IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 13, 2020, accepted January 30, 2020, date of publication February 19, 2020, date of current version February 28, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2975072

Network Slicing: Recent Advances, Taxonomy, Requirements, and Open Research Challenges

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This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) under Grant NRF-2017R1A2A2A05000995.

ABSTRACT Fifth-generation (5G) and beyond networks are envisioned to provide multi-services with diverse specifications. Network slicing is identified as a key enabling technology to enable 5G networks with multi-services. Network slicing allows a transition from a *network-as-an-infrastructure* setup to a *network-as-a-service* to enable numerous 5G smart services with diverse requirements. Although several surveys and tutorials have discussed network slicing in detail, there is no comprehensive study discussing the taxonomy and requirements of network slicing. In this paper, we present and investigate key recent advances of network slicing towards enabling several Internet of Things (IoT) smart applications. A taxonomy is devised for network slicing using different parameters: key design principles, enablers, slicing resources levels, service function chaining schemes, physical infrastructures, and security. Furthermore, we discuss key requirements for network slicing to enable smart services. Finally, we present several open research challenges along with possible guidelines for network slicing.

INDEX TERMS 5G, 6G, network slicing, software-defined networking, network function virtualization, Internet of Things.

I. INTRODUCTION

Recent digital transformations empowered by emerging technologies: Edge computing, cloud computing, network function virtualization (NFV), Internet of Things (IoT), and software-defined networking (SDN), open up novel smart services for subscribers [1], [2]. Such smart services include smart health-care, smart transportation systems, smart buildings, smart grids, and smart agriculture [3]–[6]. These smart services require connectivity but with varying requirements. Network slicing enables connectivity for the smart services with diverse requirements via multiple logical networks over the top of the physical network infrastructure. For instance, consider accident reporting of autonomous driving cars using intelligent transportation schemes. In such a scenario of autonomous car accident reporting, strict latency constraints must be fulfilled to enable timely reporting of the accident for minimizing the impact of damage. On the other hand, smart agriculture generally has lower latency requirements than smart transportation systems [1]. Therefore, smart transportation slices must be more latency sensitive than smart agriculture slices. Several methods can enable network slicing. One possible approach is using a dedicated end-to-end network for every service. However, this approach will significantly increase the operational cost [7]. Therefore, it is a viable solution to enable shared usage of a common physical infrastructure for different smart services [8]. The physical infrastructure includes wireless access networks, edge computing servers, cloud computing, satellites, unmanned aerial vehicles, and Wi-Fi access points, to name a few. Enabling smart IoT services via network slicing requires successful interaction between a variety of physical infrastructure players. To enable interaction between these different physical infrastructures via network slicing, numerous challenges need to be resolved. These challenges are interoperability, mobility-awareness, efficient end-to-end orchestration, and novel business models.

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

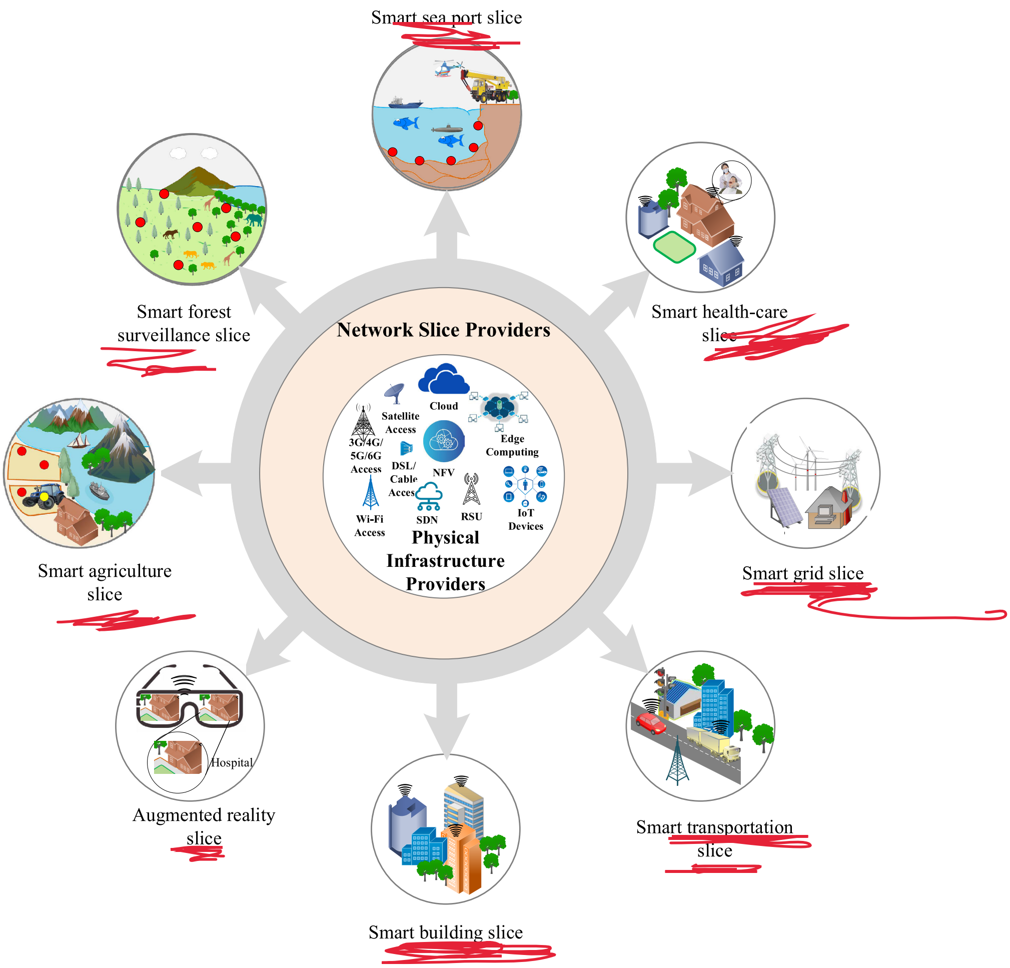

FIGURE 1. An overview of network slicing in enabling smart services.

Network slicing has been defined by various standard development organizations in numerous ways [7], [9]–[11]. However, there is not a common definition of network slicing. In fact, network slicing refers to all the attempts of enabling availability of the *networks-as-a-service* according to user demands. Network slicing can be enabled mainly by NFV, SDN, cloud computing, and edge computing [8]. NFV offers the use of generic hardware for cost-efficient implementations of network functions, while SDN enables separation of the control plane from the data plane to offer efficient and flexible resource management [12]. Therefore, NFV and SDN-based network slicing can be considered as an indispensable networking technology for fifth-generation (5G), sixth-generation (6*G*), and beyond networks [13].

A. NETWORK SLICING MARKET STATISTICS

The network slicing market will grow at a compound annual growth rate (CAGR) of 21.9% from 112.3 million US Dollars in 2017 to 302.2 million US Dollars in 2022 [14]. In 2017, North America had the highest market share of network slicing. The primary causes of increase in the slicing market in North America are agile networks, Industrial Internet of Things (I-IoT), and smart connected devices. The Asia pacific region and Europe are expecting significant growth in terms of network slicing market share. However, the Asia pacific region is expected to have the highest CAGR growth rate. The main sources of increase in network slicing market in the Asia pacific region are tactile internet, I-IoT, augmented reality, and adoption of new technologies for cloud radio access network. It is clear from the statistics that network slicing market will suffer from significant increase in the foreseeable future. On the other hand, smart cities are expected to expand rapidly due to fast migration of people in which every week, approximately 1.3 million people are migrating to cities [15]. The number of mega cities is expected to increase from 3 in 1975 to 29 in 2025. From the above statistics on smart cities and network slicing, we can infer that network slicing in smart cities will offer many opportunities for research and development.

B. EXISTING SURVEYS AND TUTORIALS

Several papers [8], [16], [17] surveyed network slicing in detail. Foukas *et al.* in [8] presented an overview of network

TABLE 1. Summary of existing surveys and tutorials with their primary focus.

Reference	Internet of Things	Taxonomy	Requirements	Remarks
Foukas *et al.* , [8]	✗	✗	✗	They present the state-of-the-art advances, generic framework, and open research challenges for 5G network slicing.
Afolabi *et al.* , [16]	✗	✗	✓	The authors comprehensively discuss the design principles, enabling technologies, network slice orchestration and management, radio access network and core network slicing requirements.
Alexandros Kaloxylos , [17]	✗	✗	✗	The authors mainly focus on the 3rd Generation Partnership Project (3GPP) standardization activities of network slicing.
Our survey	✓	✓	✓	Our survey presents recent advances, taxonomy, general requirements, and open research challenges of network slicing.

slicing architectures. They have discussed the state-of-the-art advances in network slicing at different layers: the infrastructure layer, network function layer, and service layer. Additionally, several open research challenges were presented in the paper. In [16], Afolabi *et al.* comprehensively surveyed enabling technologies, design principles, and management and orchestration of network slicing. Additionally, several requirements of the radio access network and core network for enabling network slicing are presented. Finally, a few open research challenges on slice resource allocation and security were discussed. Another survey in [17] discussed 3GPP standardization process of network slicing. Specifically, authors discussed the recent research trends and few open research challenges for enabling network slicing in 5G.

C. OUR SURVEY

To the best of our knowledge, we are the first to present the taxonomy and general requirements for network slicing. A comparison of our survey contributions with other existing surveys is given in Table 1, which shows the novelty of our contributions compared to existing surveys. Our survey has the following contributions:

- We present and investigate recent advances in network slicing for enabling different smart services.
- We devise a taxonomy for network slicing based on different parameters: key design principles, slicing resources levels, service function chaining schemes, key enablers, physical infrastructure, and security.
- We highlight several indispensable requirements for implementing network slicing.
- Finally, we present several open research challenges along with their possible solutions for enabling network slicing in 5G and beyond networks.

The structure of our survey is illustrated in figure 2. In section II, we discuss recent advances of network slicing. A taxonomy based on different parameters is presented in section III. Section IV outlines the indispensable requirements for network slicing. Several case studies of network slicing are presented in section V. Section VI presents important open research challenges with their possible solutions. Finally, lessons learned and future recommendations are given in section VII and VIII, respectively.

D. TERMINOLOGY

1) NETWORK SLICE

A network slice represents a logical network built on the top of the shared physical infrastructure including radio access networks, core networks, cloud, edge computing nodes, unmanned aerial vehicles, and satellites.

2) TENANT

A tenant refers to a group of users accessing the shared resources with specific access privileges and access rights. A tenant in a network slicing environment requests the creation of network slice instances.

3) NETWORK SEGMENT

This refers to a network portion characterized by a set of common features, especially in terms of physical resources and their purpose. For instance, wireless networks and wired networks can be considered as different segments.

4) NETWORK FUNCTION VIRTUALIZATION

Network function virtualization allows the use of generic hardware for cost-effective implementation of different network functions.

5) SOFTWARE-DEFINED NETWORKING

Software-defined networking offers separation of control plane from the data plane and thus, enables easier network management.

6) NETWORK SLICE PROVIDER

The job of the network slice provider is to manage and control slices. More specifically, the network slice provider buys

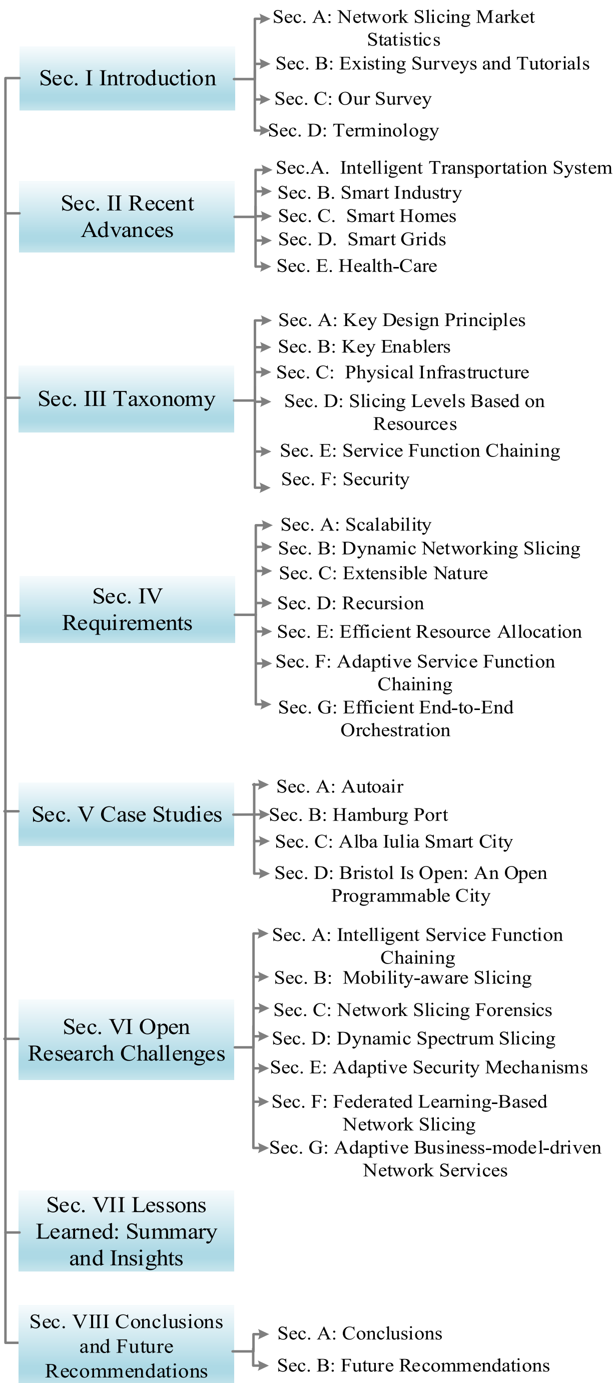

FIGURE 2. Structure of the survey.

resources from the physical infrastructure providers, and then uses these resources to offer different smart services slices.

II. RECENT ADVANCES

This section presents the recent advances made towards enabling smart applications via network slicing. We categorize, critically discuss and evaluate these advances. Tables 2 and 3 summarize the features and merits of these recent advances.

A. INTELLIGENT TRANSPORTATION SYSTEM

Intelligent transportation systems enable vehicle-to-vehicle communication, vehicle-to-infrastructure communication, in-car infotainment services, and autonomous driving.

A service-oriented network slicing scheme is proposed in [18] to virtually divide the Air-Ground Integrated VEhicular Network (AGIVEN) architecture into multiple slices with good quality of service (QoS) guarantee. The physical infrastructure of the AGIVEN consists of high-altitude platforms (HAPs) and densely deployed roadside units (RSUs) to enable proactive content broadcasting to vehicles and on-demand high-rate uni-cast services, respectively. Other than these, onboard caching is provided for vehicles that resulted in data rate enhancement by reducing the requests from RSUs. Although AGIVEN offers significant advantages, it suffers from high resource management complexity due to heterogeneity in traffic and resources. To cope with this high management complexity, the proposed scheme leverages service-oriented slicing to enable multiple logical networks for different slices on the top of the shared physical infrastructure. Three types of slices, i.e., high definition map for navigation (MaNa) slices, file of common interest (FoCI) slices, and on-demand transmission (ODT) slices, have been defined. Furthermore, two types of SDN controllers, i.e., local and central controllers, are used in AGIVEN. Local controllers are used in controlling HAPs and RSUs, whereas the central controller monitors local controllers. More specifically, the job of the local controllers is to monitor mobile traffic demands and report them to the central controller. The central controller handles the logical resources slicing with a QoS guarantee and instructs the local controllers to enable the allocation of physical resources. The authors extensively investigated large scale provisioning of resources using statistical information on traffic requests, content popularity, and vehicle mobility. It is preferable to consider small scale information to enable dynamic slicing to achieve further performance enhancement.

In [19], Campolo *et al.* surveyed the network slicing vision to provide general vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2X), and improved transport services. Additionally, they discussed the V2X services specified by 3GPP and gave an overview of the network slicing that enables them. Apart from that, a set of different slices is proposed, including autonomous driving slices, teleoperated slices, vehicular infotainment slices, and the vehicle remote diagnostics slices. To enable these slices, certain configurations are required, such as radio access technology (RAT) settings, communication mode, QoS treatment, hybrid automatic repeat request (HARQ) options, scheduling mechanisms, and transmission time interval (TTI). Finally, several indispensable operational and business research challenges for enabling vehicle-to-infrastructure (V2X) slicing are presented.

A network slicing model leveraging downlink communication in heterogeneous cellular networks for V2X communication is proposed in [20]. Two types of slices,

TABLE 2. Summary of the recent advances.

Application	Reference	Feature	Merit
Smart Transportation System	Zhang *et al.* [18]	• Propose a service-oriented network slicing architecture to virtually divide the Air-Ground Integrated VEhicularNetwork (AGIVEN) architecture into multiple slices with QoS guarantee. • The physical infrastructure of the AGIVEN consists of high-altitude platforms (HAPs) and densely deployed roadside units (RSUs) to enable proactive a prior content broadcasting and on-demand high-rate uni-cast services, respectively	• Onboard caching by vehicles resulted in data rate enhancement by reducing requests from RSUs. • Two-level of controllers is used which enables more scalable operation.
	Campolo *et al.* [19]	• A network slicing vision for enabling V2V, V2X, and improved transport services is presented • Discussed the V2X services specified by 3GPP	• The set of configurations: RAT settings, communication mode, QoS treatment, HARQ options, scheduling mechanism, and TTI, are provided for the autonomous driving slice, teleoperated slice, vehicular infotainment slice, and the vehicle remote diagnostics slice. • Few operational and business research challenges to enable V2X slicing are presented.
	Khan *et al.* [20]	• A network slicing model leveraging down-link communication in heterogeneous cellular networks for V2X communication is proposed • Two types of slices, such as infotainment slices and autonomous driving slices are generated on the top of the shared physical infrastructure	• The proposed slicing scheme is evaluated using system level Long Term Evolution Advanced (LTE-A) simulator , that revealed significant improvement in packet reception ratio.
	Oliva *et al.* [21]	• A 5G-TRANSFORMER concept based on evolution of mobile transport network towards edge computing/ network function virtualization/ software-defined networking based 5G mobile transport is proposed • The proposed 5G-TRANSFORMER concept consists of mobile transport and computing platform (MTP), service orchestrator (SO), and vertical slicer (VS).	• The design of 5G-transformer is based on addition of new functional blocks into the ETSI management and orchestration based design.
Smart Industry	Rost *et al.* [22]	• Propose a network slicing based 5G test-bed at sea port of Hamburg • The test-bed was implemented using 3GPP LTE Release 14, that offers the opportunity of creation of dedicated logical networks using enhanced Decor(eDECOR)	• The test-bed has proven the feasibility of mulitenancy, flexible slice customization, and slice isolation • Few open research challenges with guidelines are provided
	Theodorou *et al.* [23]	• Propose a scheme for enabling industrial applications using cross-domain slicing • Two-level architecture is presented. The first level for network service providers slices followed by second level QoS-orchestrator to manage all network service providers slices (defined at the fist level)	• Two-hierarchical level operation offers more scalability in terms of addition new network service provider with distinct functions • Network slicing test bed with software and system level details is presented
Smart Homes	Chaabnia *et al.* [24]	• Propose a two level slicing mode for IoT-based smart home • Mininet is used as a test bed for experimental evaluation of the proposed scheme	• Division of smart home applications into four different classes based on their bandwidth requirement, traffic type, and usage • Classification of the network traffic into different slice types based on their required data rates.
	Boussard *et al.* [25]	• Propose a secure smart home prototype consists of future spaces instances connected through different technologies, such as 5G, Wi-Fi, and DSL, among others. • The function of future space instances is to enable computation, storage, and gateway capabilities in smart homes	• The future spaces instances can be either a physical or virtual execution environment, that is connected through secure tunnels in an ad-hoc virtualized network • A distributed architecture is used to enable scalability

TABLE 3. Summary of the recent advances.

Application	Reference	Feature	Merit
Smart Grid	Kurtz *et al.* [26]	• Propose an approach based on SDN and NFV driven queueing schemes for network slicing • A testbed consisting of 13 servers is also presented	• Scalable slicing solution • Delay sensitive operation for critical communication • Proposed solution is validated for smart grid and smart transportation
Smart Health-care	Celdran *et al.* [27]	• Propose a network slicing architecture using ontologies for managing complete slicing cycle • Two sets of polices: intra-slice and inter-slcie polices are defined for management	• The proposed architecture provides detailed implementation of network slicing using ontologies and provided reasonable latency in slicing that occurs from start till final commissioning • Proposed architecture is validated via experimental implementation

infotainment slices and autonomous driving slices, are generated on the top of the shared physical infrastructure. The physical infrastructure used in the paper consists of a set of vehicles and a set of RSUs. The link between the vehicles and RSUs is modeled using a macro to relay path loss model and geometry-based stochastic channel model. The proposed slicing scheme is evaluated using a system-level Long Term Evolution Advanced (LTE-A) simulator, which revealed significant improvement in the packet reception ratio. The 5G-TRANSFORMER concept is proposed in [21], which is based on the evolution of mobile transport networks towards edge computing, NFV, and SDN enabled 5G mobile transport networks. The proposed 5G-TRANSFORMER concept consists of a mobile transport and computing platform (MTP), service orchestrator (SO), and vertical slicer (VS). The job of the MTP, SO, and VS is to manage the underlying physical mobile transport network, slices virtual resources, and coordination of vertical slices requests along with service function chaining. The key advantage of the proposed 5G-TRANSFORMER is offering the flexibility of adding new functional blocks into the ETSI management and orchestration based design.

B. SMART INDUSTRY

Smart industries are envisioned to enable industrial automation by leveraging cognitive computing, cloud computing, edge computing, IoT, and cyber-physical systems, among others.

1) 5G NETWORK SLICING TEST-BED FOR HAMBURG SEA PORT

In [22], Rost *et al.* discussed the network slicing-based 5G test-bed at the sea port of Hamburg by Hamburg Port Authority, Deutsche Telekom, and Nokia. First, the three main important design aspects, i.e., the dynamic management of isolated slices, resilience, and service diversity support, are identified. In addition, the test-bed cases for 5G (Sensor Measurements, Live Remote Site Support, and Traffic Light Control) used at the Hamburg port are discussed. The test-bed was implemented using 3GPP LTE Release 14, which offers the opportunity of creation of dedicated logical networks using an enhanced Decor (eDECOR) with necessary modifications. Furthermore, the authors discussed future research challenges and provided guidelines for their solutions.

2) CROSS-DOMAIN NETWORK SLICING FOR INDUSTRIAL APPLICATIONS

In [23], Theodorou *et al.* proposed a scheme for enabling industrial applications using cross-domain network slicing. The proposal was designed for the EU funded VirtuWind project, which considered an industrial wind park scenario. Management of the industrial wind park is performed using Supervisory Control and Data Acquisition (SCADA) within a private network that is positioned near the actuators and controllers. Different external services (grid response, energy regulation, and maintenance access) are provided by the industrial wind park via remote access interfaces. To enable efficient management of the industrial wind park, a two-level hierarchical structure is proposed. The first level uses separate SDN controller for every network service provider to manage the intra-domain network. The second level uses a logically centralized QoS orchestrator to enable coordination among all network service providers. More specifically, VirtuWind is based on two-level hierarchy-based network slicing. In the first level, every network service provider is set to have at least one slice with different attributes (packet loss, latency, and bandwidth) which provide end-to-end path segments for inter-network service providers slices. These inter-network service provider slices enable different industrial functions. In the second level, the QoS-orchestrator creates slices for different industrial applications.

C. SMART HOMES

Smart homes are used to provide state-of-the-art control and automation facilities, such as smart security, smart elevators, smart plug-in hybrid electric vehicle charging, and smart meters.

1) HIERARCHICAL SMART HOME SLICING

In [24], Chaabnia *et al.* presented a two-level slicing model for IoT-based smart homes. These two slicing levels are control plane slicing assisted by flowvisor and home gateway slicing. The flowvisor allows sharing of a physical switch through virtualization between logical networks with distinct forwarding mechanisms and addressing schemes. Moreover, the proposed slicing architecture considered a single vSwitch for the whole smart home network. In the first stage of hierarchical slicing, all the applications are divided into four different classes based on their bandwidth requirement, traffic type, and usage. Apart from the slice specifications, queues are defined for every slice type according to their data rates and priorities. The second stage of slicing classifies the network traffic into different types based on the their required data rates. Applications with similar traffic are assigned for the same slices. Finally, Mininet is used as a test bed for experimental evaluation of the proposed scheme.

2) SECURE SMART HOME PROTOTYPE

In [25], Boussard *et al.* proposed a secure prototype named *future spaces* using SDN and NFV as the key enabling technologies for IoT asset management in smart homes. The authors considered group-based slicing for achieving fine-grained control of the smart home network. Group-based network slicing forms multiple virtual networks on top of the common smart home network. The proposed future space prototype consists of future space instances connected through different technologies, such as 5G, Wi-Fi, and digital subscriber line (DSL). These future space instances can be either a physical or virtual execution environment that is connected through secure tunnels in an ad-hoc virtualized network. The function of future space instances is to enable various computational, storage, and gateway capabilities. Additionally, these instances can be deployed on a variety of IoT devices and virtual machines. To enable slicing based operations, the words vPlace and vSpace are defined in the paper. vPlace is a collection of resources, whereas, vSpace is used to enable fine-grained control of communication and access to resources. More specifically, vSpace is a virtual room that allows secure communication between its members. These vSpaces are actually embodied into slices called *software-defined LANs*. Apart from that, the proposed scheme uses NFV and SDN to control the whole network. Although the authors used SDN and NFV for network isolation to enable secure operation, SDN has its own security concerns that must be handled carefully.

D. SMART GRID

Smart grid uses information and communication technologies with emerging computing technologies for the transformation of conventional grids to offer reductions in global warming, operational expenditure, and smart meters. In [26], Kurtz *et al.* proposed an approach based on SDN and NFV driven queueing schemes. The authors extended the ETSI NFV architecture to provide 5G functionalities. To evaluate the performance of the proposed scheme, a testbed is created that consists of 13 identical servers with specifications of six 1GBaseT Ethernet ports from two Network Interface Cards (NICs), 16GB of RAM, and an Intel Xeon D-1518 CPU. Apart from that, the operating system used in the experiments is Ubuntu Server 16.04.3 LTS. Three virtual switches are deployed by running Open vSwitch version 2.5.2. Four machines are used to implement SDN controllers and six servers are used to setup as hosts. The authors validated their proposed scheme for smart grid and smart transportation system scenarios. The proposed work offers the benefits of higher scalability and low end-to-end delay for critical communication. However, the authors did not consider the orchestration of policy-based slices, which might be required for individual services.

E. HEALTH-CARE

Smart health-care is based on enabling low-cost and effective real-time health-care facilities using emerging technologies. In [27], Celdran *et al.* proposed a network slicing architecture using ontologies for managing complete slicing cycles. The proposed policy-based architecture offers dynamic orchestration of resources to meet the diverse scenarios requirements. The authors defined two types of policies: inter-slice and intra-slice policies. An inter-slice policy defines the management of shifting from one slice to another, while an intra-slice policy defines management of a slice itself. Furthermore, the authors considered the case of remote health-care and multimedia services. Although the proposed architecture provided detailed implementations of the network slicing using ontologies with reasonable latency in slicing that occurs from the start until final commissioning. However, the authors did not consider predictive and monitoring analytics for the analysis and collection of different metrics. These analytics can be used in addition to the proposed scheme to offer autonomic computing capabilities for self-managing features.

III. TAXONOMY

A taxonomy (presented in Figure 3) of the literature is devised in this section using the parameters of key design principles, slicing resources levels, key enablers, service function chaining schemes, physical infrastructure, and security.

A. KEY DESIGN PRINCIPLES

Enabling network slicing by using a shared infrastructure to enable a variety of smart applications poses significant challenges due to the wide variety of players. These players include edge computing, cloud computing, telecommunication operators, and IoT-networks. Enabling network slicing requires successful interaction among these players which is a challenging task. Therefore, we must pay considerable attention to the design of network slicing [7]. The key design principles of network slicing are isolation, elasticity, and end-to-end optimization [7], [8], [16], [17], [28], [29]. Generally, a network slicing architecture consists of three layers:

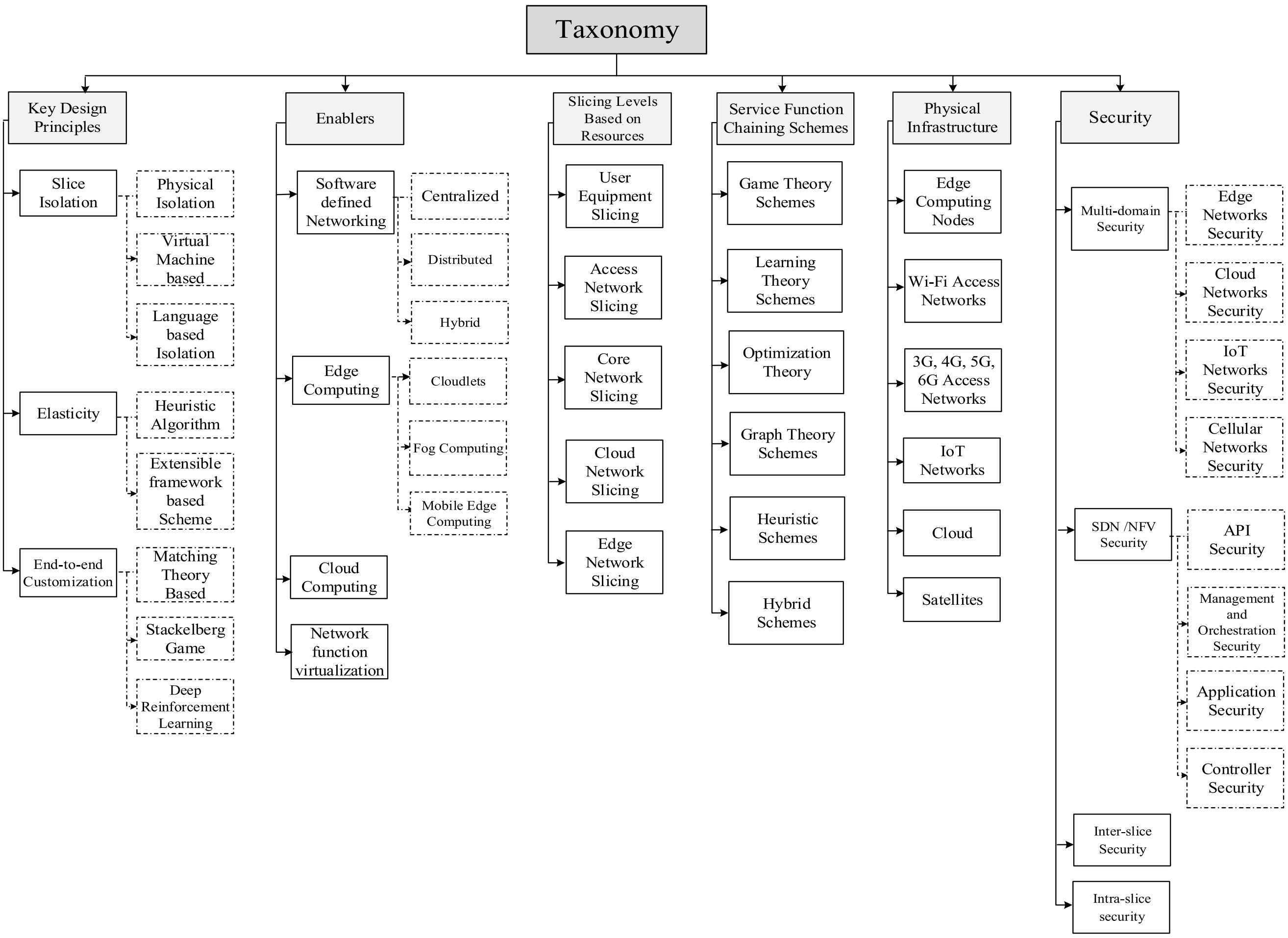

FIGURE 3. Network slicing taxonomy.

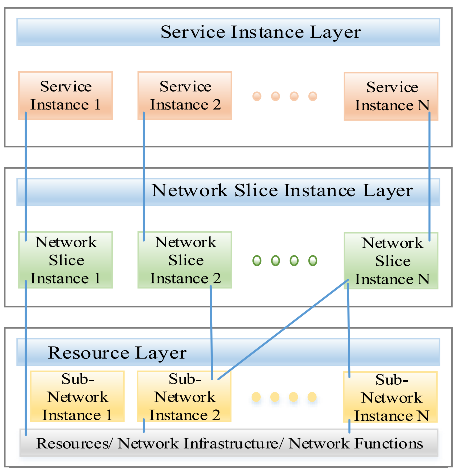

FIGURE 4. Network slicing layers.

a network infrastructure layer, network slice instance layer, and service instance layer, as shown in Figure 4 [30]. Depending on the layer, isolation of slices can be performed in many ways: language-based isolation, physical isolation, and virtual machine based isolation [31]. Language-based isolation can be performed at network slice instance layer and service instance layer, whereas physical-based isolation is preferable at the infrastructure layer. However, virtual machine-based isolation can be performed at the resource layer and network slice instance layer.

Elasticity refers to the availability of slice resources in an adaptive way according to user demands. The availability of fixed resources in a slice might result in under-utilization and over-utilization of resources due to variations in users demands [7]. Therefore, it is necessary to design network slicing with an elastic nature to simultaneously meet users QoS and optimize the overall network expenditure. In [32], Li *et al.* presented elastic service function chaining using a heuristic algorithm. In [29], Zhang *et al.* proposed a share constrained slicing scheme that offers load driven elasticity, envy fairness, and slice-level protection. The share constrained slicing scheme consists of two main phases of resource allocation. The first phase deals with the allocation of shared resources to the slices, whereas the second phase allocates resources among users of a particular slice. The proposed scheme has the advantage of considering the slicing scenario where the users require different proportions of heterogeneous resources. The processing rates of the users have a linear scaling relationship with the number of heterogeneous resources assigned to them. Therefore, dynamically assigning resources to the users while protecting other slices offer significant performance improvement. On the other hand, an extensible framework for elastic service function chaining is proposed in [33]. Other than elasticity, end-to-end optimization deals with the efficient use of all resources efficiently without compromising QoS. In [34]–[36], different approaches based on a matching game and prey-predator food chain model have been considered to enable efficient network slicing.

B. KEY ENABLERS

The wide variety of applications with extremely diverse requirements poses serious challenges regarding network design. These challenges include on-demand computing resources for resources, efficient network orchestration, and generic programmable hardware for network function implementation. Enabling the network to overcome these challenges via network slicing requires the use of cloud computing, edge computing, NFV, and SDN [7], [37]–[40]. SDN offers easier and effective management of the network functions. The SDN control plane can be implemented in different ways: a centralized control plane, distributed control plane, and hybrid control plane. In a typical centralized controller, the single controller capability significantly affects the scalability. Additionally, the signalling overhead between the switches and controller also limit the scalability. More specifically, the flow setup with the collection of statistics affects the scalability of the network. In a single controller, the scalability is limited due to processing of all flow initialization requests, followed by sending flow installation messages by a single controller. Apart from flow initialization request and installation messages, the controller performs the transmission of periodic state requests to obtain the resource states of all the switches under its control. The centralized control does not properly address the challenge of scalability because of the latency for large networks. Distributed and hybrid controllers on the other hand use multiple controllers to enable scalable operation. Therefore, selection of an SDN controller is primarily affected by the network characteristics.

On the other hand, there is a large variety of 5G and beyond network applications that need computational resources [41]–[43]. One way is to use a dedicated computational resource, however, this will increase the implementation cost. Another feasible way is to use on-demand computational resources. Cloud computing can be used to provide on-demand computing resources, but it has limitations in terms of high latency [44]. To cope with this challenge of high latency, we can use edge computing. Edge computing pushes the cloud computing resources to the network end, and thus minimizes the delay [1]. Several technologies such as cloudlets, fog computing, and mobile edge computing have been used in the literature to denote pushing computing resources to the network edge. NFV allows the use of generic hardware with virtual machines running on it to enable network functions in a flexible way [37], [45], [46]. In other words, there is no need to change the entire hardware when implementing new functions. Virtual machines can be used to implement these new functions on the existing hardware [47].

C. PHYSICAL INFRASTRUCTURE

Network slicing for different smart services involves diverse communication networks and computing technologies at the infrastructure layer [48]. These technologies include edge computing technologies, cloud, IoT networks, telecommunication networks, and satellites. Computing technologies such as edge and cloud offer computing and storage resources on demand [1], [7]. However, cloud computing has more delay and resources than edge computing. Therefore, edge computing is a preferable solution for latency sensitive applications, such as smart transportation, augmented reality, and smart forest fire detection. Other than computing technologies, numerous telecommunication technologies such as 3G, 4G, 5G, and 6G can be used for physical communication [41], [49]. Additionally, Wi-Fi has significant potential for use in various smart applications. Furthermore, satellite, unmanned aerial vehicles (UAVs), and IoT networks provide a physical communication infrastructure for smart services, especially for smart transportation, smart industries, and smart health-care [50], [51].

D. SLICING LEVELS BASED ON RESOURCES

The slicing of physical infrastructure can be done at different levels, such as the user equipment level, access network slicing, core network slicing, and edge network slicing. User equipment enables device-to-device communication. Furthermore, caching at the user equipment level enables instant content access. Enabling user equipment to provide caching and device-to-device communication requires an attractive incentive mechanism [52]. Therefore, resources at the user equipment level need effective slicing strategies [7]. The network slice provider uses these user equipment resources to enable different slices, while in turn providing incentives to the users. On the other hand, radio access network slicing has been considered in [34], [35], [53]. In [34], [53] and [35], orthogonal frequency division multiple access and non-orthogonal multiple access have been considered for a radio access network, respectively. Apart from the user equipment level and radio access network, core network, cloud, and edge computing resources must be shared effectively between different tenants while fulfilling the general design requirements.

E. SERVICE FUNCTION CHAINING

In network slicing, numerous smart network functions are implemented through combination of different service functions implemented on virtualization enabled switches. Each virtualized network function either runs on a single switch or multiple switches. Numerous smart applications have diverse requirements in terms of bandwidth, latency, energy efficiency, security, among others. It is necessary to trade-off between different design parameters. For instance, consider the implementation of network functions via virtual network functions running on different networks nodes. Considering the latency and number of active network nodes as design parameters, minimizing both of these is not possible [54]. Therefore, we must trade-off between the number of active nodes and latency.

On the other hand, there exist significant challenges in resource allocation for implementation of service function chaining to enable efficient network slicing. These challenges are the dynamic nature of network traffic, multiple service providers, and mobility [55]. The highly dynamic nature of the network traffic results in complexity due to varying requirements of resources at run time. To cope with such type of issues, we can use dynamic service function chaining [56]. Apart from the dynamic nature of the traffic, the presence of multiple network functions providers poses the challenge of enabling effective coordination among them [57], [58]. The 5G network mobility imposes limitations on the implementation of the service function chaining because of its significantly different nature than the Internet. In [59], Taleb *et al.* discussed the elastic and on-demand cloud-based mobile core network deployment. Moreover, the authors presented challenges and requirements for the implementation of the core network as an evolved packet core as a service. In [54], energy-efficient and traffic-aware virtual network function placement has been performed via a matching game. In [60], Sun *et al.* proposed a Q-learning framework hybrid module algorithm (QLFHM). In [61], Zhang *et al.* proposed service function chaining based on graph theory. On the other hand, a greedy heuristic-based solution is provided in [62] for service function chaining. Considering this, we can use hybrid schemes based on game theory and learning theory for service function chaining.

F. SECURITY

Generally, slices security can be divided into inter-slice security and intra-slice security [63]. Inter-slice security deals with security schemes pertaining to all slices of different smart applications, whereas intra-slice security refers to slices of specific applications. The wide variety of smart application slices have diverse security requirements. For instance, smart health-care slices have more security concerns than smart infotainment slices. Therefore, there must be effective security algorithms for intra-slice security. On the other hand, enabling network slicing for multiple tenants with distinct requirements using a wide variety of physical infrastructures through SDN and NFV involves different networks. Enabling network slicing suffers from serious security concerns, including multi-domain security, such as edge computing security [64], cloud security [65], telecommunication networks security, and IoT networks security [66].

The key enablers of network slicing SDN and NFV have their own security challenges. In SDN, numerous different types of controllers are available for controlling SDN switches and SDN enabled access points/base stations.A malicious user can access the controller and alter the network functions [67], [68]. Additionally, a malfunctioning controller can interrupt the whole network operation. Different SDN controllers include a centralized controller, distributed controller, and hybrid controller [69]. All of these controllers pose novel security challenges depending on its type. A centralized controller controls the whole network and is located at a central location, whereas hybrid and distributed controllers are located in a geographically distributed fashion. Therefore, the type of controller poses novel security challenges. A single controller is more sensitive to security attacks than other controllers but has easier management [70]. Apart from that, a hybrid controller and distributed controller offer more scalability and more robust operation than a centralized controller, but with complex management functions [69].

IV. REQUIREMENTS

This section highlights indispensable requirements for enabling network slicing, as presented in Figure 5. These requirements include scalability, dynamic network slicing, extensible nature, recursion, adaptive service function chaining, efficient end-to-end orchestration, and a secure and dynamic business model.

A. SCALABILITY

How does one enable efficient network slicing with isolation over a shared physical infrastructure for a rapid increase in the number of users? The frequent addition of new nodes in different smart environments, such as smart transportation, smart health-care, and smart industries, has been observed [7]. This addition of new nodes poses a challenge in terms of QoS loss for these smart environments. On the other hand, several network segments exist in the network slicing with different features. Every network segment is managed using its particular set of models and abstractions. Therefore, managing the whole network using a single management unit (orchestrator) has the advantage of simplified management, but at the cost of reduced fine-grained resource control [71]. Furthermore, the use of the single orchestration unit increases complexity and delay [72]. Such type of increase in delay will be more prominent for massive machine-type communication in 5G and massive ultra-reliable low latency communication in the upcoming 6G wireless systems [41]. To cope with these issues, we can use multiple orchestrators for the whole network to reduce the complexity. Every orchestrator is designed to control particular network segments. These multiple orchestrators are then controlled by another entity called a hyperstrator whose job is to control the overall network resource allocation [71]. Such a framework can be used to enable scalable operation based on network slicing. Other than multiple orchestrators, network slices must be handled elastically to avoid the underutilization of resources. Avoiding under utilization of resources results in accommodation of more users by the system.

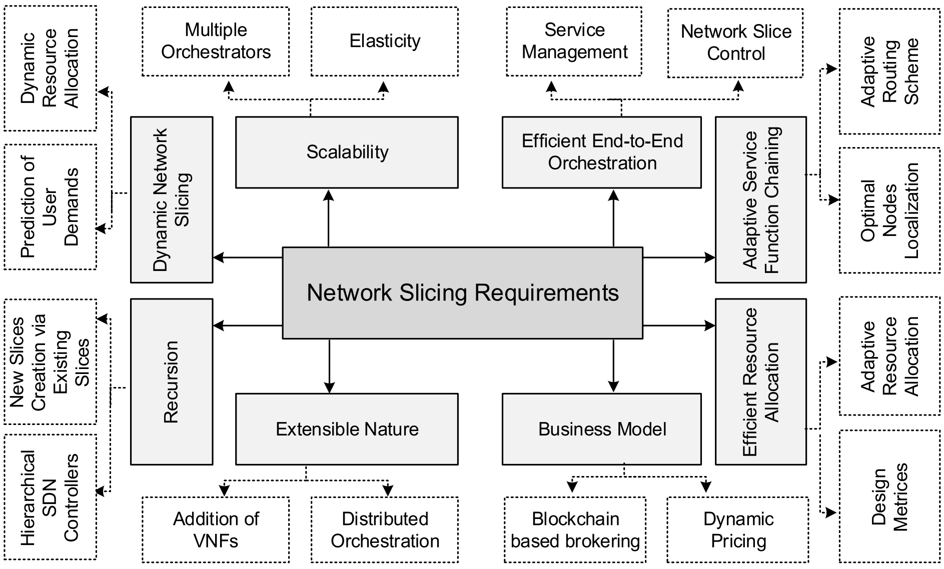

FIGURE 5. **Network slicing enabled smart city requirements.**

B. DYNAMIC NETWORK SLICING

How do we enable network slicing that dynamically allocates resources according to user demands? In [34], [35], [73]–[75], it is assumed that user demand remains fixed during the resource management process. However, there exist significant variations in user demands during the resource management process. The users may dynamically join and leave the system. Therefore, to enable network slicing for smart cities with varying user demands, it must dynamically allocate resources. To enable dynamic network slicing, it is necessary to accurately estimate the user demands and dynamically allocate resources accordingly. Several learning theory schemes such as deep learning and reinforcement learning can be used for the prediction of user traffic. After accurate prediction, effective resource allocation schemes can be used for enabling dynamic network slicing. In [76], Costanzo *et al.* proposed a dynamic network slicing scheme for the co-existence of IoT services and enhanced mobile broadband. Furthermore, the authors validated their proposed solution using a 5G testbed-based on a cloud radio access network that uses the FlexRAN SDN controller [77] and open-air interface.

C. EXTENSIBLE NATURE

How does one enable network slicing that is capable of extending its functionalities? The extensible nature of smart application slices aims to extend their capability through the addition of extra functionality using a modification of the existing virtual network functions. One way to achieve an extensible network slicing architecture is the use of hierarchical orchestrators based architecture. Such a network slicing architecture consists of a set of orchestrators used to control the network segments with similar features. Subsequently, the second-level orchestrators are used to control the first-level orchestrators. The first-level orchestrators can be used to offer new functions to second-level orchestrators by using the associated virtual network functions [78].

D. RECURSION

How does one enable a new slice from existing slices? Recursion is the ability of a network slicing architecture to enable the creation of new slices from existing slices [79]. The creation of a new slice has more complexity than building one from existing slices. Therefore, this key requirement must be fulfilled when designing the network slicing architecture. Modifications in the SDN control plane can be used to offer recursion in network slicing by using multiple hierarchical controllers. These hierarchical controllers are used to define multiple levels server/client relationships. Such hierarchical relationships allow a controller to use resources (such as other SDN controllers) via its server context to create new slices for its client [80].

E. EFFICIENT RESOURCE ALLOCATION

How does one efficiently allocate the computing capacity, spectrum, and link bandwidth in network slicing to jointly optimize the user performance and operators profit? Enabling different smart services involves a wide variety of diverse requirements. On the other hand, all resources have limitations. Therefore, smart services put significant limitations on the design of network slicing. To enable efficient network slicing, it is necessary to accurately compute the requirements of slices, which is followed by resource allocation. Resource allocation can be based on different design matrices. These matrices include the energy, latency, QoS, and user-defined utility [81]. The allocation of resources in network slices must be adaptive to ensure QoS. For instance, smart transportation slices have strict latency constraints. Therefore, more resources must be allocated to smart transportation to reduce the delay.

F. ADAPTIVE SERVICE FUNCTION CHAINING

How does one enable service function chaining that simultaneously optimizes the overall performance of the network? Network slicing uses virtually enabled functions to enable services with diverse requirements. These virtually-enabled functions are implemented using virtual machines running on one physical node or multiple nodes. Every node has certain costs of running particular network functions. These costs are subjected to the physical node capacity and link constraints [54]. For instance, the cost can be network latency and operational expenditure. Therefore, it is necessary to optimally localize the nodes to enable service function chaining in an adaptive way. Two main challenges in adaptive service function chaining are optimal nodes and the routing scheme for the selection of nodes. In [54], the service function problem is formulated as the optimization of joint network traffic and operational cost. To solve this problem, a matching theory-based solution was proposed. On the other hand, the service function chaining problem is formulated to minimize the total link flow [82]. The authors proposed a *penalty successive upper bound minimization algorithm* and its variant the PSUM-R algorithm to solve the problem.

G. EFFICIENT END-TO-END ORCHESTRATION

How do we enable efficient management of virtual network functions and their infrastructure for several slices with diverse features? The network slicing architecture is comprised of two layers: a service management layer and a network slice control layer [16]. The job of the service management layer is service creation, while the network slice control layer performs resource management. The orchestration of network slicing deals with the efficient management of the network slicing process. To enable effective network slicing, it is necessary to propose an efficient network slice orchestration architecture. In [71], a network slice orchestration architecture was proposed that consists of end-to-end service management, an orchestrator, virtual resource orchestration, a network resource programmable controller, and a life cycle management component. On the other hand, Salvat *et al.* in [83] considered slice overbooking to provide mobile operators with more profit. First, a hierarchical control plane is proposed for the efficient management of network slices. Second, the slicing orchestration problem is formulated as a stochastic yield management problem that is solved using two algorithms. Finally, the authors provided experimental proof-of-concept to validate their proposal. Furthermore, the authors showed that slice overbooking results in a significant increase in revenue. Other than that, we can use artificial intelligence for performance improvement of overbooking to network slicing [84].

H. SECURE AND DYNAMIC BUSINESS MODEL

How do we enable secure and dynamic business models for network slicing in the presence of a wide variety of smart services and multi-vendor systems? Numerous vendors such as edge servers providers, cloud providers, and telecommunication service providers, provide resources to enable different smart services. The service providers must be given incentive to offer their services via a network slice provider. These incentives must be dynamic to effectively increase the overall profit without QoS loss. For instance, different smart services may request edge computing resources to obtain on-demand computing resources with low latency. We need an effective dynamic pricing model for such type of interaction between edge computing service providers and users [85]. The price of computing resources must take into account the frequency of requests, the duration of use, and the number of active requests within a particular duration. To enable such interactions, buying and selling of resources by the network slice provider is implemented. There are many ways to enable secure interactions between sellers and buyers (brokering). One way is the use of a blockchain-based secure brokering mechanism for selling and buying a resources among the network slicing players.

V. CASE STUDIES

This section outlines the leading case studies and synergies pertaining to network slicing. Furthermore, key objectives, organizations involved, deployment status, and deployment country are summarized in Table 4.

A. AUTOAIR

This project is aimed at development of a shared platform to offer services for different private and public operators though network slicing [86]. More specifically, the shared platform enables the rapid development and validation of connected and autonomous vehicles (CAV) based on 5G technologies. To enable seamless communication between the vehicles and infrastructure (V2X), dense deployment of the 5G small cells is considered. These 5G small cells use mmWave and a licensed sub-band of 6GHz. Additionally, the project leverages emerging multi-access edge computing technology to offer strict latency traffic services. On the other hand, the testbed will be implemented at Millbrook Proving Ground, Bedfordshire. It consists of 70km roads with a 3km circumference bowl, off-road areas, hills, and a 1-mile straight road. Along with this, a railway track is located beside the mile straight road.

B. ALBA IULIA SMART CITY

This project enables the creation of smart connected transport, smart air quality monitoring, ultra specific location technology, smart lighting, and city analytics and sustainability using network slicing [87], [88]. The purpose of the project is to install sensors throughout the city to collect different

TABLE 4. Summary of the case studies.

Case Studies	Key Objectives	Deployment Status	Organizations Involved	Country
AutoAir	• Network slicing based 5G testbed • Intended for testing of connected and autonomous vehicles • Dense deployment of 5G small cells for seamless v2X communication • Multi-access edge computing for strict latency services • Open platform	Not completely deployed	• Surrey University's 5G Innovation Centre • Airspan • VIAVI Solutions • Celestia Technologies • Cobham Wireless • ARM • Real Wireless • Millbrook • Quortus Limited • Blu Wireless Technology Limited • McLaren Applied Technologies • Dense Air Limited	UK
Alba Iulia Smart City	• Smart city slices as a service • Smart lighting • Smart aur quality monitoring • Ultraspecific location technology • City Analytics and sustainability	Not completely deployed	• Orange Romania • Samsung • CISCO	Romania
Hamburg Port	• Smart interactive augmented reality • Smart logistics and transportation • Smart real-time environmental data collection using ships with sensors	Not completely deployed	• Hamburg Port Authority • Nokia • Deutsche Telekom	Germany
Bristol is Open	• An open programmable smart city • Enable a playable smart city infrastructure • Offer Big data visualization • Enable collaborative environment for multiple smart city players • Access to multiple transport facilities at common point	Not completely deployed	• University of Bristol • Bristol city council • NEC • Interdigital • Nokia	UK

information, such as smart meters, water distribution, smart lighting management, and air quality. To provide the collection and processing of smart city information, LoRa WAN, LoRa, FTTH fiber, Wi-Fi, 4G, and 5G technologies will be used as physical infrastructure. More specifically, the smart city services are provided in the form of slicing-as-a-service.

C. HAMBURG PORT

The Hamburg port implements a 5G network slicing testbed for smart city applications, such as smart interactive augmented reality, smart environment measures, smart logistics, and smart-transportation [89]. This project is a part of the *5G Mobile Network Architecture for diverse services, use cases, and applications in 5G and beyond)* (5G MoNArch). To enable network slicing at Hamburg port, NFV and SDN are adopted. Furthermore, the players of the network slicing enabled smart port are the 5G UEs, BSs with support for slicing, central cloud, edge cloud, and data centers. To turn the vision of network slicing into reality, a transmitter is installed at a television tower at the port. Moreover, sensors are used at the port authority ships to enable real-time environmental measurements.

D. BRISTOL IS OPEN: AN OPEN PROGRAMMABLE CITY

This project is a joint venture between Bristol city council and University of Bristol to achieve an open programmable city [90]. The industrial partners involved in this venture are NEC, Interdigital, and Nokia. The primary goal of this project is to create a programmable network that shares information to ease the creation of a multi-service and multi-tenant network. To enable such programmable smart city, SDN and NFV were considered. The Bristol smart city has three main networks: the IoT mesh, wireless network (3G, 4G, and 5G), and optical fiber network. Apart from the networks, Bristol smart has four nodes: the playable city, watershed, engine shed, and Bristol data dome. The Bristol data dome is a 98-seat dome located at Bristol Planetarium, that has a stereo 3D hemispherical screen with 4K resolution. The dome creates virtual reality environments with a unique viewpoint for individuals. The dome is connected to a high-performance computer situated at the University of

TABLE 5. Summary of the research challenges and their guidelines.

Challenges	Causes	Guidelines
Intelligent service function chaining	• Optimal node localization • Low-latency routing	• Deep learning-based intelligent service function chaining • Reinforcement learning-based scheme
Adaptive security scheme	• Significant variations in latency requirements of smart applications • Security requirements diversity of different smart applications	• SDN ochestrator based adaptive security scheme • Novel light weight authentication schemes for strict latency application slices
Mobility-aware slicing	• Handover across different radio access networks • Ultra-high density of future 5G and 6G networks along with high mobility	• Lagrangian dual decomposition based solution • Matching theory-based slicing schemes
Network slicing Forensics	• Serious vulnerability to attacks • Wide variety of infrastructure providers	• Forensic Models • Forensic tools
Dynamic Spectrum Slicing	• Spectrum scarcity • Variations in users demands	• Policy based dynamic slicing spectrum slicing scheme
Federated learning-based network slicing	• Large variety of tunable parameters in 5G and beyond systems transceivers • Privacy leakage in a traditional machine learning enabled networks	• Double deep Q-learning agents-based edge intelligence for computational offloading and caching. • Federated learning-based radio resource allocation
Adaptive Business-model-driven Network Services	• Involvement of multiple players in network slicing • Profit reduction due to variations in users traffic	• Dynamic service level agreements between network slicing players

Bristol through a 30Gb/s fiber link. The second node, i.e., the engine shed, is the hub of collaboration between the social innovators, academics, entrepreneurs, and businesses. The third node, the water shed, is situated at Bristol's historic harbourside and enables different transport links such as the bus, bike, ferry, and car with less effort. Finally, the fourth node, the playable city allows people to play at the city heart by enabling the user-to-user and user-to-city connections.

VI. OPEN RESEARCH CHALLENGES

This section presents several open research challenges and possible solutions for network slicing. The challenges discussed in the existing surveys of network slicing [8], [16], [17] are radio access network virtualization, service composition with fine-grained network functions, end-to-end slice orchestration and management, network slicing techno-economics aspects, radio access network slicing and traffic isolation, security, slice optimality, and user equipment slicing. In our survey, we present novel challenges whose summary is given in Table 5.

A. INTELLIGENT SERVICE FUNCTION CHAINING

Service function chaining aims to implement different network functions via virtual machines running either on a single or multiple nodes. Every node is specified by limited computational resources and bandwidth constraints regarding communication with other nodes. Therefore, the performance of service function chaining significantly depends on node selection and their corresponding communication links. To enable efficient service function chaining, it is necessary to choose optimal nodes that jointly improve the energy efficiency and computational latency. Other than node selection, routing protocols with low latency must be devised for service function chaining nodes. A reinforcement learning-based service function chaining scheme was proposed in [91]. Another study used a deep learning-based scheme to enable intelligent service function chaining via learning routing and prediction [92]. Although both proposals considered latency in their designs, the authors did not consider joint minimization of the energy and latency.

B. MOBILITY-AWARE SLICING

The mobility of users in wide variety of smart applications poses significant challenges to resource allocation for network slicing. Mainly, these challenges are due to handovers for different access networks and ultra-high density of 5G networks along with high mobility. To cope with mobility issues, it is necessary to use a mobility-aware slicing scheme. For instance, frequent handovers will occur with in autonomous cars on a highway when compared to augmented reality-based applications. Therefore, we need to devise novel on-demand slicing schemes. In [93], a Lagrangian dual decomposition-based solution was proposed to enable mobility-aware network slicing. The authors proposed revised schemes for handovers in mobility scenarios for a network slicing environment. Finally, a resource allocation scheme for different 5G scenarios was presented. Other than the Lagrangian dual decomposition-based solution that uses a relaxation of binary variable into a continuous variable, we can also use game theoretic solutions.

C. NETWORK SLICING FORENSICS

In network slicing, the involvement of a large number of resource players with different security levels increases the vulnerability of cyberattacks. Therefore, it is necessary to devise new forensic techniques so researchers can study network slicing attacks. The existing forensic techniques for IoT and cloud computing forensics must be modified and combined with other novel forensic techniques for network slicing [94], [95]. We must propose novel forensic techniques for network slicing considering the origin of attacks, worst case attacks, reliability of evidence, and detection of attacks in uncertain situations [96]. The main aspects of network slicing research are forensic models and forensic tools. Therefore, we must design novel forensic models and tools for network slicing.

D. DYNAMIC SPECTRUM SLICING

To meet the growing demands of users, it is necessary to efficiently utilize the available spectrum via slicing. There exist significant variations in users demands. A user of a particular tenant enter or leave the system. Therefore, fixed spectrum allocations might result in underutilization or overutilization. To cope with these issues, it is necessary to perform dynamic spectrum slicing. In [97], Gebremariam *et al.* presented a policy-based dynamic spectrum slicing scheme that considers network traffic variations. The distribution of user traffic is modeled using a Markov process, which has benefit of considering the correlations between consecutive points of user traffic. Moreover, the use of Markov modeling enables accurate estimation of the inter-arrival time, which further improves the performance of the slicing algorithm.

E. ADAPTIVE SECURITY MECHANISMS

The multiple infrastructure layer technologies, service level agreements between different parties, and the key enablers (SDN and NFV) in the network slicing pose serious and complex security challenges. These security challenges include: multi-domain security, slicing orchestrator security, inter-slice security, and intra-slice security. The presence of different service providers may have different security policies, which makes the design of network slicing security more complex. On the other hand, different scenarios have different latency-requirements. For instance, ultra-reliable low-latency communication (URLLC) services have more strict latency constraints than enhanced mobile broadband (eMBB). Therefore, the authentication applied for URLLC slices must be light weight with low complexity. One possible solution for an adaptive security mechanism in network slicing is an SDN orchestrator-based adaptive security scheme. The SDN-based orchestrator can perform node selection and path selection as per the security requirements of the slice in an adaptive way.

F. FEDERATED LEARNING-BASED NETWORK SLICING

It is expected that there will be more than 2000 tunable parameters in a typical intelligent 5G transceiver [98]. Therefore, there is a need to train the transceivers using an effective machine learning model to provide efficient radio resource allocation. Federated learning is considered to be an inevitable game-changer in the future wireless networks for prediction, intelligent resource management, and intelligent policy control [99]. These functions can be implemented via traditional machine learning algorithms. However, privacy preservation is a concern in traditional machine learning, which is satisfied using federated learning. Federated learning offers learning without moving data from devices to a centralized server, thus preserving user privacy. Therefore, it is recommended to enable future network slicing via federated learning. In [98], federated learning has been used to train double deep Q-learning agents at the network edge for caching and computational offloading decisions in a resource optimized way and preserving the users' privacy.

G. ADAPTIVE BUSINESS-MODEL-DRIVEN NETWORK SERVICES

Network slicing is not only a promising technology for 5G and beyond networks, but also resembles a business model. It involves a wide variety of players to interact and provide users with different smart services. Although standalone business models are available for different technologies (e.g., cloud computing), we need to devise novel business models for network slicing. All the operators require appropriate adaptations to changes by providing services. It is necessary to transition from product-based to service-based business models. In this case, the demands of the users may change with time. Therefore, we must design adaptive business-model-driven network services to increase the operator profit and user performance simultaneously. These adaptive business-model-driven network services require a service level agreements (SLA) between the users, network slice providers, and physical infrastructure providers. However, the creation, reporting, and management of SLAs are challenging tasks. Therefore, effective SLAs must be made between network slicing players to enable adaptive business-model-driven network services.

VII. LESSONS LEARNED: SUMMARY AND INSIGHTS

In this paper, we investigated the recent advances of network slicing towards enabling smart IoT applications.

Furthermore, we devised a taxonomy and presented requirements for network slicing. We learned following lessons from this study:

- We derived that network slicing will be one of the key enabling technologies of future smart cities. A typical smart city offers a wide variety of smart applications. These applications are smart transportation, smart industries, smart health-care, smart farming, smart security, smart gaming, among others [1]. The smart city applications are characterized by a wide variety of distinct features and requirements. For instance, consider the reliability and security of the smart grid using nuclear power plants and the smart industry. A nuclear power plant based smart grid must be provided with more security and reliability than smart industries. Therefore, it is necessary to develop novel slices for smart city applications. On the other hand, the typical requirements for a smart city application are sustainability, scalability, reliability, security, elasticity, and inter-operability [1], [100]–[102]. We must define new specifications for smart city slices and resolve the challenges in enabling them.
- It is indispensable to propose novel protocols for the SDN control plane with multiple controllers to enable extensible and scalable network slicing. In traditional SDN, a logically centralized controller is used to control the overall network. The purpose of using a centralized controller is to enable efficient management of the network by decoupling control plane from the data plane. However, the centralized controller has certain limitations in terms of latency and robustness. A single logically centralized controller suffers from high-signaling overhead when the network size grows. On the other hand, scalability and reliability (as discussed already in the paper) have been considered indispensable requirements of the network slicing. Therefore, it is necessary to use multiple controllers for enabling network slicing. However, enabling network slicing through multiple controllers requires novel protocol designs for the SDN control plane that offers enhanced scalability and reliability.
- Novel economic models are needed for network slicing to enable 6G networks. In 6G, novel use case and service providers are expected such as haptics communication service providers, 3D cellular network providers, telemedicine providers, nano-IoT service providers, among others, compared to 5G networks [41], [43], [103]. These novel service providers enable novel services that have significantly different nature than most of the 5G services. Therefore, there is a need to develop novel economical models for 6G enabled by network slicing.
- We derived that there is a need to develop novel virtualized mobile core networks (novel evolved packet core) for 5G and beyond networks. The evolved packet core was developed to offer potential services that are able to fulfill the increasing demands of the users [104]. However, it seems difficult to fulfill the varying and diverse requirements of users. Therefore, to enable users with diverse smart applications, there is a need to develop novel virtualized mobile core networks [104], [105]. Mainly, the virtualized core network offers the striking features of scalability and reliability. As most of the IoT-based smart services require the key features of scalability and reliability, therefore the virtualized core network seems to be a preferable solution for enabling smart IoT services. The virtualized mobile core network allows scaling of virtual network functions (i.e., mobility management entity and gateways) as per the demands of service. Such type of flexibility in the scaling of core network capacity can be achieved by adding resources of the control plane without affecting the control plane.
- We derived that it is necessary to propose novel decentralized security mechanisms for network slicing enabled smart IoT services. One way to enable security for network slicing based smart services is the use of centralized security mechanisms. However, this approach will result in an increase in latency which is undesirable for a variety of smart applications such as smart transportation, smart industries, and smart gaming, to name a few. On the other hand, a significant increase in the number of smart IoT devices for different services is expected in the foreseeable future [1]. Therefore, there is a need to develop novel decentralized security mechanisms for network slicing enabled IoT services. The use of decentralized security mechanisms will offer security with low latency which is one of the primary design parameters of 5G and beyond networks.
- We learned that the adaptive network slicing life cycle management schemes must be proposed. The typical network slice life cycle consists of creation, update, and deletion of the slice by the slicing orchestrator. Such a life cycle is different than a traditional network and suffers mainly from the challenge of varying life cycles depending on the service time of the slice. Different services slices have different life cycles [106]. Other than this, the slice requirement may vary as per the users' demands. To cope with these challenges, it is necessary to propose a novel adaptive network slicing life cycle management schemes.

VIII. CONCLUSIONS AND FUTURE RECOMMENDATIONS

A. CONCLUSIONS

In this paper, we discussed recent advances for enabling IoT-based smart environments via network slicing, taxonomy, requirements, use cases, and open research challenges. We concluded that network slicing is absolutely necessary to enable a wide variety of 5G and beyond systems (i.e., 6G). Furthermore, network slicing will be a key enabling technology to transform the current cities into a smart ecosystem that uses emerging technologies for significantly improving the quality of life.

B. FUTURE RECOMMENDATIONS

Our key recommendations for future research are as follows:

- 5G cellular networks are intended to provide a wide variety of smart services. However, there are several limitations: enabling of heterogeneous Internet of Everything (IoE) services via high-frequency millimeter wave communication, extended reality services (encompassing virtual reality, mixed, and augmented reality), connected autonomous systems, telemedicine, heptics, and flying vehicles. For instance, 5G wireless networks are based on short packets for ultra-reliable low latency communication. However, numerous 6G applications (i.e., extended reality and autonomous connected vehicles) require long packets with ultra-high data rates and ultra-high reliability. These limitations heavily influenced 6G research activities [41]. As network slicing is considered to be a key technology of enabling 5G networks, it is thus necessary to develop novel network slicing algorithms for future 6G services.
- Three-dimensional (3D) cellular networks consisting of drone-based user equipment and drone-based BSs are expected to be one of the key drivers of 6G cellular networks [103]. Therefore, it is recommended to consider slicing for 3D cellular networks whose management and orchestration require significant efforts due to their different nature compared to traditional cellular networks.
- Machine learning has been considered to an integral part of 6G and beyond networks to enable different smart applications [41]–[43]. It is expected that machine learning will be used to enable intelligent cognitive radio for efficient resource management in 6G and beyond networks. However, training of machine learning needs extensive simulations to tune the machine learning model parameters. We can use meta-learning to enable machine learning model to effectively learn parameters within less time. On the other hand, different machine learning models have different nature and complexity. Therefore, there is a need to develop novel meta-learning models for machine learning-enabled network slicing.

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