A Smart RAN Slicing Approach

• mainly relied on three prevailing trends:

  1. Integration of distributed energy resources (DERs), which results in high power system dynamics and a growing need for real-time grid supervision to ensure stability. On top of the drivers mentioned above, the deregulation of energy markets and the need for advanced security against hostile cyberattacks have a significant impact on the transformation of power systems.

  2. Large-scale information acquisition, with the massive deployment of smart meters to keep track of energy consumption.

  3. Reliable monitoring, protection, and control, where intelligent electronic devices (IEDs) offer situational awareness and rapid fault detection.

Instrumental to this paradigm shift is the underlying communication infrastructure deployed for robust, scalable, and reliable connectivity among the power system components [1]. Connectivity in power systems currently involves a plethora of technologies, ranging from optical fibers and power line communication to wireless technologies and satellite networks. Among those, wired connectivity schemes have been extensively used in power systems for localized mission-critical applications. Notwithstanding, wireless solutions exploit the advantages of lower deployment/maintenance cost and their intrinsic scalable characteristics to offer enhanced grid functionalities [2]. For example, in distribution automation, IEDs need to timely exchange protection-related messages for fast decision-making to avoid extensive disturbances to the entire grid. On the other hand, advanced metering installations require highly scalable network deployments to manage meter readings from consumers located at disparate spatial locations.

The advent of fifth-generation (5G) and beyond communication networks is expected to revolutionize traditional power systems by supporting a wide range of real-time and autonomous operations [3]. Unlike previous mobile network generations, 5G systems are designed to enable three key generic services with broadly diverging operational requirements: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low latency communication (uRLLC). Cellular networks are progressively becoming ubiquitous with omnipresent applicability in vertical industries. Thus, the business potential of 5G in the smart grid domain can be remarkably high with the realization of unprecedented use cases, such as millisecond-level precise load control, decentralized fault detection and self-healing operation, and predictive maintenance of grid infrastructure [4]. Among the pivotal 5G novelties, radio access network (RAN) slicing allows the partition of radio resources by interpretation as a RAN slice. RAN slicing is hence gaining momentum as an enabling platform for the integration of vertical services over a shared physical infrastructure.

One of the key challenges for the realization of RAN slicing relates to the efficient resource management among RAN slices, each of them customized to meet diverse quality-of-service (QoS) requirements. A RAN soft-slicing approach based on network-level resource pre-allocation is proposed in [5] to enable opportunistic resource

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**Abstract**
Fifth-generation (5G) and beyond systems are expected to accelerate the ongoing transformation of power systems toward the smart grid. However, the inherent heterogeneity in smart grid services and requirements pose significant challenges toward the definition of a unified network architecture. In this context, radio access network (RAN) slicing emerges as a key 5G enabler to ensure interoperable connectivity and service management in the smart grid. This article introduces a novel RAN slicing framework which leverages the potential of artificial intelligence (AI) to support IEC 61850 smart grid services. With the aim of deep reinforcement learning, efficient radio resource management for RAN slicing is attained, while conforming to the stringent performance requirements of a smart grid self-healing use case. Our research outcomes advocate the adoption of emerging AI-native approaches for RAN slicing in beyond-5G systems, and lay the foundations for differentiated service provisioning in the smart grid.

**Introduction and Motivation**
In recent years, the ongoing modernization of the aging power systems toward the smart grid has mainly relied on three prevailing trends:

1. **Large-scale information acquisition**, with the massive deployment of smart meters to keep track of energy consumption.

2. **Reliable monitoring, protection, and control**, where intelligent electronic devices (IEDs) offer situational awareness and rapid fault detection.

3. **Integration of distributed energy resources (DERs)**, which results in high power system dynamics and a growing need for real-time grid supervision to ensure stability. On top of the drivers mentioned above, the deregulation of energy markets and the need for advanced security against hostile cyberattacks have a significant impact on the transformation of power systems.

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sharing among slices and support instantaneous service demands. With the aim of improving resource utilization efficiency, the RAN slicing control strategy in [6] adopts multiple time-resource granularities, where radio resources can be dynamically shared between slices. However, the potential of RAN slicing on addressing the inherent smart grid service heterogeneity has not yet been adequately explored in the literature. Focusing on smart grid service provisioning, this article introduces a beyond-5G RAN slicing framework utilizing the IEC 61850 standard to define smart grid communication requirements. In summary, our contribution is threefold:

- We present a comprehensive categorization of 5G-enabled smart grid services, highlighting the role of RAN slicing on their efficient integration.
- We propose a novel RAN slicing framework empowered by artificial intelligence (AI) for the accommodation of IEC 61850 services in beyond-5G systems.
- We demonstrate the feasibility of our approach in a smart grid self-healing use case, where efficient radio resource allocation is achieved while conforming to peculiar QoS requirements.

The rest of the article is organized as follows: The next section presents a classification of smart grid services enabled by 5G systems and their associated sliced services. Following that we describe key aspects of RAN slicing and highlight the major benefits for smart grid communication from technological and business perspective. Then we introduce our proposed RAN slicing framework for IEC 61850 services, with a comprehensive description of its building blocks. Following that we outline our AI-based methodology and present a performance assessment pertaining to a smart grid communication scenario. Finally, concluding remarks are summarized.

Classification of 5G-Enabled Smart Grid Services

Two interdependent domains form the smart grid infrastructure: a hierarchical power system, covering multi-directional power flow steps from generation to final consumption; and a two-way communication system, enabling extensive information exchange. In what follows, we provide a categorization of 5G-enabled smart grid services and we highlight the relationship with 5G network slices based on their requirements.

Smart Distribution Automation

Distribution automation allows power distribution systems to reconfigure themselves when a fault occurs, restricting the problem to a smaller area [2]. Rapid fault location, isolation, and service restoration offered by IEDs and other controllable units reduce the total outage time and the number of interruptions. 5G-enabled distribution automation aims to achieve real-time situational awareness and quasi-real-time analysis of the grid behavior by supporting advanced functionalities, for example, automated feeder switching and optimized restoration dispatch. Such operations are often linked to stringent performance requirements, that is, very low end-to-end latency and ultra-high reliability, falling under the uRLLC network slice.

Wide-Area Monitoring, Control, and Protection

Power system operators install sensors on critical grid components, such as power lines and transformer banks, to measure equipment status parameters. Such measurements provide real-time alerts for abnormal conditions and outage information to support utilities in predicting equipment maintenance and replacement. By exploiting 5G and beyond communication infrastructure, wide-area monitoring systems aim to enhance traditional supervisory control and data acquisition (SCADA) systems, offering advanced supervision capabilities [3]. Since the characteristics of the monitoring elements vary, this service category requires a synergistic mix of uRLLC, mMTC, and eMBB slices.

Metering Data Acquisition

The massive deployment of smart meters for large-scale information acquisition constitutes one of the principal components of next-generation power systems [7]. Smart meters continuously evolve to sophisticated computing units, which gather, process, and transmit user consumption information to data aggregation units for further processing and analysis. The advanced mMTC capabilities of beyond-5G systems are instrumental for generating unprecedented volumes of metering information. In addition, advanced metering systems can leverage the distributed information processing and storage architecture of 5G and beyond core networks, supporting fog computing platforms for localized decision-making.

Distributed Generation Integration and Microgrids

By providing higher fault tolerance and islanding detection, 5G-enabled smart grids enable safer and more reliable connections of distributed generation units, for example, solar photovoltaic panels, wind turbines, and natural-gas-powered fuel cells. The increasing penetration of renewable energy sources gives rise to the microgrid paradigm, which acts as a single controllable entity concerning the grid, that is, operation in either a grid-connected or island mode. Integrating intermittent renewable sources and microgrid management require advanced control techniques and networking schemes for seamless operation, especially when the energy storage capacity is low. The diverse requirements introduced by this service category are a combination of traditional uRLLC and mMTC network slices.

Volume and Price Balancing

The introduction of smart grid has pushed the roll-out of demand response programs with flexible management of energy consumption at consumer ends in response to supply conditions regulated by the utility providers [4]. Through extensive information exchange provided by 5G networks, energy consumers can be transformed into prosumers, who interact and collaborate by producing, consuming, storing, and exchanging energy on a peer-to-peer basis. Such decentralized energy optimization strategies, performed locally, allow markets to determine prices accurately, resulting in cost savings. Considering a high number of prosumers and market information exchanges with historical load data, this service category requires a combination of mMTC and eMBB.
networks to tenants, RAN slicing clearly differentiates from other network sharing techniques, offering new roles to energy players.

**Guaranteed SLA:** RAN slicing offers differentiated service provisioning with QoS guarantees based on negotiated SLA. A management and orchestration entity is responsible for mapping the requirements established in SLA into the functional elements of RAN slices. Due to the mission-critical nature of certain smart grid services, SLA monitoring needs to be predictive while ensuring efficient radio resource utilization. In this context, the exploitation of emerging AI techniques holds the promise of conforming to SLA by exploiting slice state information.

**Customization Capabilities:** The implementation of customized functions is a key RAN slicing feature, given the highly diverse service ecosystem in smart grids. By leveraging edge computing, decision-making and intelligence can be shifted closer to the network endpoints, achieving faster response times and targeted operational actions. Agile function placement facilitates the support of new use cases and often results in reduced installation/operational cost for utilities.

**Distributed Architecture:** RAN slicing promotes a decentralized structure of the smart grid against the traditional model, in which non-cooperative systems are deployed and managed independently in a hierarchical manner. On-demand deployment of virtual functions facilitates the seamless integration of DERs and paves the way toward a prosumer-centric vision of future power systems. Smart grid protection services requiring low latency can be performed autonomously rather than being delegated to a central management unit [3].

**Business Potential**

The support of 5G-enabled smart grid services via RAN slicing comes along with a continuously rising number of subscriptions and traffic demand, giving rise to significant business opportunities. The stakeholders, that is, the beneficiaries in the network slicing ecosystem, consist of the network slice subnet instance (NSI) provider, the intermediate-intermediate-network slice instance (NSI) provider, the end-to-end network slice instance (E2E-NSI) provider, the slice tenant, and the end customer. In some cases, multiple network slice providers may coexist to provide an E2E slice.
while in other business scenarios a single mobile network operator (MNO) may undertake the role of E2E slice provider. The service-based business model promoted by RAN slicing, motivates MNOs to move beyond traditional subscription-based schemes with fixed rental fees to more flexible pricing policies and direct value propositions to the smart grid utilities, for example, revenue split schemes and incentive strategies. As a result, the new electricity business models on ownership, operation, maintenance as well as usage, will be defined according to performance-based SLA and relevant key performance indicators of the electrical infrastructure, which could be complemented by the added value on each utility.

From the perspective of power system utilities, service provisioning and cost efficiency empowered by RAN slicing, in conjunction with the deregulation of the energy sector, reinforce new business practices. The opportunities of this evolving market context are expected to alter the way transmission/distribution system operators use connectivity technologies in the grid. Leveraging RAN slicing, novel use cases and diversified requirements can be supported using a unique communication infrastructure with significant cost savings.

A qualitative comparison between RAN slicing and existing radio access technologies (RATs) for the smart grid is illustrated in Fig. 2. It is worth noting that in terms of technology availability, existing RATs have an essential advantage compared with RAN slicing, related to the maturity of communication standards and the already well-established ecosystems adopting such technologies. The same applies when local spectrum licenses are in force. Nonetheless, enhanced security mechanisms, reconfiguration capabilities, overall system cost, control of the critical infrastructure, and incorporation of artificial intelligence are some of the aspects where RAN slicing demonstrates clear superiority.

**The Proposed Framework**

The diverse QoS requirements in the smart grid provide a fertile ground for the application of an agile RAN slicing approach. Our methodology is devised to cope with the rising complexity of supporting 5G-enabled smart grid services, achieving not only more manageable RAN slices...
but also conforming to the business propositions sought by network operators and smart grid utilities. The proposed framework complements the RAN slicing enhancements introduced in [9], by bridging the gap between IEC 61850 services and the 3GPP-standardized radio resource sharing strategies.

**The IEC 61850 Standard**

In terms of power industry communication standards, the IEC 61850 standard is of particular note. Originally defined to cover the stringent requirements for automation within electrical substations, IEC 61850 emerges as a versatile interoperable standard that can be applied beyond the substation boundaries to facilitate intersubstation message exchange, wireless transmission of synchrophasor information and DERS' communication. IEC 61850 promotes abstract and application-specific data models and services that are decoupled from the underlying communication technologies. As the applicability of the standard expands continuously, there is growing interest to integrate IEC 61850 services with wireless protocols and overcome the physical limitations and high installation costs of the default Ethernet technology.

The IEC 61850 standard defines the performance classes and communication requirements for various message types exchanged between power system components. In this context, the IEC 61850 message classification can be intrinsically associated with the RAN slicing concept. In particular, Type-1 and Type-6 messages impose requirements that fall under the uRLLC slice, as they are linked to real-time substation protection actions and time synchronization, respectively. For instance, in line phase comparison for analog protection, Type-1 messages must be delivered with ultra-high reliability levels, that is, a packet loss rate in the order of 10⁻⁵ [10]. Other message types, related to continuous IED data streams (or large file transfers) and sporadic medium-speed event reports, can be mapped to eMBB and mMTC slices, respectively.

**RAN Slicing for IEC 61850 Services**

Our RAN slicing framework aims to accommodate IEC-61850 services over a single shared infrastructure and lays the foundation for a fine-grained service management in the smart grid. As illustrated in Fig. 3, it is primarily composed of a number of interworking functional components with programmable capabilities, aiming at a flexible instantiation of IEC 61850 services. In what follows, we provide a concise description of the building elements defined for RAN slicing.

**RAN Architecture RANA:** The next-generation NodeB (gNodeB) is a key component in the RAN slicing architecture. It provides RAN slice subnets which consist of the centralized unit (CU), multiple distributed units (DUs) and multiple radio units (RUs). Heterogeneous IEC 61850 requirements can be supported by appropriate RAN operating principles that involve different functional roles among the RUs, the DUs and the CU. Such roles are determined based on the RANA index value, offering QoS flexibility to MNOs to select the appropriate deployment option. For certain RANA values, the transmission of IEC 61850 message types follows a centralized (i.e., client/server) architecture to support traffic types with moderate end-to-end latency levels. On the other hand, proper RANA configurations may also enable a (fully) distributed architecture that relies on a disaggregated functional split to DUs and/or RUs. In this case, processing functions are primarily located closer to the DUs and/or RUs, achieving lower latency levels for critical IEC 61850 messages, for example, IEC 61850 traffic types with ≤ 10ms or ≤ 3ms latency budgets [10].

**RAN Isolation Level (RIL):** Considering that isolation represents the state in which the performance degradation of one slice does not impact the performance of other slices [11], the RIL functional element defines the required isolation level among slices, which reflects a trade-off between isolation and system efficiency. In an inter-slice sharing strategy, radio resource management for IEC 61850 messages reduces the associated slice tenant costs. On the other hand, a conservative
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isolation policy employs dedicated radio resource assignments, conforming to stringent security and privacy enforce

**RAN Slicing Function (RSF):** This building element is mainly associated with the functionalities performed in the DUs. To ensure a future-proof element design, a portion of these functionalities is carried out into two well-defined subelements. The RSF1 comprises the already standardized 5G/NR functionalities and involves the scalable 5G/NR numerology on the frame structure [11]. This subelement is associated with fundamental RAN functions, such as tiling, scheduling and puncturing. Tiling refers to the assignment of radio resources into different tiles defined in the time/frequency space, which can be individually configured according to the IEC 61850 service requirements and the respective SLA. Scheduling refers to the allocation of radio resources, while traffic puncturing allows efficient multiplexing of various IEC 61850 services by prioritizing the transmission of time-sensitive message types. On the other hand, the RSF2 subelement consists of customized baseband functionalities to support vendor-specific operations or features not yet specified by standards. It considers beyond-5G technical enhancements, paving the way for next-generation connectivity enablers to be incorporated in the RAN slicing framework.

**RAN Slicing Management (RSM):** This component monitors the necessary capabilities of the aforementioned RANA, RIL and RSF elements. With a supervisory and management role in the RAN domain, the RSM handles RAN slice instantiation and lifecycle management of IEC 61850 services. The RSM interacts with the data traffic awareness module, a specialized function used to process, analyze and evaluate the IEC 61850 data flows. Its intent-driven operation needs to rigorously consider the diversified SLA of IEC 61850 services designated by the core network. The fundamental hallmark of RSM element is therefore to guarantee a harmonic co-existence of multiple RAN slices and their respective SLAs.

**Intelligent RAN Slicing Scheduler (IRSS):** This element adds cognition to the proposed framework. The key operation of IRSS lies in the knowledge extraction from the aggregated IEC 61850 traffic for RAN slice scheduling and radio resource assignment. The exploitation of advanced AI techniques by the IRSS holds the promise of achieving a high degree of automation and operational efficiency for RAN slicing. Radio resource allocation in IRSS needs to ensure an efficient multiplexing of IEC 61850 services by prioritizing the transmission of time-sensitive message types. To ensure such contextual decision-making, the IRSS interacts with all aforementioned elements of the framework for RAN slice awareness, for example, SLA monitoring and resource isolation.

**Performance Assessment**

**Network Scenario**

To evaluate the feasibility of the proposed RAN slicing framework, we consider the smart grid self-healing scenario in [12], where automatic reconfiguration occurs after a short-circuit fault. The IEDs, smart substation controllers (SSCs), and merging units (MUs) are equipped with 5G interfaces to transmit IEC 61850 messages in a multi-cell network topology. As illustrated in Fig. 4, connectivity is provided by gNodeBs deployed to provide coverage in the different segments of the power system denoted as (i)-(vi). The SSCs, IEDs, and MUs are equipped with 5G interfaces, and exchange system-related information by sharing available radio resource blocks.

![FIGURE 4 Smart grid self-healing use case with a cellular network deployment supporting IEC 61850 services. The gNodeBs provide connectivity to different segments of the power system denoted as (i)-(vi). The SSCs, IEDs, and MUs are equipped with 5G interfaces, and exchange system-related information by sharing available radio resource blocks.](image)

**IRSS Implementation**

To address the joint radio resource assignment and power control problem for smart grid devices, the IRSS employs two deep reinforcement learning techniques by the IRSS holds the promise of achieving fundamental hallmark of RSM element is therefore to provide coverage in the different segments of the power system denoted as (i)-(vi). The SSCs, IEDs, and MUs are equipped with 5G interfaces, and exchange system-related information by sharing available radio resource blocks.

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(DRL) algorithms which collaboratively aim to maximize the achieved spectral efficiency of all active IEC 61850 communication links. DRL models sequential decision-making problems with an agent and an environment interacting and exchanging information in the form of states, actions, and rewards [14]. With the aid of deep neural networks for function approximation, smart grid devices successively learn two policies to determine their assigned radio resources and transmit power levels, and maximize the expected sum of rewards. The reward function, common for both algorithms, takes into account the achieved spectral efficiency of each smart grid device, and the interference level caused to other devices. As illustrated in Fig. 5a, IRSS employs the following two learning layers:

- A deep Q-network (DQN) algorithm is considered for resource assignment to the different RAN slices. DQN is a value-based algorithm, applicable to environments with discrete action space. To strike a balance between exploring state-action pairs and exploiting knowledge, we adopt a Boltzmann policy to steer exploration toward more promising actions off the Q-value-maximizing path, instead of selecting all actions with equal probability [14]. During training, experiences gathered by older policies are stored in a replay memory, and are reused to improve sample efficiency.
- An actor-critic algorithm is applied to manage the continuous action space for transmit power allocation. In actor-critic schemes, two components are learned jointly; an actor, which learns a parameterized policy, and a critic which learns a value function to evaluate state-action pairs. The actor first receives as input the

**FIGURE 5.** a) DRL-based IRSS implementation for radio resource assignment and power control of smart grid devices. The DQN layer provides the resource assignment decision to the actor-critic algorithm, which, in turn, determines the transmit power levels; b) RAN slice performance assessment for three IEC 61850 services in terms of latency and SLA violation rate in a smart grid self-healing use case. For slices labeled with symbol +, DRL-based IRSS takes into account the beyond-5G configuration options for RANA, RIL, and RSF elements. Latency requirement for time-sensitive GOOSE and SV services is set to 0.3 ms and 0.5 ms, respectively, whereas a latency budget of 40 ms is specified for MMS services [10].
resource block assignment decision from the DQN layer. Using a learned value function, the critic provides a reinforcing signal to the actor which can be more informative for a policy than the rewards from the environment. In our method, we learn an advantage function as the reinforcing signal, which measures the extent to which an action is better or worse than the policy’s average action in a state. The estimation of advantage function is performed using an exponentially weighted average of a number of advantage estimators with different bias and variance [15].

RESULTS

The top plot in Fig. 5b illustrates the latency performance for GOOSE, SV and MMS slices for two different simulation setups. In particular, the transmission latency for each IEC 61850 communication link is measured as the ratio of the packet size (prescribed in [10]) over the achieved throughput. In the first setup (i.e., slices labeled with symbol +), the DRL-based IRSS element takes into consideration the beyond-5G configuration options for RANA, RIL and RSF elements, as described earlier in this chapter. In this context, the augmented state-action space for each smart grid device opens up the possibility of discovering better states and ways of acting in the quest for the optimal resource and power decisions. In the second setup, the DRL-based IRSS element uses default 5G configurations for resource assignment and power control according to [13]. It can be observed that IRSS achieves superior latency performance in the first setup compared to the second one, while conforming to the SLA requirements for GOOSE, SV and MMS slices as specified by the RSM element. The considered SLA refers to the latency requirements for IEC 61850 services, and an SLA violation occurs when the achieved latency level becomes higher than the threshold value [10]. In addition, IRSS learns to prioritize time-sensitive GOOSE and SV services, resulting in significant latency reduction compared to the default 5G configuration. This, in turn, leads to fewer SLA violations, as illustrated in the bottom plot of Fig. 5b.

We note that the transient latency behavior for all RAN slices identified in the first time slots is attributed to the exploration phase of the DRL-based IRSS, which may result in suboptimal actions by each smart grid device. However, as training progresses, the rate of exploration gradually decays, and smart grid devices learn better policies for their assigned resources and transmit power levels.

CONCLUSION

The smart grid paradigm undoubtedly represents an essential showcase for 5G and beyond systems, mainly because of the heterogeneous connectivity landscape and the wide range of service requirements. In this context, RAN slicing poses elevated merit for a fine-grained smart grid service management with a shared communication infrastructure.

The smart grid paradigm represents a remarkable opportunity for the integration of IEC 61850 services, and their incorporation in our RAN slicing framework. This will facilitate predictive slice provisioning by ensuring traffic-aware admission control policies. The introduced signaling overhead for RAN slicing control will also be quantified.

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