security requirement, it becomes crucial to ensure high security of localization and navigation for autonomous driving applications against malicious attacks, such as GPS spoofing attacks [96].

Secondly, similar to localization and navigation services, driving/transportation safety applications have less stringent requirements on latency and data rate, while they often have a higher requirement on the reliability, especially for the successful delivery rate of warning messages [97]. Meanwhile, driving/transportation safety applications have no critical requirements on both data storage and computing [98]. However, they often have a stringent requirement on security [99].

Thirdly, compared with localization and navigation services as well as driving/transportation safety applications, autonomous driving has extremely critical requirements on all three aspects of V2X communications. For example, as shown in [100], the latency requirement is less than 1 ms, which is challenging to incumbent 4G cellular networks as well as dedicated short-range communications (DSRC) systems though the emerging 5G cellular networks can fulfill this critical requirement. Meanwhile, autonomous driving also has critical requirements on computing and security though data storage and cache may not be the critical issue.

Lastly, infotainment services are usually latency-tolerant, while they have diverse requirements on data rate, ranging from 0.5Mb/s for web browsing to 15Mb/s for HD video streaming [97]. Considering massive volumes of videos and social-media data, infotainment services have high requirements on data storage and cache. The emerging augmented reality and virtual reality (AR/VR) applications in future in-vehicle infotainment services may also bring higher demands on computing.

3) Network slicing architecture: To fulfill the emerging requirements of diverse smart transportation applications, network slicing technologies have been proposed and developed. Fig. 10 depicts a general network slicing architecture for the above four typical use cases in smart transportation. The lowest layer in this architecture is essentially the infrastructure layer, which can provide upper-layer applications with networking and computing services.

The infrastructure layer consists of diverse communications resources as well as computing resources (also including storage facilities). Communications resources include DSRC, 4G cellular networks, and 5G cellular networks, as well as the corresponding networking facilities. DSRC mainly provides short-range and line-of-sight communications [101]. The 4G cellular networks also refer to Long Term Evolution Advanced (LTE-A) networks, which are an upgrade from original LTE networks. In 4G cellular networks, vehicles and user equipment (UE) are connected to an evolved NodeB (eNB) or multiple eNBs via radio access networks (RAN). The eNBs are connected to the evolved packet core (EPC) network via backhaul links [102]. The 5G cellular networks are essentially a revolutionary architecture in contrast to the existing LTE-A networks. Similar to eNBs, 5G base station nodes (gNBs) interconnect vehicles or UE via wireless links. The gNBs are connected to 5G core (5GC) networks via backhaul links. In addition to communications resources, the provision of diverse computing resources can enable various smart transportation applications. Computing resources include computing facilities provided by remote cloud services providers and data centers and/or edge/fog computing facilities deployed at eNBs or gNBs in close approximation to UEs and vehicles.

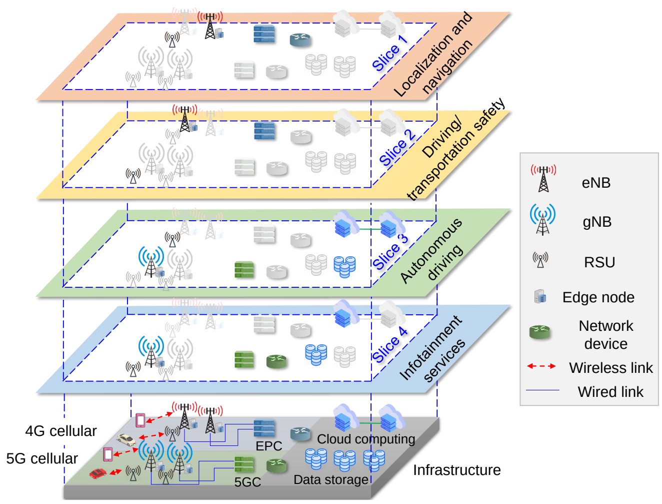

Fig. 10. The network slicing architecture for smart transportation

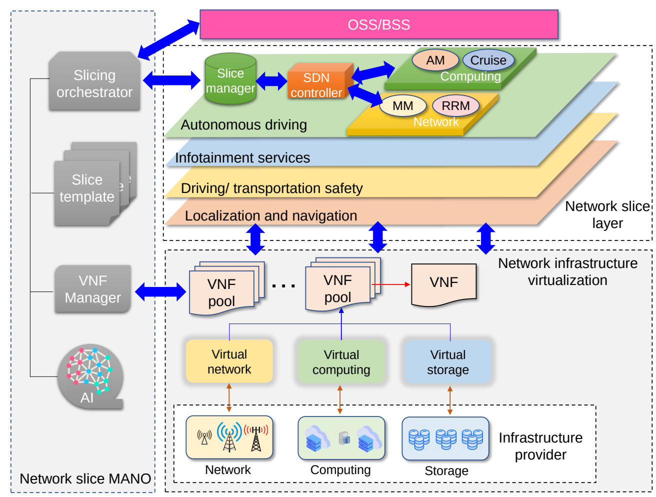

Fig. 11. The network slice orchestration architecture

4) Key enabling technologies: This architecture includes both evolutionary (e.g., DSRC and LTE-A) and revolutionary (e.g., 5G) resources, whereas the underlying physical network infrastructure can be utilized to support multiple concurrent network slices, each of which accommodates a specific smart transportation application. During this process, network slicing plays a crucial role to achieve this goal.

However, network slicing of smart transportation heavily depends on two key supportive technologies: NFV and SDN. In particular, NFV can create multiple virtualized network instances from a sole network infrastructure, thereby achieving the flexible deployment and elastic network services for transportation scenarios. SDN makes network functions (NF) be programmable and dynamically adjusts network traffic flows to fulfill the emerging demands of diverse transportation applications. The in-depth integration of NFV and SDN can achieve scalable and flexible network slicing services though it is non-trivial to achieve this amalgamation.

B. Network Slice Orchestration and Management

As mentioned above, both NFV and SDN play an important role to achieve network slicing. NFV is essentially enabling multiple VNFs on top of physical networks while SDN facilitates the network control by separating the control plane from the data plane. To fully unleash the potentials of NFV and SDN, an orchestration of diverse NFV and SDN services is a necessity. We then present a network slice orchestration architecture for smart transportation.

1) Network slice orchestration architecture for smart transportation: Fig. 11 depicts the network slice orchestration architecture for smart transportation. This architecture consists of the following components: 1) network infrastructure virtualization, 2) network slice layer, 3) OSS and BSS, and 4) MANO.

In network infrastructure virtualization, infrastructure providers provide different types of hardware resources including communications/networking resources, computing and storage resources. Those hardware resources can be virtualized through computing virtualization (e.g., VMs and containers) and network virtualization (e.g., NFVs), consequently forming VNF pools. It is worth mentioning that infrastructure providers often refer to two types of operators: (i) Mobile Network Operators (MNOs) maintain and manage physical hardware resources; (ii) Mobile Virtual Network Operators (MVNOs) lease and manage virtual resources (VNFs) being virtually created by MNOs.

In the network slice layer, each slice can be implemented by underlying network infrastructure virtualization services. For example, the autonomous driving slice is composed of a number of virtual or physical functions (i.e., VNFs or PNFs). We broadly categorize them into two types: (1) computing-related and (2) network-related VNFs/PNFs. Regarding network-related VNFs or PNFs, the autonomous driving slice mainly includes mobility management (MM) and radio resource management (RRM), as autonomous driving has critical requirements on communications. With respect to computing-related VNFs or PNFs, the autonomous driving slice has authentication management and cruise services, since both security and self-driving authentication are crucial to autonomous driving [92]. However, both computing-related and network-related VNFs or PNFs need to be properly controlled by SDN controllers, which facilitate the network control by separating the control plane from the data plane (i.e., VNFs or PNFs). SDN helps to construct the correct service chain, which consists of a number of VNFs or PNFs.

On top of the network slice layer, both OSS and BSS play a role of a middleware between underlying network slices and the tenants. OSS/BSS offers slice descriptions to tenants who may redefine their requirements [97]. Finally, SLAs can be reached after several rounds of negotiations.

Network slice MANO plays a crucial role to manage network infrastructure virtualization and network slices. Firstly, VNF managers can monitor and supervise the VNF pool. Secondly, MANO may provide a tenant with a predefined slice template so as to simplify the decision made by users [108].

TABLE VI
COMPARISON OF NETWORK SLICING SOLUTIONS FOR SMART TRANSPORTATION

Network slicing approaches	Enabling technologies	Architectures	Orchestration and management	Use cases
Mei et al. [97]	SDN, Deep Reinforcement Learning	Combination of edge/cloud for Vehicle to Everything (V2X) services	VNF management and network slice configuration management	Transportation safety, autonomous-driving services
Bega et al. [37]	MEC, Reinforcement Learning	p Close-loop admission/resources management	AI-based slice management	Admission control and dynamic resource allocation
Shen et al. [103]	Deep Reinforcement Learning	RAN-slicing framework	Network planning and network resource scheduling	Radio Access Technology (RAT) and caching-centric resource management
Ksentini and Frangoudis [104]	MEC, NFV	Network service-oriented architecture	NFV orchestrator	Multi-tenancy
Cominardi et al. [10]	MEC, SDN, NFV	MEC-in-NFV architecture	MEC/NFV Orchestration	End-to-End multiple slices and Multi-tenant slices
Huang et al. [105]	Optical Underlay, NFV, VNF	Slice control and orchestration architecture	VNF manager, NFV orchestrator	End-to-End multiple slices
Gomes et al. [106]	Elastic Optical Networks, Multi-path provisioning	Reliability-based architecture	Network slices management	QoS reliability
Fan et al. [107]	Encryption, Authentication	Authentication and access control architecture	Network-slice orchestration	Cross-slice authentication

On the one hand, the slice orchestrator may interact with OSS/BSS to fulfill requirements defined in SLAs. On the other hand, the slice orchestrator also communicates with the slice manager per slice (i.e., each slice has a slice manager) to further tailor functions of the slice.

2) AI-assisted management and operation: Although the network slice orchestration architecture facilitates the management of network slices, it is challenging to efficiently manage various network/computing resources to fulfill the dynamically-varied user demands. Firstly, either physical hardware network/computing facilities or virtual network functions may suffer from various failures, malfunctions, and even malicious attacks. How to adjust VNF pools to promptly remedy the lost VNFs or PNFs is a challenge, especially for those real-time smart transportation services. Secondly, the dynamically-changed topologies of vehicular networks also lead to the difficulty in managing underlying network infrastructure resources. Thirdly, smart transportation applications vary in complexity. For example, the driving-safety application may only need to send warning messages in time, while infotainment services may have different data rates and latency requirements, e.g., web browsing versus 4K video streaming. It is very difficult to capture the varying patterns of applications in smart transportation [103].

Recent advances in big data analytics and AI [109] bring the opportunities to overcome the above challenges in network slice orchestration for smart transportation. In particular, either vehicles and UE collect massive vehicular data, which can be further analyzed to extract valuable information. The vehicular data can be analyzed by ML/DL algorithms so as to capture user behaviours and demands. To this end, there are several recent attempts [37], [103], [110]. The work [110] put forth deploying AI into 5G network slicing framework with two cases to demonstrate the PoC. In [37], the authors presented an AI-based framework for network slice management, especially for the admission control and dynamic resource allocation. Shen et al. [103] proposed that AI can be included into the network slice management in next-generation wireless networks. The integration of AI with network slice management demonstrates numerous benefits, such as flexibility of RAN slicing and content-caching management.

3) MEC-empowered network slicing: As discussed in Section IV-A, smart transportation applications such as autonomous driving and infotainment services often have high computational requirements on computing facilities. For example, autonomous driving often needs to deal with computer vision tasks like object detection, which nevertheless requires extensively training deep learning models using massive data [111]. Meanwhile, the training process of these DL models is often required to be done at remote clouds equipped with Graphics Processing Units (GPUs). However, uploading massive training data and DL models to remote clouds inevitably causes high end-to-end latency and consumes substantial bandwidth. These overheads constrain the wide adoption of DL algorithms in smart transportation applications.

MEC/fog technologies can offload the computing/storage tasks from remote clouds to approachable nodes, such as gNBs, eNBs, and RSUs, thereby significantly reducing the latency and alleviating the bandwidth consumption. Thus, MEC that can complement cloud computing, essentially plays an important role in facilitating smart transportation applications. It is worth investigating the fusion of MEC with network slicing technologies. There are also some efforts along this line [10], [104]. In [104], the authors attempted to address the compatibility issue when integrating MEC with network slicing, since two different standardization systems of MEC and network slicing made by ETSI and 3GPP may cause the compatibility problem. Cominardi et al. [10] investigated the issues when integrating network slicing into MEC. They proposed the solutions to address some challenges in terms of evolving MEC toward supporting E2E multiple slices and multiple tenants.

4) Reliability and security: It is extremely important to ensure ultra reliable communications in critical smart transportation applications like autonomous driving. However, existing network slicing technologies may not fulfill the close-to-100% reliability. There are several efforts working toward achieving ultra reliable communications [105]. The work [106] analyzed the reliability requirements in SLAs and presented an algorithm to achieve efficient slice allocation and network reliability. Meanwhile, the work [105] proposed an optical underlay network to achieve network slicing with high reliability and low E2E latency. In addition to the adoption of optical networks, Shahriar et al. [112] explored bandwidth-squeezing and multi-path provisioning technologies to further improve reliability.

In addition to reliability, security is another important issue for network slicing technologies [113]. As summarized in [114], security threats cover the entire life cycle of network slicing as well as intra-slice and inter-slice management. Countermeasures against the security threats include the authentication management [107], access control and authorization [115], and incorporation of blockchain [116].

Table VI compares representative network slicing solutions for smart transportation.

C. Challenges and Open Issues

Despite opportunities brought by network slicing technologies, the real deployment of network slicing into 5G and B5G networks still poses a number of challenges. We next discuss these challenges according to the following perspectives.

1) Cross-domain slicing: One of the major challenges in implementing network slicing for 5G networks lies in the cross-domain slicing when considering complex and heterogeneous smart transportation applications across different domains. Cross-domain slicing requires properly handling service function chains (SFC), which often span diverse business sectors and networking/computing domains. For example, in-vehicle infotainment services may be offered by different Over-The-Top (OTT) service providers, each of which signs an SLA with MNOs/MVNOs. Consequently, the infotainment services may be involved with multiple MNOs/MVNOs across multiple virtual/physical domains. Therefore, it is challenging to address the optimization in cross-domain network slicing. Although recent studies such as [69], [77] have partially addressed this challenge by Mixed Integer Linear Programming optimization and cross-domain coordinator, the solutions to real smart transportation scenarios are still unexplored.

2) Performance issues: Diverse requirements of smart transportation applications reflect some performance issues in network slicing implementations. For example, autonomous driving may require extremely low latency, while infotainment services demand a high data rate. In addition, the safety of autonomous vehicles has been a major concern to public confidence [117]. However, how to quantify the safety as well as the performance metrics (like speed, transportation efficiency, and other performance metrics) is still an open question. There are some attempts toward solving this issue. For example, Wang and Wei [118] proposed two concepts: safe-driving capacity and safe-driving throughput, both of which can be used to evaluate the safe traffic efficiency, though there is still a long way to go before comprehensively solving this issue.

3) Business models (Interfaces, standardization): As discussed in Section IV-A, there are diverse smart transportation applications corresponding to different business/economic models. Meanwhile, multiple OTT service providers interact with MVNOs and MNOs via multiple SLAs, which specify the QoS levels as well as expiration time of services. These stakeholders in smart transportation applications have different requirements and profit goals. It is challenging to establish business/economic models to optimize these business interactions across different domains. Despite some advanced techniques made by recent studies such as [119], [120] on establishing game-theoretical as well as tenant business models in general wireless networks, there is a long way to go before establishing a general framework for smart transportation.

Besides business and economic models, the interactions between multiple stakeholders also pose challenges in establishing subscriptions on network slicing services offered by different MVNOs and MNOs. The emerging brokerage services can simplify the complex interactions [121]. Meanwhile, the introduction of blockchain and smart contracts to brokerage services can further automate the interactions such as payment and settlement processes between multiple stakeholders [122]. However, the real implementation of blockchain-based brokerage services for network slicing in smart transportation is still expected in the future.

4) Deployment issues (feasibility study): Although there are a number of PoC projects of network slicing, both realistic deployment and full implementation of network slicing in smart transportation still pose some practical challenges. For example, the recent work [123] indicated that the lack of clear QoS definitions (especially for performance metrics) leads to design and implementation challenges. Moreover, there are also other challenges in practical deployments of network slicing [124], [125]: (1) identifying and capturing requirements from users; (2) modelling the SFCs according to the classification of user requirements; (3) breaking down the SFCs into network slices; (4) orchestrating underlying VNFs to fulfill the requirements. However, it is still challenging to address the above issues when deploying network slicing services.

D. Discussion and Remarks

1) Computational complexity and resource availability: The implementation of autonomous driving and smart transportation is subject to complex constraints and criteria. Therefore, a set of algorithms need to be developed to fulfill the objectives while satisfying constraints [126]. For example, Dijkstra's shortest-path algorithm can be used to find paths between two links of a road [127]. However, the computational complexity of algorithms (e.g., computing time) should be considered in autonomous driving applications [126], [128].

Besides the computational complexity of algorithms, resource constraints should also be considered when developing autonomous driving and smart transportation applications [129]. For example, the limited battery capacity of vehicles leads to the infeasibility of computational-complex algorithms being deployed at vehicles. Therefore, the orchestration between edge and cloud computing facilities becomes a necessity [130], in which some computational-complex algorithms can be offloaded to remote clouds while latency-sensitive algorithms should be conducted at edge nodes (deployed at gNB or RSU).

2) Datasets and simulators: With the development and implementation of network slicing techniques in smart transportation and autonomous driving, there are a number of datasets available for conducting experiments and PoC testing. Some recent studies summarize those datasets on smart transportation and autonomous driving [117], [131], [132]. For example, [131] described a dataset of aerial images and airborne LIDAR images covering 8,439 km of roads in Toronto city, while this dataset is only available for students/employees at the University of Toronto. The work [132] presented a survey on 27 public-road datasets. Guo, Kurup and Shah [117] provided a state-of-the-art survey on 54 public driving datasets with categorizations according to different drivable factors such as environmental factors and behavioral factors. It is expected to conduct experiments of network slicing based on those publicly available datasets.

In addition to the datasets, there are also lots of simulators for either advanced driver-assistance systems and autonomous vehicles. For example, Car Learning to Act (CARLA) [133] presents an open-source simulator for developing, training, validating autonomous vehicles[21]. Another tool set offered by NVIDIA's DRIVE Sim and Constellation[22] can simulate various driving environments. Moreover, Apollo[23] offered by Baidu also provides functions for driving simulations. Furthermore, the provision of Cruden's software and simulators[24] can also support driving simulations and advanced driver-assistance systems. However, as far as we know, there is *no network-slicing simulator for either smart transportation or autonomous driving*.

3) Performance evaluation and benchmarks: Regarding performance evaluation of autonomous driving and smart transportation, there are a few studies [117]. For example, [117] proposed the *driveability* property to evaluate how autonomous driving is feasible from various factors covering environments and driving behaviours. Moreover, traffic signs are also crucial to advanced driver-assistance systems and autonomous driving. Therefore, there are several benchmarks as well as datasets for traffic sign recognition and traffic sign detection [134]–[137]. In particular, German Traffic Sign Recognition Benchmark (GTSRB) [134] and German traffic sign detection benchmark (GTSDB) [135] were mainly constructed on traffic signs of Germany. The recent studies [136], [137] have further extended GTSRB and GTSDB datasets to European traffic signs. However, there is no study on performance evaluation and benchmarks on either smart transportation or autonomous driving.

[21] https://carla.org/
[22] https://www.nvidia.com/en-us/self-driving-cars/drive-constellation/
[23] https://apollo.auto/
[24] https://www.cruden.com/automotive-driving-simulators/

4) Future research directions: Network slicing technologies for smart transportation and autonomous driving are still under development. There are a number of future research directions. We enumerate some of them as follows.

Privacy. In smart transportation applications, massive transportation data have been generated from vehicles, RSU, transportation infrastructure, gNBs, and eNBs. The transportation data is then transferred to MEC nodes or remote clouds for further processing and analysis. During this process, user-sensitive data may be deliberately or unintentionally leaked to others. Moreover, in contrast to other scenarios, the trajectory privacy of vehicles is also a critical concern in smart transportation. Take localization and navigation services as an example, in which users' GPS information can be maliciously misused for launching side-channel attacks [138]. How to protect data privacy in smart transportation is an open issue.

Security. Moreover, the security of network slicing in smart transportation is still a critical issue in 5G and B5G [92]. First, it is challenging to conduct troubleshooting to identify faults and security vulnerabilities in network slicing, especially for cross-domain slicing. Second, as a supportive technology for network slicing, SDN is based on a centralized architecture, thereby suffering from single-point failures (SPF) or distributed denial-of-service (DDoS) attacks. Therefore, it is expected to address the security concerns of network slicing for smart transportation applications in the future.

V. Smart Energy

This section presents the review of network slicing solutions to smart energy. We start from critical requirements of smart energy and then present the network-slicing architecture to address these requirements. We next present network slice orchestration and management followed by a discussion on challenges as well as open issues. We also discuss the future directions.

A. Requirements and architecture

Smart energy has been a hot topic receiving a growing interest from both industry and academia [139]. Smart energy has further extended "smart grid" to a broad area covering not only existing energy systems but also emerging renewable energy systems [140]. During the evolution of smart energy, network slicing as well as other network softwarization technologies play an important role [141]. In particular, various sensors, smart meters, advanced metering infrastructure (AMI) devices, actuators, and controllers deployed in smart energy systems can obtain various ambient sensory data, which can be used to detect faults, discover system bottlenecks [142], identify malicious user behaviours, and make immediate actions/decisions [143].

Smart energy is proliferating diverse smart energy applications, which have various requirements on underlying network infrastructures. In what follows, we analyze the critical requirements of typical smart energy applications.

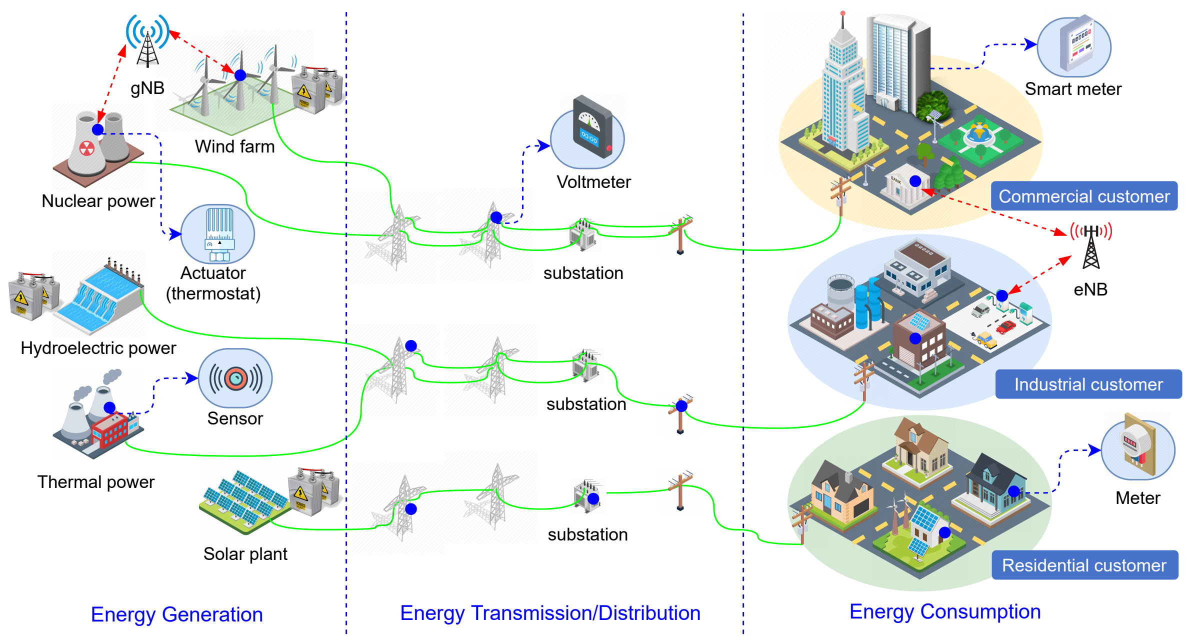

Fig. 12. Lifecycle of smart energy.

1) Use cases of network slicing in smart energy: The entire lifecycle of smart energy systems includes energy generation, energy transmission, and energy consumption, as shown in Fig. 12. Energy generation includes not only traditional energy sources such as thermal (fuel) power and nuclear power, but also renewable energy sources such as solar plants, hydroelectric power, and wind farms. Energy has usually been sent out in a form of electricity via power lines from energy sources to substations that then transmit and distribute electricity to different types of electricity consumers, such as commercial, industrial, and residential electricity customers. It is worth mentioning that smart energy systems have been evolved from centralization to distribution, exhibiting in purely centralized energy generation to distributed renewable energy generation. In each component of smart energy systems, there are diverse sensors, actuators, voltmeters, and smart meters, which can be used to sense, monitor, and perform control actions. Those sensors, actuators, and smart meters are connected in a wireless or wired manner. Typical wireless communication systems include wireless LAN (IEEE 802.11), LTE-A, 5G cellular networks, ZigBee (IEEE 802.14.4), Narrowband IoT (NB-IoT). Besides wireless communications, power-line communications have also been widely adopted in smart grids.

There are a diversity of smart energy applications. We mainly consider three typical use cases and analyze the critical requirements of them. In the following, we elaborate them in detail.

Energy measurement management. The proliferation of advanced metering infrastructure (AMI) establishes bidirectional communications between energy providers and customers [144]. AMI consists of diverse sensors and smart meters, which are interconnected via wireless or wired networks. In addition, AMI also includes computing and storage facilities that manage the measured data from entire smart energy systems. Both AMI and data management can provide customers with interactive services of energy usage and accurate billing. Moreover, energy measurement management also prevents electricity thieves, frauds, and other malicious behaviors [143]. Furthermore, measurement data should be stored either at the control centers or remote clouds for an in-depth analysis, which is beneficial to other applications such as pricing strategy, outage reactions, and demand response [145].

Distribution control and automation. As a key step between energy transmission and energy consumption, energy distribution delivers electricity to diverse customers via substations and dispatchers. In contrast to conventional electricity distribution manners, recent advances in power-system automation have greatly promoted the upgrading of energy distribution systems attributed to the wide adoption of diverse programmable logic controllers (PLCs) and supervisory control and data acquisition (SCADA) systems [146]. Electricity substations collect the electricity-load data and plan optimal routes for energy distribution across complex energy transmission networks. Dispatchers also monitor the electricity usage and manipulate electricity distributions in a real-time manner.

Renewable distributed energy sources. Renewable (RE) energy sources including solar plants, hydroelectric power, and wind farms, play a growing role in replacing conventional fuel energy sources with environment-friendly and sustainable features. However, RE energy sources are typically less stable and reliable than conventional energy sources. Thus, it is a necessity to investigate the stable and reliable energy supply from both conventional energy sources and emerging renewable energy sources. The adoption of energy storage systems to RE energy sources is a solution to the provision of reliable and consistent energy supply, while the measurement of the status of energy storage is important [147]. Moreover, the

TABLE VII
CRITICAL REQUIREMENTS OF TYPICAL USE CASES OF SMART ENERGY

Use cases \ Requirements	Communications			Data storage	Computing	Security
	Latency	Data rate	Reliability			
Energy measurement management	up to 1000 ms	10 Kb/s ∼ 500 Kb/s	99.9%	★★★	★★★	medium to high
Distribution control and automation	10 ms ∼ 100 ms	10 Kb/s ∼ 100 Kb/s	close to 100%	★★	★★★★	high
Renewable distributed energy sources	50 ms ∼ 100 ms	10 Kb/s ∼ 100 Kb/s	99.9%	★	★★★	high

Requirement level: from the lowest (★) to the highest (★★★★★)

RE energy sources are also susceptible to varied weather and environmental conditions. Therefore, the accurate forecasting of weather and environment is also crucial for RE energy management.

2) Critical requirements: Smart energy applications have various requirements on communications, data storage, computing facilities, and security. Table VII presents a summary of critical requirements of the above three typical use cases of smart energy.

Regarding energy measurement management, communications requirements vary with different phases of the entire energy life cycle. For example, the latency requirement for energy generation is more stringent than that for energy consumption, while the maximum latency requirement is still less than 1000 ms as indicated in [148]. Compared with smart transportation applications as in Section IV, energy measurement management has a relatively lower requirement on data rate while still having a high requirement on the communication reliability. Moreover, the measured data can be stored at edge nodes, substations and remote clouds for further analysis, thereby leading to higher requirements on data storage and computing than the other two use cases.

In contrast to energy measurement management, both energy distribution control and automation have stringent requirements on the latency and reliability of communications. For example, it requires detecting faults and making corrections in substation automation in near real-time [146]. Moreover, distribution automation also has rigorous requirements on monitoring, controlling, and coordinating energy distribution components in a real-time and ultra-reliable manner. Furthermore, it is of vital importance to ensure cyber-security of energy transmission and distribution against malicious attacks [149].

RE distributed energy sources have similar requirements to distribution control and automation, that is, low latency, high reliability, and security. Meanwhile, the widely-adopted energy storage systems also bring the demands of collecting the status of energy storage, thereby leading to the proliferation of various sensors and meters to energy storage systems. It is also crucial to assure the high reliability (nearly 99.9%) of the entire communication network connecting RE distributed energy sources since the highly-reliable communication network is a prerequisite to monitor and react to unstable supply (even outage) of renewable energy sources [148].

3) Network slicing architecture: To fulfill the emerging requirements of diverse smart energy applications, network slicing as well as the corresponding network softwarisation technologies have been presented. Fig. 13 depicts a general network slicing architecture for the above three typical use cases in smart energy systems. The lowest layer in this architecture is essentially the infrastructure layer that can provide upper-layer applications with networking and computing services.

The infrastructure layer consists of diverse communications resources as well as computing resources (also including data storage). Communications standards in smart grids include ZigBee [150], IEEE 802.11 ah [151], NB-IoT [152], LoRa WAN [153], PLCs, 4G cellular (LTE-A) networks, and 5G cellular networks, as well as the corresponding networking facilities. In particular, ZigBee and IEEE 802.11 ah can offer a short-range coverage of home area networks (HAN), business area networks (BAN), and neighborhood area networks (NAN) with 10 meters to 500 meters. The recent low-power wide-area network (LPWAN) technologies such as NB-IoT and LoRa WAN can provide both customers and electricity operators with wide-area network (WAN) coverage. Similar to smart transportation systems as stated in Section IV, both LTE-A and 5G cellular networks also offer connection services for massive IoT devices, thereby supporting smart energy applications such as measurement, distribution control, and RE energy management. In addition, various computing facilities such as cloud/edge/fog computing as well as data storage devices are also deployed in this infrastructure.

4) Key enabling technologies: This network slicing architecture includes both evolutionary technologies and revolutionary technologies. The evolutionary technologies include ZigBee, IEEE 802.11 ah, PLCs, 4G LTE-A, and LoRa WAN, while the revolutionary technologies include NB-IoT and 5G. The integration of legacy network technologies with revolutionary technologies can offer a cost-effective solution to smart energy systems. During this process, network slicing plays a crucial role in achieving this transformation.

It is worth mentioning that network slicing alone cannot address the emerging smart energy applications with various critical requirements. The full implementation of network slicing to smart energy systems is dependent on NFV and SDN. Specifically, multiple network functions created by NFV can enable flexible and elastic network services that can support vertical smart energy applications. Moreover, the programmable NFs can be dynamically adjusted to fulfill the emerging demands from diverse smart energy applications by SDN. Therefore, it is a necessity to integrate NFV and SDN

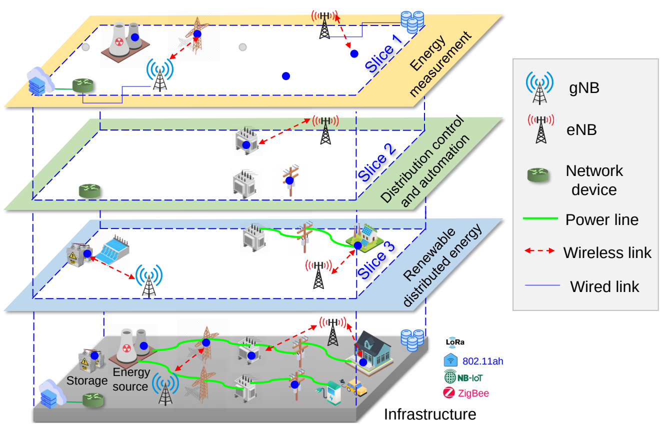

Fig. 13. The network slicing architecture for smart energy applications

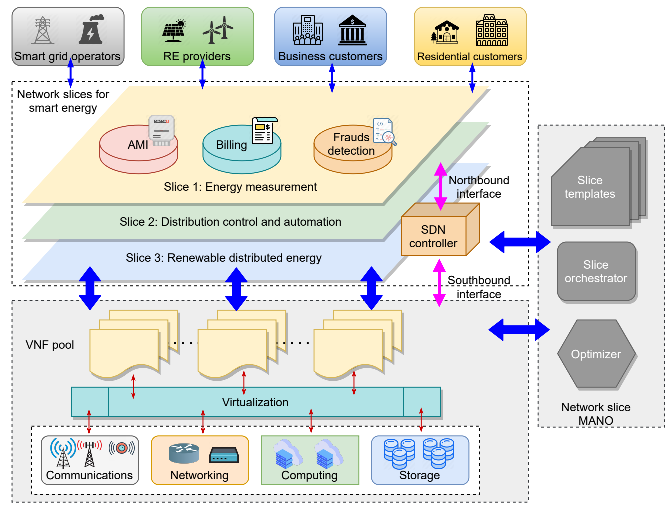

Fig. 14. Network slicing orchestration for smart energy

so as to provide both energy customers and services providers with scalable and flexible network slicing services.

B. Network Slice Orchestration and Management

Various communications and networking resources can be virtualized to provide a number of VNFs and PNFs in order to support upper-layer network slicing services. It is crucial to orchestrate underlying VNFs and PNFS to fulfill the diverse demands of smart energy applications. During this process, SDN technology plays an important role in dynamically adjusting network devices to configure networks in order to meet different types of traffics in smart grids [154]. In the following, we present a network slice orchestration architecture for smart energy applications.

1) Network slice orchestration architecture for smart energy: Fig. 14 presents a network slicing orchestration architecture for smart energy. This framework is composed of the following components: 1) a virtualized network infrastructure consisting of VNFs and PNFs, 2) network slices for smart energy, and 3) network slice MANO.

In the virtualized network infrastructure, there are diverse communications, networking, computing, and data storage resources. Those hardware resources can be virtualized by computing virtualization and network virtualization, consequently constructing a number of VNF pools.

Those VNF pools can support diverse network slices, each of which can be implemented by the underlying virtualized network infrastructure. For example, the energy measurement slice may include functions such as AMI, billing, and frauds detection. Those functions can be decomposed into a number of VNFs or PNFs, which can be further orchestrated and managed by SDN controllers. SDN controllers can construct the entire service chain (being composed of a number of VNFs or PNFs) and facilitate the network control by separating the control plane from the data plane, thereby achieving the flexibility of network control [155].

Network slice MANO also plays an important role to manage virtualized network infrastructure and network slices, consequently providing diverse network slicing services to vertical customers in smart energy [156]. In particular, network slice MANO can monitor the status of VNF pools. Meanwhile, the provision of predefined slices by MANO can simplify the network slicing design of customers. Moreover, MANO is also responsible for performance optimization of network slices.

2) AI-assisted management and operation: During the network slice orchestration for smart energy applications, AI-based algorithms can achieve the flexible and efficient management of network slices [37]. On the one hand, AI algorithms like deep neural networks can learn from historical data, identify faults or malicious behaviours, and consequently make decisions to enhance the entire system. For example, DL methods can be used to analyze and detect electricity thefts in smart grid [143], [157]. On the other hand, AI algorithms like reinforcement learning schemes can be adopted to optimize the system performance of smart energy systems. There are a number attempts toward this goal. For example, the work [158] proposed a deep reinforcement learning (DRL) algorithm to optimize the average throughput and save energy consumption in an energy-harvesting-enabled IoT system. In addition, Gao et al. [159] designed another DRL algorithm for achieving an optimal control of the ventilation and air condition system with the consideration of users' thermal comfort.

The integration of AI algorithms like DL and DRL with network slicing and network softwarization becomes an inevitable trend. For example, the work [160] presented an overview of using DL algorithms to achieve privacy protection in network slices of heterogeneous networks. Moreover, it is reported in [161] that DRL can be used to efficiently manage multiple network slices from radio, networking, and computing resources. However, the above studies only concentrate on existing cellular networks or emerging 5G networks. To the best of our knowledge, there are few studies on leveraging DL and DRL algorithms for smart grid and smart energy systems.

3) MEC-empowered network slicing for smart energy: Both data-driven smart energy applications or decision-making processes in smart energy systems have stringent requirements on computing. Similar to other applications such as smart transportation, computational-intensive tasks like DL training

TABLE VIII
COMPARISON OF NETWORK SLICING SOLUTIONS FOR SMART ENERGY

Network slicing approaches	Enabling technologies	Architectures	Orchestration and management	Use cases
Mehmood et al. [156]	Intent Analysis, MANO	Intent-based network slicing management	Slice orchestrator, SLA management	Distribution Grid
Liu and Han [161]	Deep Reinforcement Learning, SDN, edge computing	End-to-end network slicing architecture	Orchestration of RAN, transportation network and MEC	Object detection
Trajano et al. [162]	MEC, LTE cellular	MEC-based network slicing architecture	MEC and MNO management	Smart meter measurement
Sattar and Matrawy [163]	5G core, slice isolation	Network-slicing isolation framework	VNF, VM management	DDoS attacks
Thantharate et al. [164]	Deep Learning, slice management	Deep Learning-based network slicing framework	VNF management	Volume-based and Sproofing attacks
Ricart-Sanchez et al. [165]	MEC, RAN	Self-healing edge-to-core network for smart grid	Network slice orchestration	Smart grid control, user, and management traffic

on massive electricity usage data have often been offloaded to remote cloud servers. However, it cannot fulfill the stringent requirement on the latency to offload computing tasks to remote clouds, especially for the application of distribution control and automation as mentioned in Section V-A1. Therefore, it is necessary to offload those latency-critical tasks to nearby edge computing nodes [166].

There are research efforts in integrating MEC with smart energy systems. In particular, Feng et al. [167] presented a survey on applying MEC in smart grid in latency-sensitive, cognitive, and security aspects. In [162], the authors investigated deploying MEC nodes to 4G (LTE) cellular networks to meet the requirements of smart-grid applications like smart meters. The work [168] presented an MEC framework for real-time monitoring in smart grids. Despite recent advances in applying MEC in smart grid and smart energy systems, few efforts have been conducted on applying MEC for dedicated network slices for smart energy applications.

4) Reliability and security: Both reliability and security are crucial for smart grid and smart energy systems, which are serving a key infrastructure for industrial sectors and urban dwellers. As a disruptive technology in reforming existing energy systems, network slicing also needs to ensure reliable and secure network services, especially for applications like distribution control and automation (i.e., nearly 99.99% reliability and extremely high security) [146].

There are also several research attempts to ensure the reliability and security of network slicing services. In [169], the authors investigated security challenges in network slices and proposed some solutions to address these challenges. The work [163] proposed a method to tackle DDoS attacks by leveraging network slice isolation. In particular, the authors designed the framework to isolate the attacked slices while guaranteeing the reliability and availability of normal network services. Similarly, the work [164] also presented a system to quarantine the network slicing services being attacked so as to improve the network security and reliability. It is worth mentioning that this work also leveraged a DL method to detect potential threats.

Table VIII summarizes representative network slicing solutions for smart energy.

C. Challenges and Open Issues

Although network slicing has the potential to drive the evolution of smart energy systems, there are a number of challenges to be addressed before the full adoption of network slicing.

1) Cross-domain slicing: A network slice in smart energy systems may contain communications, networking, and computing resources from different operators. To reduce the operational expenditure, those multiple operators may collaborate with each other. Take an energy measurement slice as an example, in which power grid operators, RE providers, business customers and residential customers may belong to different network operators. Moreover, different communications/network protocols may be adopted by cross-domain operators. The cross-domain slicing leads to the heterogeneity and complexity of network slices, thereby posing challenges in deploying network slices in smart energy systems [170]. For example, different network operators and accessing/networking technologies have different QoS-assurance mechanisms [171]. It is challenging to assure the stringent requirements (e.g., extremely low latency and high reliability) across multiple domains in the same slice.

2) Performance issues: As discussed in Section V-A2, there are diverse key performance indicators (KPIs) for different network slicing services. For example, distribution control and automation slices may have a much higher requirement on latency and reliability than the energy measurement slice. Moreover, the consideration of multiple KPIs together may lead to the complexity of the optimal algorithms, that is, difficulty in finding polynomial-complex algorithms [172].

3) Business models (Interfaces, standardization): Although network slicing technologies are promising to enhance incumbent smart energy systems, both business models and profit models are still under development, consequently disinclining operators and customers from widely deploying network slices. Meanwhile, it is also challenging to develop economic models to optimize interacts across different domains while fulfilling different requirements and profit-making goals [173].

Besides business models, research efforts on developing interfaces of network slicing services as well as standardization efforts are expected. Despite recent efforts in standardization like ETSI, NGMN, ONF, IETF, 3GPP, ITU, etc., there are few standards dedicated for smart energy systems. Most of standard organizations only take smart energy systems (or smart grid) as a use case for network slicing technologies.

4) Deployment issues (feasibility study): There are some PoC projects of network slicing for smart energy applications. For example, according to the report of Global System for Mobile communications Association (GSMA)[25] that China Telecom, State Grid Corporation of China (SGCC), and Huawei completed the first network slice for power grid in 2019. Meanwhile, the work [165] reported a 5G network-based testbed of the self-healing network slice for smart grid. This project has essentially been funded by the European Commission Horizon 2020 5G PPP Programme. In this testbed, programmable hardware devices (such as FPGA) are adopted to ensure uRRLC for self-healing operations of smart grid.

Despite the advances in those deployed network slicing projects for smart grid, there are few PoC projects on other smart energy applications with the consideration of requirements like mMTC and eMBB. There are several issues with the practical deployments of network slicing technologies to smart energy systems. 1) The low return on investment (ROI) rate of network slicing services like video surveillance discourages power operators from widely adopting high-investment network slices [174]. 2) It is more difficult to achieve efficient radio resource sharing than that of computational and networking resources. The root cause of this challenge lies in the scarce spectrum resources [175].

D. Discussion and Remarks

1) Computational complexity and resource availability: Both the heterogeneity of the cross-domain slices and the diversity of multiple KPIs of network slices lead to computational complexity of optimal algorithms. For example, it is shown in [176] that it is a NP-hard problem to optimize RAN slicing with the consideration of multiple factors such as QoS of users, the profits of MVNOs and limited spectrum resources. Thus, it is a necessity to design less computational complex algorithms to address the emerging issues especially for smart energy systems, which heavily depend on RAN slicing.

Moreover, smart meters and other IoT nodes deployed in smart grid often have limited computational capability and battery capacity. As a result, the collected smart-meter data is often uploaded to remote clouds for further processing and analysis, though it may cause extra latency especially for those time-sensitive tasks. Therefore, it is worth exploring the orchestration of edge and cloud computing for smart energy systems [167]. For example, time-sensitive tasks should be offloaded to nearby MEC nodes while time-insensitive and computational-complex tasks can be conducted at remote clouds.

[25]https://www.gsma.com/futurenetworks/wp-content/uploads/2020/02/Network-Slicing-Proof-of-Concept_Power-Grid_CMCC_Huawei_CSG_GSMA_Apr20.pdf

2) Datasets and simulators: With the growing interest on smart grid and smart energy systems, there are lots of datasets available for data analysis and developing PoC projects of network slices. For example, the work [177] described a dataset of electrical-grid stability based on simulations[26]. Moreover, the work [143] also reported a data analytics on electricity-theft behaviours according to a dataset (containing more than 40,000 customers within nearly three years) released by SGCC[27]. In addition, Open Energy Information (OpenEI)[28] also maintains more than 1,700 datasets including eight sectors from smart grid to renewable energies. However, to the best of our knowledge, there are few datasets on network slicing for smart energy systems.

With respect to simulators, there are also a number of commercial products and open-source tools available. In [178], the authors summarized nearly 20 smart grid simulators (commercial and open source). The work [179] described an open-source smart grid simulator[29]. There are almost no network simulator for network slicing in smart grid or smart energy systems. As far as we know, there is only one open-source simulator namely SliceSim[30] for network slicing simulations, though it can only simulate handovers and mobility of users (i.e., not suitable for smart grid scenarios).

3) Performance evaluation and benchmarks: There are a few studies on performance evaluation and benchmarks on smart energy systems. In [180], the authors presented a benchmark framework on smart meter data. This framework can generate a large smart-meter dataset from a small seed of real data. Regarding communications and networking for smart grid, there are a few studies on performance evaluation. Bian et al. [181] presented performance evaluation on communications and networking protocols in smart grid. This study based on OPNET simulator, investigates operations in smart grids, such as smart meter, distribution automation, demand response, charging electric vehicles (EV), etc. However, there is no benchmark and performance evaluation on network slicing for smart grids and smart energy systems.

4) Future research directions: There is still a long way to go before the full adoption of network slicing technologies for smart energy systems. We discuss several major research directions in the future as follows.

Business model for smart energy. Despite the advances in applying economic and game theories to smart grid and smart energy systems [182], [183], the mature profit models on network slicing for smart energy systems are still missing. It is a necessity to design the profit models of network slices across energy providers, network operators, and customers. Moreover, rather than just assuring performance and network functions, network operators may offer energy providers and customers with value-added services, such as data visualization, data analytics, and computing facilities (e.g., edge computing nodes) of smart energy data. Business models

[26]https://www.kaggle.com/pcbreviglieri/smart-grid-stability/version/1

[27]https://github.com/henryRDlab/ElectricityTheftDetection

[28]https://openei.org/datasets/

[29]https://portal.findresearcher.sdu.dk/en/publications/scalable-open-source-smart-grid-simulator-sgsim

[30]https://github.com/cerob/slicesim

that comprehensively consider the above issues need to be proposed.

Security and reliability. Reliability and security are crucial to smart energy systems, while there are few studies on offering security-assurance network slices for smart energy. On the one hand, there are arising malicious attacks and mischievous behaviours towards smart energy systems [149]. Network slicing as well as network softwarization can offer effective countermeasures against malicious attacks on smart energy systems. On the one hand, the faulty network slices due to malicious attacks can be isolated from the entire system so as to avoid the disruption of services. On the other hand, network softwarization technologies such as SDN can redirect the malicious network traffic toward a VNF (or several VNFs) to avoid paralyzing the entire system. It is expected to develop a comprehensive network softwarization solution for reliable network slices of smart energy systems.

VI. Smart Factory

5G network slicing introduces notable innovations to enable the trend of digitalization in Industry 4.0 and smart factory verticals. Factories increasingly rely on network connectivity for introducing new services and achieving better efficiency. To accommodate various traffic types, dynamic resource requirements, and time-varying utilization rate arisen from different applications, factory networks press for the abilities of flexibility and isolation. The network slicing paradigm exploits the NFV and SDN networking techniques to create multiple logical network instances over a shared network infrastructure. Each instance can be adjusted for specific QoS requirements of industrial services and use cases. This section focuses on providing an industrial perspective on the concept of network slicing and its usage in smart factory networks.

A. Requirements and architecture

Smart factory is an essential element for the revolution towards Industry 4.0, where machines and sensors will creat huge quantities of data that can be utilised to enhance manufacturing operations through near real-time feedback and coordination. [184]. The networks of smart factories can achieve more flexibility and better QoS through network slicing. By creating logically isolated virtual networks, network slicing can simultaneously support multiple industrial use cases with different QoS requirements over the same physical infrastructure [185]. However, there is a lack of deep analysis dedicated to the design and management of network slices for smart factories. Network slice management for smart factory verticals needs to consider the unique architecture of factory network, various types of resources, multiple network domains, and stringent demands of business specifications, which require well-defined management models and intelligent strategies. Next, we survey the state-of-the-art research works to find out the existing demands for network slicing and the missing capabilities of supporting smart factory use cases.

Network slicing plays a crucial role in supporting the trend of digitizing key industrial verticals such as manufacturing, transport, robotics and automotive [186]. The digitization

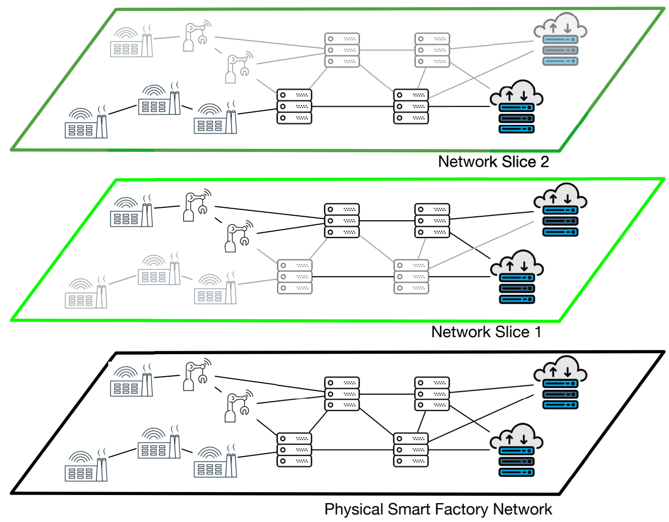

Fig. 15. Dividing a physical smart factory network into two logical network slices. Network slice 1 offers URLLC service to high priority manufacturing service, while network slice 2 provides resources for non-critical services.

transformation will lead to more intelligent and efficient factories for safer, greener and non-defective manufacturing [187]. Two major groups, the 5G Alliance for Connected Industries and Automation (5G-ACIA)[31] and the 3GPP[32], have defined several smart factory use cases that can be implemented through 5G network slicing [188]. These use cases include manufacturing control, monitoring of prod uction, automation and maintenance. These usage scenarios cover applications with a range of data rates, reliability and latency requirements.

1) Smart factory service requirements: Smart factory automation falls in one of the fundamental services in 5G known as URLLC. It typically has unprecedented requirements for determinism, low latency and reliability [189], [190]. However, some applications do not necessarily require extremely high capabilities. For example, applications such as surveillance cameras and customer support may require high data rates but not extremely low latency, while in other applications like manufacturing and IIoT, support of multiple concurrent connections of machines and sensors is a necessity. The new smart factory services need to embrace all three types of slices foreseen in 5G, including eMBB, mMTC and URLLC [191].

It is a great challenge, as the network cannot be optimized for a certain sort of service, to meet diverse needs by means of a one-size-fits-all approach. The network slicing technology divides a smart factory infrastructure into multiple virtual isolated networks, and each of those networks can be optimized for a specific application with unique features [192]. Fig. 15 illustrates a physical smart factory network supporting two slices, where one network slice offers mission critical services for high priority manufacturing activities and the other slice sharing the infrastructure provides the resources for other high-bandwidth communication services or surveillance. Nevertheless, current network slicing paradigms are mostly intended to meet high bandwidth or traffic throughput requirements.

[31] https://5g-acia.org
[32] https://www.3gpp.org

TABLE IX
SMART FACTORIES SLICES AND THEIR USE CASES AND REQUIREMENTS [188]

Slice type	Supporting use cases	Applications	Latency	Payload	Bandwidth	Density
Deterministic periodic slice	Motion control	Printing machine	$\leq$ 1 ms	$\leq$ 1 KB	-	★★★
	Control to Control	Machines coordination	3 - 10 ms	$\leq$ 1 KB	-	★★
	Massive sensor networks	Monitoring	1 - 10 ms	60 - 270 bytes	-	★★★★★
Deterministic aperiodic slice	Mobile robots	Emergency stops	3 - 10 ms	30 - 240 bytes	-	★★
	Closed-loop control	Automation	5 - 10 ms	10 - 100 bytes	-	★★★★
	Human-machine interaction	Cooperative control	5 - 10 ms	10 - 100 bytes	-	★★★
Non-deterministic slice	System maintenance	Software/firmware updates	Non-real-time	-	100 - 500 Mbps	★★★★
	Safety panels	User interaction	Non-real-tim	-	5 - 20 Mbps	★
	Plan asset management	Software updates and reconfiguration	Non-real-tim	-	1 - 100 Mpbs	★★★★★

Density level: from the lowest (★) to the highest (★★★★★)

There is an urgent need for the ability to service smart factory applications properly, when stringent latency or time-critical transport are common. Next, we investigate several typical use cases of smart factories and categorize them according to their requirements.

2) Use cases of smart factory: 3GPP technical specification group has identified five general types of smart factory use cases, including factory automation, human-machine interaction (HMI), process automation, logistics and warehousing, and monitoring and maintenance [188]. Next, we introduce several key smart factory use cases and applications, and then we group them into three types of slices.

Factory automation copes with multiple complex processes within a factory. These processes include control automation, automated monitoring of both processes and workflows, and optimization of them. Factory automation includes diverse perspectives, suc has closed-loop control applications, robotics, and computer-integrated manufacturing. Factory automation is a crucial enabler for high-quality and cost-effective industrial mass production. The underlying connection infrastructure is frequently subjected to the most stringent standards, particularly in terms of latency, availability of communication services, and determinism. In smart factories, new modular production systems that offer great flexibility and versatility will gradually replace static sequential production systems. Therefore, more effective and powerful wireless communication and localization services are required for increasingly mobile production assets.

HMIs and production IT include not only all types of devices for the human-plant interactions, such as machine-attached panels or manufacturing lines, but also conventional IT devices. In addition, the emerging augmented-reality (AR) and virtual-reality (VR) applications are expected to play a crucial role in fostering human-plant interactions. Production IT covers IT-based applications, such as manufacturing execution systems (MES) and enterprise resource planning (ERP) systems. Both systems depend on enormous quantities of data steaming from the manufacturing process in near real-time.

Process automation deals with both the production control and the substance handling, such as handling chemicals, food and beverage, pulp, etc. It increases the productivity, energy consumption of the facilities, and plant safety. Various sensors that are deployed in a plant make continuous measurements, like air density, pressure, humidity, temperature. They are working in closed loops via centralized and decentralized controllers that act on certain actuators, e.g., air/liquid valves, pumps, and heaters. Process-automation facilities may be geographically distributed in a range from several 100m^2 to a few km^2. A plant might contain many 10,000 measuring points and actuators depending on its size.

Logistics and warehousing involve with the control and management of supply chains of both raw materials and products during the entire industrial production. In this regard, logistics in a certain factory involves guaranteeing the uninterrupted supply of raw materials at the production site using mobile robots and automated guided vehicles (AGVs). Warehousing that involves the storage of resources and commodities is becoming increasingly automatic with the utilization of conveyors, cranes, and automated storage and retrieval systems (ASRS). The localization, tracking and monitoring of assets are of great importance for logistics applications, requiring stringent latency and service availability.

Monitoring and maintenance include the monitoring of specific processes and assets during industrial production. Different from the closed-loop control system in factory automation, monitoring and maintenance have no an immediate impact or a direct effect. Typical examples include applications, such as condition monitoring and sensor-based prediction maintenance, as well as big data analytics to optimize future process parameter settings. The data acquisition procedure in this use case is typically not latency-critical, but a large number of sensors need to be efficiently interconnected.

The above smart factory use cases have various resource demands of networking slicing specified in reliability, bandwidth, latency, scalability and serviceability, and they can be categorized into three different types of slices according to their traffic characteristics [188], i.e., deterministic periodic, deterministic aperiodic, and non-deterministic. Deterministic periodic slice generates traffic periodically and has stringent requirements for communication deadline [193]. As the most common and critical slicing class of smart factories, deterministic periodic slice is characterized by the bounded latency that has to be satisfied for the supported use case, such as motion control, control to control communication, and sensor-generated traffic for monitoring. The user cases under deterministic aperiodic slice, including mobile robot communication, closed-loop control for autonomous process, and human-machine co-operations generate traffic without a preset sending time, but it should always be transmitted with a specific time limit. Traffic generation of this type of slice is event-driven where a transmission is prompted by the occurrences of certain events. Non-deterministic slice subsumes the non-real-time periodic and aperiodic traffic. The transmission time limits for such traffic are not obviously specified. Applications that do not have a strict deadline, such as system maintenance, updates of software/firmware, can be supported by non-deterministic slice. Table IX summarizes the criteria for the three types of slices where use cases and applications are categorized according to their slice class.

3) Key enabling technologies: Both the success and effectiveness of smart factory network slicing heavily depend on the adoption of emerging networking and computation technologies, such as IoT, cloud manufacturing, and networking techniques, such as SDN and NFV [192], being incorporated into diversified manufacturing processes.

The increasing interconnection of digital sensors and smart devices that emerges from the IoT paradigm expands its advantages fast in industrial factory environments. Collecting the data from these devices allows the digital representation of real industrial machine tools, enabling a comprehensive vision of the production environments [194]. To achieve this enhanced vision in monitoring, controlling, diagnosing, and maintaining processes, the ability of efficiently collecting, analyzing, and extracting vital information from diverse data sources across multiple smart factory network domains is needed. As a result, the smart factory infrastructures need to evolve in order to effectively accommodate the significant change towards the network slicing paradigm for keeping effectiveness and competitiveness in the future.

Cloud manufacturing is an industrial version of cloud computing that efficiently combines cloud virtualization techniques in the domains of manufacturing and enhances the processing of data. Cloud manufacturing [195] is an emerging interdisciplinary paradigm that centrally manages manufacturing resources and transforms them into manufacturing services. An evolved manufacturing system that is built within a cloud platform is proposed to support flexible manufacture [196]. The enhanced proficiency gained through virtualization technology is used to transform the demands of consumers into particular production tasks. In this regard, the rigorous remote control requirements and the high latency of remote cloud data centers have promoted the implementation of the edge computing. in terms of remote control and the fact that remote cloud data centers can suffer from high latency, have encouraged the adoption of edge computing [197]. However, it is still the infant phase to deploy network slices via heterogeneous edge servers for industrial applications.

To enhance the industrial networks, SDN has gained considerable attention recently to achieve better network flexibility and enable the programming of network behavior. By decoupling traffic engineering and network configuration from the underlying infrastructure, a logically centralized controller enables intelligent control and management of the whole network to meet the needs of industrial applications. SDN-based industrial networks were presented in [198] to support dynamic manufacturing environment and substantial energy savings, through enabling real-time optimization and suspending redundant production lines. NFV is also gaining great momentum in industrial networks as one of the most promising solutions to improve the resource allocation and network scalability. It coverts a network function into a VNF, and enables the deployment of VNFs on a common physical infrastructure [199]. SDN in combination with IoT, NFV and manufacturing cloud can offer a powerful boost to the advancement of network slicing in smart factory networks.

B. Network Slicing Orchestration and Management

Both network slicing resource orchestration and service management need to support the creation and life-cycle administration of various network slices through smart factory infrastructures to provide unrivaled performance, flexibility, reliability and scalability for smart factory applications. In this section, we provide a deep investigation of network slicing architecture and analyze the network slice management and operation for smart factories.

1) Network slicing architectures: Smart factories need to accommodate highly varied traffic flows with potentially competing requirements in terms of performance, reliability, and flexibility. Therefore, dedicated network slices of smart factories need to be created on-demand over factory network infrastructures. In Fig. 16, each slice provides the desired logical connectivity and is composed of a set of VNFs and virtual links to support the services and meeting their specific requirements [200]. Since manufacturing processes are usually distributed over multiple fields, intelligent management and cross-domain configurations are required to efficiently realize end-to-end tailored network slices.

Various smart factory verticals will require distinct network slices that share the same physical network underpinning their use. Network resources will be divided in manifold to satisfy the connectivity, communication and computation needs of the dedicated vertical or solution. Therefore, network slicing for verticals means logical networks built on top of a shared infrastructure for the usage of a particular vertical case or case groups to ensure the optimal allocation of the network resources of each network domain (i.e., access/LAN, edge, core and cloud domain). As the different verticals are very diverse, network slices are used on a case-specific basis, and may come in different shapes and forms. Such diversity calls for a high degree of flexibility and agility in management and orchestration.

The devices such as actuators, cameras and sensors in a smart factory are usually controlled in a master/slave manner. The devices can be connected via cable or wireless, or combined when a tiny 5G base station belongs to the smart

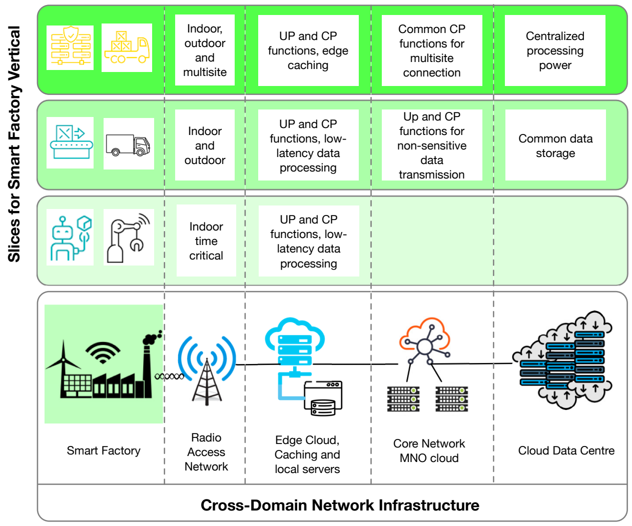

Fig. 16. An illustration of End-to-End network slicing across multiple domains in the smart factory scenario.

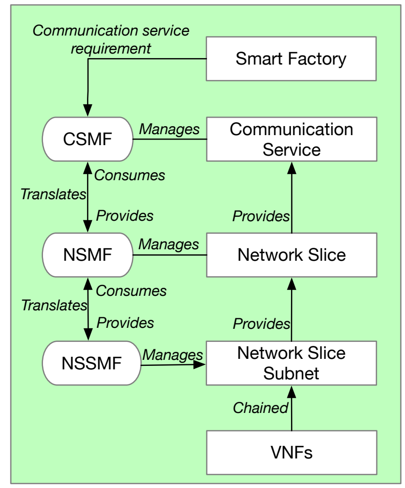

Fig. 17. 3GPP network slice management functions for network slicing

factory, e.g. if the devices demand high sync. The factory unit generally consists of a detergent and cyclic protocol, with resources available for each device in a cycle [188]. The cycle periods may vary based on the system from the level of sub-milliseconds to milliseconds. The main equipment of each plant unit are connected to an overall network that can also be connected to an external infrastructure such as the Internet. The industrial network usually consists of network protocols such conventional Ethernet or the emerging Time-Sensitive Ethernet (TSN) networking [201], and the classic TCP/IP. This comprises computer hardware and computer resources for broad purposes that may be utilised on master devices or even on components in a manufacturing. The factory network can additionally include one or more 5G base stations that can offer the plant equipment with wireless connection.

2) Network slicing management: The translation of communication requirements into network slicing and sub-net slicing requirements [202] is necessary to be capable of creating, configuring, and managing network slices on the basis of the desired services. Here translation is a conversion to network slice and subnet needs of high-level communication and flow requirements, in particular, for the requisite network functions, optimal positioning, and allocation of available resources and routing.

Since several divisions, consumers and actors will exist, different administrative responsibilities will also be required. Management and orchestration of VNFs requires the use of the SDN and NFV [192] principles. Three types of management functions have been specified by 3GPP for slice management, i.e., Communications Service Management Function (CSMF), Network Slice Management Function (NSMF) and the Network Slice SubNet Management Function (NSSMF) [188]. These functions follow a consumer-provider model and have been elaborated in Fig. 17.

The CSMF is used to translate and convey the demands of applications to the requirements of network slices, and indicates these requirements to the NSMF. The NSMF is in charge of creating network slice instances, generates the requirements of network slice sub-nets and shares these requirements with the NSSMF. The NSSMF is responsible for the management and orchestration of the network slice sub-net instances, and allocates appropriate network functions (VNFs) at the various domains in smart factory networks. The network slice sub-net instances in each network domain are chained by NSMF to form a network slice instance, and the generated network slice will be used to server a specific use case. Then the formed network slice will be managed by CSMF to provide services to the corresponding end users. The type of a slice can be specified in terms of the use case that it serves, the network functions from various network domains, and the required amount of network resource by each network function [203].

To meet the specific use cases requirements, automated end-to-end network slice design, deployment and configuration on a shared multi-domain infrastructure is an essential capability of a management and orchestration system for network slicing. A network slicing management architecture was proposed in an EU project 5G NORMA [33], which dynamically translates the service demands into pre-defined Key Performance Indicators (KPIs) that are used to build a network slice instance on demand. Another EU project 5G SONATA [34] represented an NFV management and orchestration (MANO) framework that follows the ETSI NFV referencing architecture for network service programming and orchestration, and NFV resources management.

3) Cross-domain network slicing operation: An instance of smart factory network slicing may have a large geographical footprint, thus penetrating multiple administrative network domains of the communication system in order to address various types of requests from diverse verticals [204]. The Access Network may be sliced and customized to realize and meet the performance demands for a URLLC application in both wireless spectrum and network protocol stack. From the aspect of transport network, the isolation between difference slices can be accomplished by resource sharing through virtu-

[33]https://5g-ppp.eu/5g-norma/
[34]https://5g-ppp.eu/sonata/

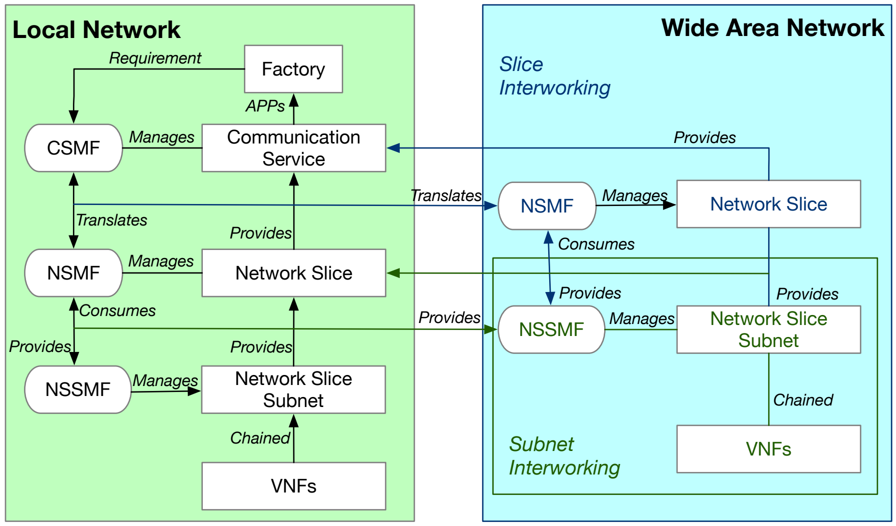

Fig. 18. An illustration of multi-domain management model for network slice in smart factories.

alization techniques or purposely built network with dedicated port and cable for a network slice. For the Core Network, smart factory networks may offer bespoke network functions, e.g. simpler mobility management for the mMTC or a sophisticated mobility management function to deal with the automobile industry with ultra-high-speed terminals.

Diverse networking domains can be exploited to fulfill the demands of both functions and resources for deploying network slices. To serve applications with strict latency requirement, the local network and edge servers within factories can be utilised for the provision of essential low-latency services. A centralized server in cloud might be used for less demanding services. For the former case, positioning the Data Plane (DP) and Control Plane (CP) controls in the local networks and servers is useful in achieving local information processing, low latency and full isolation for private data. For the latter case, certain services require connection to the broad Mobile Network Operators (MNO) networks. In the centralized MNO core, the positioning of DP and CP functions aims to assist roaming and connect between local and widespread networks. Depending on the number of instances engaged in usage, The number of network functions in each domain will depend on the type of use case, such as eMBB, mMTC and URLLC and the scale of end users [204].

For the management of cross-domain network slicing, the local operator's (e.g., Local 5G Operator (L5GO) [205]) network and MNO networks can cooperate to provide network slices on a sub-net or slice level [200], as shown in Fig. 18. Interoperability at sub-net level means that a local network operator is needed to supply the requisite sections including the required local or MNO sub-networks. Local operator's communication. Interoperability at the level of the slices indicates that both the local operator and MNO require the communications service and each customer supplies its individual slices. These alternatives depend on the competence of the factory and on the unique requirements of the case. In order to monitor and request modifications of service, the plant might be given with some control level over the CSMF. More independent control over CSMF might be carried out by a sophisticated customer company which requires independent control over the slice setup and management.

4) Network slice management model: A management model of network slicing consists of three network functions, i.e., CSMF, NSMF and NSSMF. These functions may be deployed flexibly in different network areas, dedicated to one business player or shared by several business players. The local operator must translate high-level requirements of communication services in the plant into E2E network slices using CSMF and create the connection between CSMF and NSMF. In addition, it will be responsible for translating the slice requirements by NSMF to sub-net requirements and for communicating between the NSMF and the NSSMF.

The local user can create sub-net level slices using the NSSMF function by choosing the network functions required for each network domain. It then utilises NSMF to instantiate network slicing instances by selecting the NSSI and CSMF features necessary to handle communications services that are available to the company using case-specific slices. The sub-net slices are therefore used by the NSMF to produce end-to-end network slices which in turn are utilised by the CSMF for the purpose of providing the communication service. This is done accordingly to a provider/consumer connection. In a multi operator scenario, the suggested network section management paradigm for an intelligent factory is demonstrated in Fig. 18. A cost model of network slicing is proposed in [206] to analyse the costs for virtualisation infrastructure under centralized and distributed scenarios.

Facilitating dynamic network slices is an essential capability for the management of network slicing, as slices need to fulfil varying and heterogeneous network requirements. Dynamic network slicing deployment empowers network operators to create various configurations on a common network infrastructure. Slices may be deployed and changed dynamically based on network service needs and resource availability. By assign-

TABLE X
COMPARISON OF NETWORK SLICING SOLUTIONS FOR SMART FACTORY

Network slicing approaches	**Enabling technologies**	**Architectures**	**Orchestration and management**	**Use cases**
Lopez et al. [17]	SDN, NFV	SDN and NFV-enabled 5G network slicing	Slice orchestrator, SLA management	5G industrial applications
Walia et al. [206]	Virtualization infrastructure	Centralised and distributed deployments	Cost model	network planning, and slicing deployment
Messaoud et al. [203]	Edge computing, LoRa	MEC-based network slicing architecture	Deep federated reinforcement learning-based management	Industrial IoT
Theodorou et al. [204]	SDN, NFV	Cross-domain slicing operations	Strict and flexible QoS via QoS-orchestrator	Cross-domain industrial applications
Ji et al. [207]	SDN, NFV	Network-slicing in IIoT	Network slicing architecture for remote adaptation and configuration for smart manufacturing	Remote Operation, real-time Industrial Data Monitoring, and Video Surveillance
Neumann et al. [208]	TSN, Profinet	Integration of wireless and industrial networks	Hybrid industrial networks management	Traffic monitoring
Wang et al. [209]	NFV, Deep Learning	Multi-domain networks	Deep Reinforcement Learning-based dynamic network slicing management	Resource allocation and scheduling

ing idle resources to congested slices, dynamic resource allocation improves the network's resource utilisation. The difficulty with dynamic network slices is continuous satisfaction of the desired QoS criteria. A deep reinforcement learning-based end-to-end network resource scheduling scheme is proposed in [209]. Different from a network slice with static configuration, a network with dynamic slice deployment considered the fluctuations in resource allocation over time is captured using learning-based model. The slicing structure is the same as in a static situation in the smart industry environment, but the slice characteristics and bandwidth consumption alter dynamically dependent on the type of traffic flows [207].

In addition, the manufacturer that starts operating the local network might assume these possibilities. The model comprises of various interactions between technical and business players. This multi-level slice management architecture enables the option to use the value network analysis method to examine alternative network slicing methods [208]. Table X compares representative network slicing solutions of orchestration and management in smart factory.

C. Challenges and Open Issues

1) Transport networks for industrial network slices: The vision of URLLC slices is expected to change the industry fundamentally, but the strict requirements pose new challenges. The communication in some mobile robot scenarios may require the transmission latency to be 1 to 5 ms, jitter to be less than 50% of latency, and a delivery reliability to be above six nines (99.9999 %) [210]. Another even more stringent use case in smart factory is the motion control, which critically controls the moving and rotating elements of machines. As illustrated in 3GPP TR 22.804 [188], this application specifies the requirement for end-to-end latency to be as low as 1 ms, and the reliability needs to be as high as six nines, even eight nines. Such applications often demand deterministic latency, meaning that all frames in the specific traffic flow of an application cannot exceed a prescribed bound.

TSN protocol is an ideal candidate in guaranteeing the low latency for smart factory slices, especially for the URLLC slices. The IEEE TSN Task Group [211], [212] aim to realize determinism to ensure bounded latency in data transmission over IEEE 802.1 networks. Therefore, TSN plays a key role in the autonomous and controlling applications for smart factory. It can be implemented through Ethernet to deliver the capabilities of infrastructure and protocol to support Industrial Automation and Control System (IACS) applications in real-time. In fact, TSN is becoming an essential Ethernet-based technology to achieve latency-guarantee in converged networks of smart factories [213]. For future industrial automation, it is necessary to understand the importance and relevance of the features of TSN and the capabilities which provide deterministic and time-sensitive communication in network slicing.

The transition towards smart manufacturing imposes extra demands on networking techniques and capabilities, i.e. ubiquitous and seamless connectivity whilst fulfilling real-time communication. Integration of network slicing with TSN protocol would effectively connect smart factories and make them capable of satisfying the critical criteria of industry communications technology [214].

2) Implementation and feasibility: Different network slicing techniques for a factory might be based on potential inter-working choices in network slice management needs. Factory network operators can choose different network slicing deploying strategies based on their communication networks and the desired level of automation. In a specific case, a single implementation method may be more viable than others, depending on the kind of factory, operating circumstances, QoS requirements, isolation demands, service number and administration expenses. In the feasibility studies [200], [215], [216], several potential inter-working options are investigated, in order to identify the costs and advantages for engaged stakeholders and supported application scenarios.

In an non-interworking strategy, low network exposure restricts other parties' engagement, and thus the factory will have a minimal effort and cost for network management. This strategy is feasible for factories that only need a standalone operation and the use cases do not requiring the access to wide area networks. A subnet inter-working method offers a moderate degree of factory network access and high exposure across multiple providers, which enables third parties to be involved and provides various services through a single agreement with the local network operator. For a smart factory with situations that need large-range network connectivity with one contract while having a medium administration effort, the above strategy is most viable. The slice inter-operational approach shows a high exposure level of the factory but a low exposure among different operators though multiple contracts, which allows the third-party participation, the availability of various services, and the configurability of each independent slice. For a smart factory that needs greater control of the design and administration of a slice, the inter-operational approach will be practical. Overall, the slicing of a smart factory network can exploit one or multiple strategies based on its use scenarios and desired management granularity.

D. Discussion and Remarks

1) Computational complexity and Resource availability: The optimization of network slicing resource with constraints on network elements (e.g. infrastructure topology, node computing power and link bandwidth) is often formulated as Integer Linear Programming (ILP) and Mixed Integer Linear Programming (MILP) problems [217], which are in many practical situations NP-complete. Furthermore, the increasing heterogeneity of automation production lines coupled with the high variability of demands leads to a rising complexity of smart factory network slices. The complexity of resource allocation and assuring isolation poses huge challenges. Huge computational power is required to manage the resource allocation. However, the local servers that control the sensors and actuators in smart factories are not equipped with enough computational power to handle the complex tasks, and therefore some tasks need to be offloaded to the edge servers or remote cloud servers. The smart factory tasks were categorized into two types as delay-sensitive and delay-tolerant in [218], and a game theory-based offloading decision model was developed to minimize the cost and meet the satisfactory QoS level. A framework that enables the virtualization of an IoT platform to provide services on the multi-access edge computing (MEC) nodes was developed in [219]. The framework maintained the minimum functions locally and deployed the network slices in the edge servers to address the latency limitation and high resource demands.

2) Datasets and simulators: Data generated in the manufacturing industry has long been treated unfairly in the past. While many industrial sectors have profited from the data analytic as the driver for company development and efficiency benefits, the manufacturing industry is hesitant to embrace an era of data-driven paradigms. The central control system is the foundation stone of an innovative and smart manufacturing facility. As latency is one of the most critical requirements in control system, time-series data provides incomparable value to achieve precise control, efficiency and minimum downtimes of the production process.

Currently, smart factory datasets are scarce, particularly in relation to Industry 4.0 where data of an entire production line is needed rather than individual machines. Moreover, datasets containing sensor data and failure cases of machines that can be used for a real predictive maintenance and intelligent manufacturing are also very limited. The energy consumption situation of a smart factory at a trial site in Aachen/Cologne Germany is provided by the EU FINESCE project[35]. A complete production line dataset was published by the company Bosch [220] as part of the data challenge at the IEEE BigData 2016 conference. The dataset contains data on a manufacturing line that produces chocolate souffles, totally anonymized. An RFID-enabled production dataset collected from a real-life factory is used in [221] to develop a data-driven manufacturing decision-making for smart factories. The data was cleaned by deleting all the incomplete datasets and removing incorrect data. A contextual faults dataset named CONTEXT, which contains fully recorded data in an advanced smart factory at the Darmstadt University of Applied Sciences (DUAS) was released in the work [222]. The data encompasses a production line for building electrical relays identical to those found in wind turbines, including different hardware and sensors and software modules. Table XI summarizes the available datasets of network slicing for smart factory as well as smart transportation and smart energy (as mentioned in Sections IV and V, respectively).

Simulators are important in another angle to enhance smart factories' agility, flexibility and efficiency in dealing with dynamic market and production changes. A model-based framework was developed to generate new use cases and scenarios of smart factories and carrying out simulation-based design analysis in [223]. The simulator can analyze the machine tools regarding the performance and their abilities in prognostics services. Later, the simulator has been upgraded to analyze information flows generated from the network of machines in a smart factory focusing on the run-time adaptability [224]. A simulator that contains several smart factory informational space and messages interaction models were developed in [225] for robots communication and adaptive production lines. However, we have not seen any open-source simulator designed for network slicing smart factories yet. Table XII summarizes the available simulators of network slicing for smart factory as well as smart transportation and smart energy (which are discussed in Sections IV and V, respectively).

3) Performance evaluation and benchmarks: There are limited research works on performance evaluation and benchmarks on smart factories. A smart product design framework to support key design stages in Industry 4.0 was developed in [227]. Based on the framework, a smart design performance measurement approach was proposed to produce flex-

[35] http://www.finesce.eu/

TABLE XI
THE AVAILABLE DATASETS FOR NETWORK SLICING

Datasets	Applications	Key features	Data source
TorontoCity [131]	Traffic flow prediction/control	Aerial images and airborne LIDAR images of roads in Toronto city	http://www.cs.toronto.edu/~torontocity/
Guo et. al. [117]	Autonomous driving	Driveability dataset index and comparison of 54 public driving datasets	https://sites.google.com/view/driveability-survey-datasets
GTSDB [135]	Traffic sign recognition	Traffic signs of Germany	https://benchmark.ini.rub.de/
Electrical-grid stability dataset [177]	Power grid	Electrical-grid stability	https://www.kaggle.com/pcbreviglieri/smart-grid-stability/version/1
Electricity theft dataset [143]	Electricity consumption	Electricity-theft behaviours of SGCC (China)	https://github.com/henryRDlab/ElectricityTheftDetection
OpenEI	Smart grid, renewable energies	1,700 datasets with various features	https://openei.org/datasets/
FINESCE	Smart factory energy data	Energy consumption situation of a smart factory at Aachen/ Cologne	http://finesce.eu/Results.html
Bosch production line [220]	Manufacturing line	Data on a manufacturing line that produces chocolate souffles, totally anonymized	https://www.kaggle.com/c/bosch-production-line-performance/data
RFID datasets [221]	Manufacturing decision-making	Real-life dataset collected from RIFD-enabled smart factory	Data collected in [226]
CONTEXT [222]	Production line for building electrical relays	Contextual faults dataset contains fully recorded data in an advanced smart factory, including different hardware and sensors and software modules.	https://zenodo.org/record/4034867#.Yedn3P7P2Uk

TABLE XII
THE AVAILABLE SIMULATORS FOR NETWORK SLICING

Simulators	Applications	Key features	Platform/Language
CARLA [133]	Autonomous vehicles	Developing, training, validating autonomous vehicles	Python/C++
NVIDIA's DRIVE Sim	Autonomous vehicles	simulate various driving environments	Linux/Python
Baidu's Apollo	Autonomous vehicles	Driving simulation	Linux/Python
Cruden's software and simulators	Autonomous driving	Driving simulation and driver-assistance	Linux/C++
Open-source smart grid simulator [179]	Different grid scenarios	Modelling smart grid applications households and appliances	C++ and SystemC Network Simulation Library
SliceSim	Simulating handovers and mobility	Not dedicated for smart grid	Python
Model-based framework for smart factory [223], [224]	Smart factory	Generate new use cases and scenarios of smart factories	Developed in Java and implemented in AnyLogic
Robots production lines [225]	Smart factory	Smart factory informational space and messages interaction models for robots communication and adaptive production lines.	Python

ible and customized operations during a collaborative design process. To capture the real-time performance, an IoT-based performance measurement system that integrates the business process and software architecture using the Business Process Modelling method was developed to improve manufacturing systems [228] under a smart factory environment. However, the current performance evaluation only focuses on the machine tools of manufacturing systems, and there is no framework or model considering the network slicing aspect [229].

4) Future research directions: The future smart factory will have more crucial requirements that current communication technologies may not be able to fulfill [230]. We believe that network slicing will be a promising and effective means for the provision and management of those emerging applications and scenarios.

The surveyed use cases of smart factories possess the needs for logically isolated networks over the same physical network. However, there will be a need to bridge the gap between the stringent service quality requirements and orchestration of network slicing. High QoS and service availability comes at the price of additional resources, which translated into greater costs. The system needs the capabilities to customize and optimize each network slice in order to meet different levels of QoS and various types of availability and reliability requirements.

Network slicing orchestration of smart factories is still an on-going topic in the research communities. To boost its deployment spreading over large geographical areas or including service functions that are provided by multiple operators, the involvement of heterogeneous domains in the creation and operation of network slices for providing different vertical applications is a key requirement. Furthermore, AI and Machine Learning techniques can offer significant benefits for industrial data processing and autonomous management. The network slicing management needs to achieve self-configuration and self-optimization based on run-time activities.

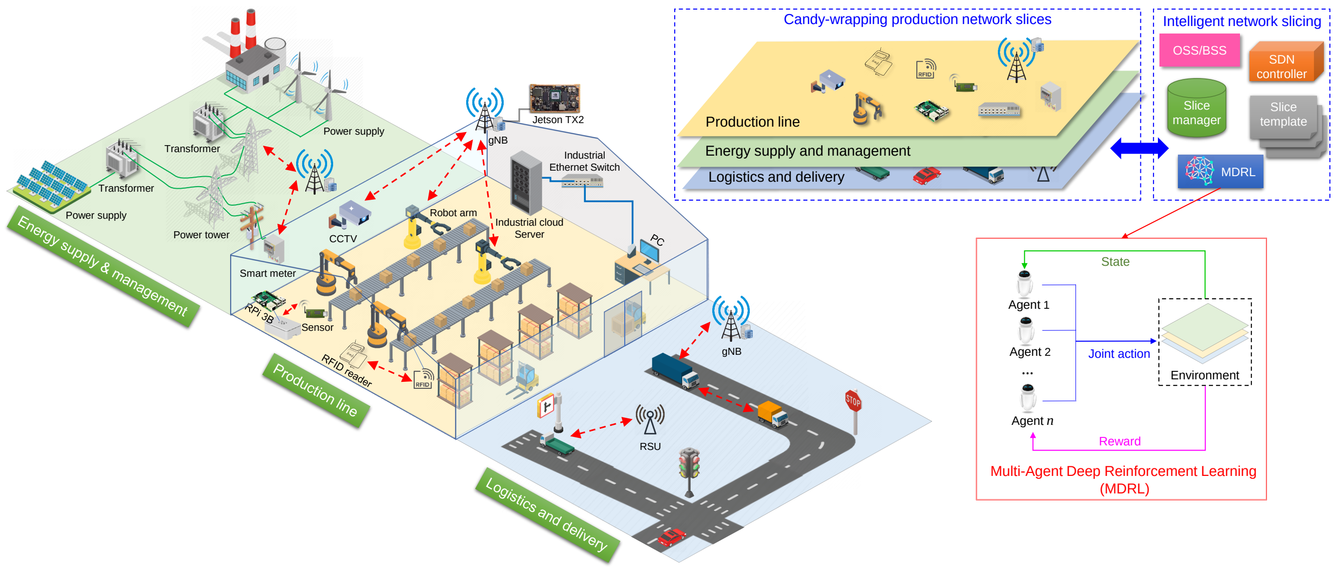

Fig. 19. Case study: A candy-wrapping production line

VII. Case Study

This section presents a case study of intelligent network slicing management for the integrated IIoT-enabled smart factory, smart energy and smart transportation. In this case study, we consider a practical candy-wrapping production line of a smart factory, with reliable energy supply and management, as well as effective logistics and delivery to end users. As shown in Fig. 19, an end-to-end network slicing consisting of three parts, i.e., candy-wrapping production, energy supply and management, and logistics and delivery, is needed. In what follows, we elaborate each part of this end-to-end network slicing, and then we illustrate how multi-agent reinforcement learning technique can be adopted to provide intelligent network slicing management for this case study.

The candy-wrapping production line is equipped with robot arms, sensors, an RFID reader, RFID tags, surveillance cameras, Raspberry Pi 3B, and a convey belt. They are connected via a time-sensitive networking (TSN) [231] empowered industrial Ethernet and a 5G base station. It is worth mentioning that the 5G base station is also equipped with an NVIDIA Jetson TX2 module, which serves as an edge computing node to process IoT data locally in the factory. To enable the required communication for data collection of candy-wrapping production, a network slicing is constructed based on the TSN-empowered industrial Ethernet and the 5G base station. To enable the required computing for candy-wrapping production, the edge computing node will be virtualized, and adequate computing resources will be added to the network slicing.

For the part of energy supply and management, a network slicing will be constructed based on the 5G base stations (this can be public 5G base stations running by network operators, or private 5G base stations operating by energy companies) and their associated edge computing nodes. This part of the slice is used to support 1) the collection of smart meter data and additional energy requirements from the factory and 2) the calculation of smart energy supply and management strategies.

For the part of logistics and delivery, another network slicing will be deployed in the area of product delivery. This slice will be also constructed based on the 5G base stations and their associated edge computing nodes. This part of the slice is used to support 1) the collection of road status data and product delivery requirements, and 2) the route calculation of autonomous vehicles for product delivery based on the real-time road situations.

The E2E network slicing for this case study is composed of the above three parts of slices. Each part of the end-to-end network slicing has its own optimization objective and management strategy. Given the varying and real-time requirements at each part of this end-to-end slicing, we resort to multi-agent deep reinforcement learning (MARDL) [232] to provide intelligent network slicing management for this case study of integrated smart factory, smart energy, and smart transportation. Agents can cooperate with each other and solve a Markov/stochastic game to reach an equilibrium. Each agent executes an action according to the system state. The system is then moved to the next state and rewards each agent. The goal of each agent is to optimize its own long-term reward by finding its optimal policy. The Nash equilibrium of the Markov/stochastic game is a joint policy of all the agents, from which none of the agents has any incentive to deviate. By using this MARDL framework, the resources of this end-to-end network slicing, including computing and networking resources, can be dynamically and intelligently adjusted subject to the requirements of energy suppliers, factory owners, and logistics companies.

The implementation of this case study is not straightforward. Several challenges need to be considered. Firstly, SDN and NFV are two important enabling technologies for the implementation of network slicing, and therefore, the implementation of this case study should have a neatly integration with the relevant standards of SDN and NFV. For example, an appropriate SDN southbound protocol needs to be selected, such as Huawei's POF and ONF's P4. In addition, official reference designs could be considered, e.g., ONF's NFV Fabric[36]. Moreover, the integration with ETSI's NFV-MANO should be considered, especially its new features such as service-based framework and MANO robustness. Apart from the above, 3GPP's Management and Orchestration of network slicing is of equal importance. Secondly, the development and training of MDRL is another important factor for the successful implementation of this case study. To propose a robust model with long-term benefits, digital twins of each part of the end-to-end network slicing can be built which can be used to better train the model. To ensure the privacy protection of each part of the end-to-end network slicing, each agent can be locally trained with the partial observation to the local part of the slicing only. For the training of MDRL, the information that needs to be shared across different agents should be encrypted using e.g. differential privacy techniques. In line with the above considerations, traditional MDRL needs to be improved. In terms of the deployment, each agent should be implemented at the edge server of each part of the end-to-end network slicing.

VIII. Conclusion

This work presented a comprehensive survey on network slicing from the perspectives of smart transportation, smart energy, and smart factory. Besides the detailed analysis for each of these three applications, in terms of application requirements, network slicing architecture, and network slicing orchestration and management, a list of important challenges and open issues were also provided for smart transportation, smart energy, and smart factory. Further, we provided a case study of the intelligent network slicing management for integrated smart transportation, smart energy, and smart factory. In summary, some lessons learnt from the above three applications include: 1) With respect to smart transportation, it is necessary to explicitly identify service function chains (SFCs) for specific smart-transportation applications so that we can orchestrate the underlying VNFs/PNFs to support such SFCs; 2) Regarding to smart energy, it is crucial to guarantee both ultra-low latency and extremely high reliability for smart energy systems; 3) The key feature and also the missing capability for network slicing to succeed in smart factory is the resource management across heterogeneous network domains during both the slice creation and operation. An autonomous and intelligent orchestration strategy is demanded timely to achieve self-configuration and self-optimization. This survey can provide useful guidance on the future innovation and also the practical deployment of network slicing for industrial Internet of Things applications.

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