Cellular Communications for Smart Grid Neighborhood Area Networks: A Survey

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***Abstract*—This paper surveys the literature related to the evolution of cellular communications as a key enabling technology for fundamental operations of smart grid Neighborhood Area Networks (NANs). The latest releases of the LTE standard, representing the recent advancements in cellular technology, offer significant benefits to the modernization of the aging power distribution grid compared to other communication technologies. However, since LTE was not originally designed for smart grid applications, important challenges remain unsolved before it can efficiently support advanced NAN functionalities. This survey identifies the limitations of LTE and provides a comprehensive review of the most relevant proposed architectural and protocol enhancements for the communication infrastructure associated with smart grid NANs that can be found in the literature to date. As Device-to-Device (D2D) communications in LTE standards are a promising technology for reducing delay and boost reliability, this paper dwells on the potential gains that can be achieved by enabling direct communication using cellular networks, and also discusses in detail LTE-D2D applicability in representative NAN use cases in the power distribution grid. We conclude by stating open issues and providing research directions for future research in the field. This paper constitutes the first comprehensive survey of proposed LTE-enhancement and D2D solutions for smart grid NANs.**

***Index Terms*—Smart Grid, Distribution Network, Cellular, LTE, Device-to-Device, Microgrid, Substation Automation**

I. INTRODUCTION

THE transformation of the existing power distribution grid into an automated smart grid would significantly benefit from an efficient, flexible and reliable communication technology that can support advanced and autonomous grid functionalities in Neighborhood Area Networks (NANs). NANs constitute the communication infrastructure used to manage and control the distribution (at medium voltage) of the energy from its generation and transmission (at high voltage) to the final user (at low voltage). Communication in the power distribution grid already exists at the local level to support basic small-scale automatic operations. However, large-scale operations that involve deployments spanning long distances, e.g., wide-area monitoring and control systems, still rely on extensive human intervention. This is the case, for example, of Fault Location, Isolation, and Service Restoration (FLISR) where field technicians may need to move on site and perform restoration operations.

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Wireless communication technologies used today cannot meet the demanding communication requirements imposed by the automated and highly dynamic nature of the future smart grid systems. In a nutshell, the smart grid paradigm consists in building a flexible communication architecture where geographically dispersed Intelligent Electronic Devices (IEDs), as well as sensors, smart meters, protective relaying devices, and circuit breakers, exchange their status information and control instructions in an automated and distributed manner to efficiently operate the electrical grid [1]. By enabling direct interactions between consumers and the power Distribution System Operators (DSOs), it would be possible to develop new services and operations capable of efficiently satisfying the instantaneous demand-response. In addition, the increasing penetration of Distributed Energy Resources (DERs), photovoltaic cells, storage batteries, and wind energy generators located in widespread areas, introduces several challenges for achieving seamless and reliable communication within the power grid [2]. Therefore, distributed control and real-time bidirectional communication are necessary to support fundamental grid functions which often involve the transmission of mission-critical protection messages and/or massive amount of metering information [3].

Among many existing alternatives to realize communications in the smart grid, cellular technology relying on LTE-based standards has been identified as a promising technology to meet the strict requirements of various operations in the distribution grid [4]. The evolution of LTE through global standardization via the 3GPP offers a widely-deployed and future-proof technology that is provisioned to act as the catalyst for advanced - currently unrealizable - functionalities in the power distribution networks. The inherent technical characteristics of LTE, namely extensive coverage, low latency, high throughput, and Quality-of-Service (QoS) differentiation, unlock unprecedented use cases and contribute significantly to the actual operation and management of the overall power grid. Leaving technical reasons apart, many DSOs may benefit from the existing public LTE infrastructure without the need to install and maintain a proprietary communication network or have trust in uncontrolled communications for sensitive applications. In addition, the competition between Mobile Network Operators (MNOs), as a result of the increasing LTE adoption, could be leveraged to obtain competitive pricing schemes and significantly relieve DSOs from the investment, deployment, operation, and maintenance costs associated with a private solution.

Unfortunately, LTE was not originally designed for the data traffic characteristics of smart grid applications, but for human-centric broadband services with a moderate number of users per base station. Besides massive traffic volume, smart grid messages are short with sporadic nature while their associated applications are based on duty-cycling schemes for network access with minor mobility concerns. These fundamentally different requirements for Machine-Type Communications (MTC) for the smart grid compared to traditional Human Type Communications (HTC) render indispensable a major mentality shift on the way cellular systems are nowadays designed. For these reasons, the design and configuration of LTE to meet these challenges and enable reliable MTC for the smart grid has become a very intense research area over the last years.

Indeed, the 3GPP is approaching the suitability of future releases of LTE for MTC following three main actions: *i)* inclusion of a User Equipment (UE) category-0 with reduced complexity (LTE-M), *ii)* the design of a new narrow-band radio access technology for cellular Internet of Things (NB-IoT), and *iii)* inclusion of novel communication architectures which can better handle the specific needs of MTC. Among other novel communication architectures that are being proposed nowadays, LTE network-assisted Device-to-Device (D2D) communications[1] emerge as a potential enhancement of LTE technology to satisfy the demanding requirements of advanced smart distribution grids. In this scheme, intelligent grid devices in proximity of each other can exchange information utilizing cellular licensed resources over a direct link, rather than transmitting and receiving signals through a cellular base station [5]. The emerging use of D2D communications can yield a dramatic reduction in the end-to-end latency and energy consumption, boost reliability and scalability [6], and address the current limitations and performance bottlenecks of LTE technology when applied in various distribution grid services. However, the management of the communication is still under the control of a communications MNO, offering a Service Level Agreement (SLA).

This survey provides an in-depth and comprehensive discussion on the applicability of cellular technology for the fundamental NAN operations in the power distribution grid. The current State of the Art related to ongoing research works on LTE for NAN applications is thoroughly presented and discussed. Motivated by the identified architectural and performance limitations of current cellular networks, D2D communications in LTE standards is proposed as a promising network approach to support the demanding requirements imposed by the ongoing modernization of the distribution grid.

Up to our knowledge, there is no other similar work available in the literature. Some important implementation issues related to network topology, gateway deployment, routing algorithms, and security have been already discussed in [7], where the authors present a variety of networking architectures and design requirements for NANs with emphasis only in non-cellular communication solutions. A survey on energy-efficient communication systems and data centers in the smart grid is presented in [8]. The authors in [9] provide a generic overview of the challenges of wireless communication technologies for smart grid applications with no particular emphasis on LTE technology and its feasibility on NAN use cases. A complementary state-of-the-art work is given in [10] along with a comprehensive comparison of the available wireless technologies. The scope of the authors in [10] mainly resides in identifying the suitable technology for each segment of the power grid without focusing on cellular improvements to address the listed challenges. In contrast, this survey discusses and interconnects already proposed key cellular technology enhancements and options for the NAN segment of the power grid. Existing solutions are classified according to their approach to enable LTE-NAN integration. Being D2D a key promising technology to overcome the current cellular limitations and fulfill the smart grid potential, this survey also discusses LTE-D2D applicability in representative NAN scenarios. Design aspects of network assisted D2D communications in cellular spectrum are studied in [5]. An extensive review of available literature on D2D communications in cellular networks was presented in [11]. However, in that work there is no particular focus on their usage for MTC and the smart grid. Both D2D communications and smart grid NANs have been separately examined in previous studies, but no joint survey that falls in the intersection of these two fields exists. This constitutes a key motivation for this paper. The acronyms included in this survey are summarized in Table I.

The remainder of the paper is organized as follows. Section II provides an overview of smart grid NANs and their fundamental grid operations. Section III presents in detail the various communication - both wired and wireless - technologies that have been proposed to support NAN applications, discussing pros and cons of each alternative. The motivation for the preferred use of LTE connectivity for the distribution grid is thoroughly covered in Section IV and the challenges related to the integration of smart grid NAN traffic to shared public LTE networks are presented. In Section V, a comparative overview and classification of existing works in LTE for NAN applications are performed. Section VI proposes D2D-enabled LTE networks as an enhanced scheme of current cellular technology to address the identified performance limitations. Their potential benefits to three representative NAN use cases are discussed in detail. Open lines of research and concluding remarks are presented in Section VII and VIII, respectively.

II. Smart Grid Neighborhood Area Networks (NANs)

Smart grid NANs constitute the communication infrastructure for the distribution of electricity at medium voltage between the power transmission system at high voltage and the final residential/industrial consumers at low voltage. Figure 1 depicts the common hierarchical structure of an electrical grid network. Residing at the heart of the smart grid communication network, NANs incorporate a collection of numerous Home Area Networks (HANs) that are deployed in residential/commercial buildings and industrial

[1]D2D in the context of cellular communications can be classified into two groups depending on the assistance or involvement of the infrastructure in the management and control of communications: *i)* non-assisted D2D, and *ii)* network-assisted D2D.

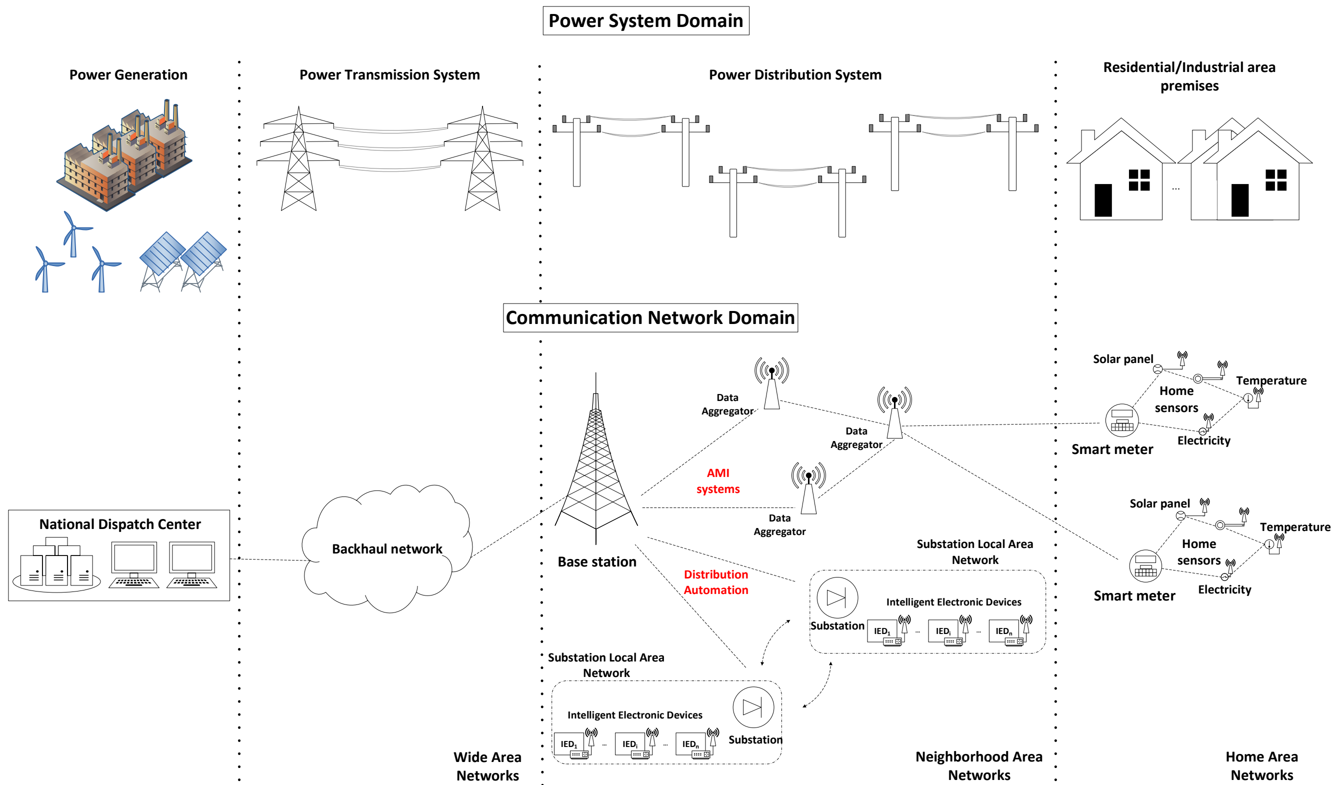

Fig. 1. Hierarchical smart grid architecture. Two parallel interdependent domains, the power system and the communication network, form the infrastructure of the smart grid. The power distribution grid along with the corresponding NAN constitute the heart of the new power system. In the figure, two fundamental grid applications within the NAN, the distribution automation and advanced metering infrastructure (AMI) systems are illustrated. Distribution automation information between substation Local Area Networks and aggregated metering data from spatially dispersed Home Area Networks, need to be transmitted through a reliable communication infrastructure.

facilities. HANs gather sensor information from clusters of smart devices at a *behind-the-meter* level and deliver to them control/management commands from utilities. At a higher hierarchical level, aggregated metering data from multiple NANs is forwarded to data/control centers owned by utility providers via the Wide Area Networks (WANs). WANs typically serve as the communication backbone for the smart grid communication system and provide broadband connection over an extensive geographical area.

As illustrated in Figure 1, NANs involve communication between diverse electric devices, e.g., IEDs, and data aggregation points, which are deployed in large and potentially complex geographical areas. IEDs reside within the substation Local Area Networks (LANs) and can be seen as controllers that get their input from voltage and currrent transformers/sensors and provide their output (commands, status information), e.g., to circuit breakers. Message exchange between substations, responsible for conducting the voltage transformation and control, is also enabled at the distribution level. The distinct communication segments in the smart grid employ different network technologies and protocols to ensure service performance at each level, end-to-end inter-operable management, and deployment/maintenance costs. Today, communication in the transmission and distribution systems typically relies on robust wired broadband links. Communication at the consumer side is typically based on short-range technologies with relaxed QoS requirements.

In the vision of the future smart grid, the distribution domain is expected to be partitioned into smaller, more-manageable, and potentially autonomous operating units that require a flexible and widely adopted communication infrastructure [12]. If a reliable communication network is available, then smart operations such as Distribution Automation (DA) and Advanced Metering Infrastructure (AMI), will be efficiently supported.

DA deals with system automatic functionalities that require communication interactions among IEDs, such as [12], [13]:

1) **Distributed control and protection**, involving the introduction of time-critical communication exchanges between substation LANs and measurement equipment installed along the distribution network, e.g., Phasor Measurement Units (PMUs). A fundamental protection operation is *fault detection and localization*, including the use of IEDs capable of exchanging protection relevant messages and reporting events to control centers for rapid diagnosis of system faults and initiation of control commands.
2) **Wide-area monitoring systems**, involving the use of combined PMU information collected over many substation LANs to perform fast decision-making and switching/isolation actions to avoid the extensive propagation of disturbances to the entire power system. Thus, *self-*

TABLE I
LIST OF ACRONYMS ALONG WITH DEFINITIONS

Acronym	Definition
AMI	Advanced Metering Infrastructure
CIoT	Cellular Internet of Things
D2D	Device-to-Device
DA	Distribution Automation
DER	Distributed Energy Resource
DSO	Distribution System Operator
FDD	Frequency Division Duplexing
FLISR	Fault Location, Isolation and Service Restoration
GOOSE	Generic Object Oriented Substation Event
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
HAN	Home Area Network
HARQ	Hybrid Automatic Repeat reQuest
HTC	Human-Type Communication
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
LAN	Local Area Network
LEO	Low Earth Orbit
LTE	Long Term Evolution
LTE-LAA	LTE-License Assisted Access
LTE-M	LTE for Machine-type communication
LTE-U	LTE-Unlicensed
MAC	Medium Access Control
MMS	Manufacturing Messaging Specification
MNO	Mobile Network Operator
MTC	Machine-Type Communication
NAN	Neighborhood Area Network
NB-IoT	Narrow-Band Internet of Things
OFDM	Orthogonal Frequency Division Multiplexing
PLC	Power Line Communication
PMU	Phasor Measurement Unit
QoS	Quality of Service
RACH	Random Access CHannel
RAN	Radio Access Network
SLA	Service Level Agreement
TDD	Time Division Duplexing
UE	User Equipment
WAN	Wide Area Network

healing and system *reconfiguration* can be achieved.

3) **Monitoring of distribution equipment**, including real-time situational awareness and supervision of capacitor bank controllers, fault detectors, re-closers, switches, and voltage regulators within substations [14].

In addition, the envisioned large-scale integration of DERs within the power grid will result in a two way power flow in contrast to the traditional one way power flow, thus adding more complexity to all aforementioned functionalities [3]. The conventional centralized power delivery logic is shifted to a more distributed one and new challenges are created for the protection, control and monitoring of the distribution grid. DA applications are associated with stringent communication network requirements in terms of network **latency** and **reliability** [15], [16].

TABLE II
SUMMARY OF RECENT SURVEYS/STUDIES FOR SMART GRID NANS

Area of focus	References
Reliability	[18], [19], [20]
Network deployment	[7], [21], [22], [23], [24]
Energy efficiency	[8], [19], [21], [24]
Security	[7], [25], [26]

Regarding metering data delivery, a typical AMI system uses smart meters to communicate information between consumers and power utilities for monitoring, operating, and billing purposes [17]. Hierarchical communication network structures have been proposed [7] to handle the data, where concentrator units aggregate consumer meter information before forwarding them to the meter management systems at the utility end for processing. In this case, latency requirements are more lenient compared to DA functionalities. Typically, AMI systems require infrequent uplink transmissions of small-sized data packets. The bandwidth requirements for an individual user are relatively low; however, the overall requirements in a NAN increase considerably due to the large number of customer premises. In AMI deployments, network **scalability** is of crucial importance. The challenge for the communication network is therefore to allocate its bandwidth resources to many spatially separated nodes efficiently.

As a critical component of the next-generation power grid, smart grid NANs constitute an active research area nowadays. Table II summarizes the most recent surveys/studies each of which focuses on a particular aspect of NANs.

III. COMMUNICATION TECHNOLOGIES OTHER THAN CELLULAR FOR THE SMART GRID NAN

Various communication technologies, both wired and wireless, have been considered to support NAN applications in the distribution domain, e.g., meter reading, monitoring, control and protection of DA equipment. A list of pros and cons of each of the most relevant technologies is included in Table III and further discussion is presented in the next sections.

A. Wired technologies

Copper- and fiber-wired technologies constitute reliable and secure data transfer options. Dedicated cables can be used for communication separately from the electrical power lines, offering increased capacity and low latency. For example, fiber optic cables offer the potential for relatively long-distance communication without the need for intermediate relays or amplification and are inherently immune to electromagnetic interference. Ethernet has been extensively implemented in current power systems for localized protection functions to provide real-time monitoring and control through LANs [27]. However, connecting power devices in large distributed areas requires a flexible and scalable network that is quickly adapted to topology changes [9]. In addition, the cost associated with the wired solutions renders them impractical for deployments spanning long distances, e.g., when connecting DERs in the future power grid, as well as in dense urban areas. Not only

TABLE III
COMMUNICATION TECHNOLOGIES APPLICABLE TO SMART GRID NANS AND THEIR CHARACTERISTICS

<table>
<tr><th>Technology</th><th>Achievable data rate</th><th>Coverage range</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Fiber optics</td><td>155 Mbps - 40 Gbps</td><td>100 km</td><td rowspan="2">• High capacity
• High reliability
• High availability
• Enhanced security
• Low latency
• Noise immunity</td><td rowspan="2">• High cost
• Low scalability
• Deployment limitations
• Regular maintenance</td></tr>
<tr><td>Ethernet</td><td>10 Mbps - 10 Gbps</td><td>100 m</td></tr>
<tr><td>Narrowband PLC</td><td>10 - 500 Kbps</td><td>300 m - 1 km</td><td>• Existing infrastructure
• Cost-effective
• Wide availability</td><td>• Channel noise
• Interference
• Attenuation when signals cross transformers</td></tr>
<tr><td>IEEE 802.15.4</td><td>20 - 250 Kbps</td><td>10 m - 1.6 km</td><td>• Low cost
• Low power consumption
• Mesh connectivity</td><td>• Low data rate
• Short range
• Interference</td></tr>
<tr><td>IEEE 802.11</td><td>2 Mbps - 6.75 Gbps</td><td>20 m - 1 km</td><td>• Low cost
• High data rate
• Wide adoption</td><td>• Short range
• Interference
• Low security</td></tr>
<tr><td>LEO satellite</td><td>2.4 Kbps - 100 Mbps</td><td>3000 - 4500 km</td><td>• Wide-area coverage
• High reliability
• Low latency</td><td>• High cost
• Non-private systems - shared bandwidth
• Signal shadowing</td></tr>
<tr><td>WiMAX</td><td>63 Mbps DL
28 Mbps UL</td><td>48 km</td><td>• High data rate
• QoS provisioning
• Scalability
• Low latency</td><td>• Not widespread use
• Dedicated infrastructure
• Limited access to licensed spectrum</td></tr>
<tr><td>Cellular</td><td>300 Mbps DL
75 Mbps UL</td><td>100 km</td><td>• Existing infrastructure and service models
• Ubiquitous coverage
• Low latency
• High data rate
• QoS provisioning</td><td>• Oriented for human broadband applications
• Coexistence with HTC
• Monthly recurring charges
• No current support for mission-critical applications</td></tr>
</table>

a significant investment on the cable deployment is required, but also the regular maintenance costs make these approaches more suitable for other smart grid domains. In particular, fiber optics seem appropriate for supporting high-speed backhaul links, e.g., in WANs, while digital subscriber line and Ethernet are widely used for small-scale deployments, e.g., in HANs and DA use cases for intra-substation communication respectively.

In its turn, Power Line Communication (PLC) offers a cost-effective option for NAN applications, e.g., electricity usage delivery, since it enables data transmission through the existing electrical power lines. The use of a single medium for simultaneous data and electric power transmission along with the wide availability of PLC networks render them as an attractive solution for several power applications in customer premises, e.g., load control, demand-response. Traditionally, electrical wires have been only intended to deliver electricity; therefore, the nature of the power line transmission medium adversely affects the signal quality (noise/interference, attenuation). Adequate channel models for PLC have not yet been standardized, and there is no widely accepted channel model similar to those derived for radio communications. Furthermore, in use cases where data signals need to cross distribution transformers, the signal attenuation and distortion caused by the transformers, limits the suitability and widespread use of PLC solution in NANs. To overcome this, hybrid network solutions have been proposed where smart meters are connected to a data concentrator through power lines and then, in a second stage, wireless technology, e.g., cellular, is used to transfer the aggregated data to the utility's data center. In PLC technology, the achieved data rate is inversely proportional to the wiring distance between the grid entities, varying from a few hundred of bits per second to millions of bits per second [17]. Therefore, PLC is mainly used for metering applications in indoor HANs [28] to provide an alternative broadband networking infrastructure without installing dedicated network wires. While applied in old power grid installations for DA purposes, PLC technology is not so common in modern substations.

B. *Wireless technologies*

In most of the smart grid NAN applications, the use of copper- and fiber-wired communication solutions can be economically and/or physically prohibitive. In addition, although PLC systems present considerable advantages, the asynchronous/periodic impulsive noise may limit their suitability in advanced distribution grid operations with increased reliability requirements. Therefore, wireless technologies are considered a promising alternative to support demanding smart grid functions within the power distribution grid, enabling seamless communication almost anywhere at relatively low cost. The advantages of lower installation cost, scalable and dynamic nature, and ease of deployment are expected to offer enhanced grid functionalities. In the next subsections, key relevant wireless communication technologies available to support NAN applications are presented and discussed.

1) IEEE 802.15.4: The IEEE 802.15.4 Standard specifies the physical layer and Medium Access Control (MAC) layer for low-rate wireless personal area networks (LR-WPAN). This standard is the foundation of the ZigBee Alliance, which is considered a possible alternative for low-cost and small-scale smart grid applications [29]. In particular, the IEEE 802.15.4g amendment has been defined to cover longer range AMI applications in NAN. It defines a network topology where a large set of smart devices in remote locations communicate with a data aggregator via peer-to-peer multi-hop techniques [7]. The standard thus facilitates large-scale grid applications capable of supporting geographically challenging deployments with minimal infrastructure requirements. However, it has some key limitations that compromise its possible use for reliable smart grid operations:

1) **Operation in license-free bands**: The use of Industrial, Scientific and Medical (ISM) bands where other technologies also operate leads to interference from other systems, e.g., WiFi networks, thus compromising the reliability of transmissions. In the particular case of the IEEE 802.15.4, the use of a very low transmission power turns it into a very vulnerable technology in ISM bands.
2) **Fairly low data rates**: The large number of supported devices as well as the low power consumption come at the expense of relatively low data rates [30]. The achieved data rates reach up to 250Kbps which might be insufficient for demanding wide-area monitoring and control NAN applications, e.g., burst data transmission related to grid protection operations.
3) **Security**: Privacy and security weaknesses become important when private and confidential metering data is exchanged. The IEEE 802.15.4 does not include inherent security mechanisms.
4) **Complexity**: Multi-hop networks have shown to be complex to manage and provide lower scalability and robustness to failures than communication networks based on single-hop transmissions.

Therefore, the applicability of IEEE 802.15.4g is limited to support connectivity only between the customer premises and the data aggregators, with a longer-range communication network providing full connectivity to utilities centers. The reliability issues restrict its use only to smart metering use cases and not for DA applications.

2) IEEE 802.11: The IEEE 802.11 Standard and associated amendments, used by the WiFi Alliance, constitute a mature and widely adopted wireless technology that is suitable for home applications in the smart grid with data rates reaching the Gbps. However, main limitations for its use in power systems refer to the relatively short coverage range and the use of unlicensed frequency bands. Its transmission range is limited to roughly 70 meters indoors and 250 meters outdoors for the IEEE 802.11n, as an example. Thus, it becomes suitable only for local interconnectivity functionalities within the power grid, such as connecting meters to a longer range network, interconnecting devices within a small area [31], or enabling intra-substation communication [32]. Unfortunately, its relatively short range hinders the support of inter-substation communications between IEDs located in remote geographical areas.

Recent efforts have been conducted to extend IEEE 802.11 over a longer range, making it feasible for use in NAN applications. Adopting the principles of a wireless mesh network architecture, IEEE 802.11s extends the IEEE 802.11 MAC layer and addresses the coverage range issue through the establishment of a self-configuring multi-hop wireless network [33], [34]. By allowing data to hop from LAN to LAN over longer distances, the IEEE 802.11s constitutes a new potential candidate for reliable and high-speed NAN applications [7]. Several data reporting strategies for IEEE 802.11s-based AMI networks have been proposed in [35].

IEEE 802.11ah constitutes another amendment, in the context of IEEE 802.11 standardization activities, aiming at the support of use cases in large-scale wireless networks, such as smart metering applications [36]. Its operation in the less congested sub-GHz band allows for better propagation characteristics and extended coverage properties (up to 1 km) while its MAC layer design achieves lower energy consumption and support of large number of devices based on a hierarchical node structure [37]. However, no QoS differentiation mechanisms are supported and there are still open technical challenges - mainly related to interference management and security -before its applicability in NAN use cases where high reliability is required. The IEEE 802.11 is today mainly used for smart metering use cases and not for DA purposes.

3) IEEE 802.16: IEEE 802.16 WiMAX technology [38] has been also proposed to support communication among utilities and a large number of power consumers in AMI systems. Unlike the IEEE 802.11 Standard, which covers ranges of hundreds of meters, IEEE 802.16 networks are designed to provide larger and sufficient coverage for the smart grid distribution system [39]. WiMAX is characterized by low latency (less than 100ms for round trip time), high data rates (up to tens of Mbps), coverage range in the order of tens of kilometers, and advanced security protocols [40]. In addition, the standard provides traffic management tools, such as traffic prioritization, and QoS support with four different classes, an important feature for smart grid traffic differentiation.

However, WiMAX-based architecture requires investments for the development of a utility-owned dedicated network; thus, the occurring installation and maintenance cost associated with WiMAX infrastructure might be prohibitive for utilities. When it comes to delivering smart grid communication solutions, the competition of WiMAX in the marketplace against the widely deployed and quickly-evolved cellular solutions, results in a limited adoption of this particular technology.

4) Satellite: Satellite communication could also constitute an alternative solution for NAN communications [41], [42]. Satellite systems offer significant broadband capabilities and tend to be both reliable and ideal for long-range backhaul applications. For example, in [43], autonomous photovoltaic systems are monitored through satellite communication links. Despite the need for installing large antennas and possible geomagnetic storm effects that may deteriorate the channel quality, satellite communication can efficiently span the wide areas that the power distribution grid typically covers.

However, in order to achieve high scalability in wide-area AMI deployments supported by satellite links, a coordinated deployment of multiple satellites (constellations) needs to be ensured. In addition, the increased energy consumption associated to the large communication distance could be a limitation for autonomously operating smart devices.

In the case of time-critical applications, the use of Low Earth Orbit (LEO) satellites [44], typically located at $500-1500$km above the Earth, is preferred compared to higher orbit satellites (e.g., geostationary) which perform large communication latencies around 300ms. LEO satellites have been used to improve stability within the power grid offering increased security and reliability of the entire power and communication infrastructure. However, there is currently a few number of public satellite network providers and the wide adoption of this technology requires international coordination and conformity with national regulations. Moreover, the installation and maintenance costs are relatively larger compared with other wireless technologies. The privatization of the space industry would therefore boost the applicability of satellite communications for power grid connectivity in rural areas with no terrestrial infrastructure.

IV. Cellular Technology for the Smart Grid NAN

A. Why Cellular?

Standardized cellular networks operating in licensed bands constitute a promising technology to address all the performance limitations of other wireless technologies for both metering and DA applications, as discussed in the previous section. Even though the functionality and capabilities of cellular technology will continue to evolve, the technology platform is mature and stable enough to be considered as the key enabler of the smart distribution grid for the years to come. Cellular networks can enable wide-area communications for applications within the distribution grid because of the following key reasons:

1) **Use of licensed bands**: Cellular networks can better control the interference than those operating in license-free bands and are more robust against security threats which may compromise the security and privacy of confidential energy data.
2) **Mature and ubiquitous coverage**: Communications rely on a mature and widely adopted communication infrastructure, thus allowing smart metering deployments to span over vast areas and remote endpoints to be connected into the same management network [10]. Thus, message exchange among grid entities that reside in complex geographical regions, e.g., the case of integrating remote DERs to the main power grid, can be efficiently supported.
3) **High performance**: Cellular networks provide *high data rate*, *low latency*, and *high system reliability*, thus enabling critical automation tasks within the distribution grid that are often associated with demanding QoS requirements, e.g., stringent transfer time bounds. Advanced grid applications, such as inter-substation communications, outage management, and FLISR can be realized through real-time monitoring and control. Cellular networks are designed with *high availability* as a basic requirement. Redundancy features, e.g., multiple data paths, fast re-routing mechanisms, overlapped cell coverage, ensure seamless operation in case a power fault occurs.
4) **Third-party operation**: MNOs offer enhanced *business models* and SLAs adapted to energy utilities to promote cellular communication solution within the smart grid; thus, they relieve DSOs from having to run and maintain a dedicated communication infrastructure. In addition, a substantial business opportunity is generated due to the large number of devices.

Therefore, cellular technology can facilitate the transformation of the existing aging distribution grid into a modernized and fully automated power distribution system [13].

B. Why LTE-based Standards?

The use of General Packet Radio Service (GPRS) technology for monitoring the operational status of remote substations has been presented in [45] and [46]. In [47], the authors propose novel access mechanisms for the Global System for Mobile communications (GSM) technology in order to handle massive number of smart metering devices in GSM networks. The pilot deployment of a virtual power plant was presented in [48], where medium-voltage remote applications were implemented over 2G or 3G mobile radio networks. It is clear from previous research works that, technically speaking, 2G and 3G could be used to facilitate communications in NAN metering and control applications. However, it is hardly likely that network operators will aim at maintaining the operation of various radio networks simultaneously in the long term. In addition, the potential and higher flexibility of newer standards, point at a future where probably available cellular networks will be preferably based on LTE standards.

Indeed, LTE constitutes a promising candidate technology for satisfying the requirements of advanced smart grid applications, including distribution automation and its demand-response management, fault detection and restoration applications. LTE offers energy utilities the advantages of low end-to-end latency in the order of milliseconds, high throughput, and peak data rates along with QoS differentiation in a single radio access technology, leveraging the existing cellular infrastructure investments [49]. Moreover, the already market-proven LTE solutions allow the extension of its applicability to other domains and energy utilities tend to adopt LTE connectivity for satisfying their communication needs in smart grids. LTE could potentially support remote control applications in the distribution domain given that grid deployments are spread over a wide geographical region. Smart grid NAN communication can take advantage of the authentication and encryption mechanisms already available in LTE to achieve high levels of security and ensure the secure transmission of sensitive energy data. Therefore, emerging applications within NANs can be realizable by exploiting the technical advantages of LTE [50]. The use of LTE was proposed in [51] for smart metering and remote control applications.

Ongoing standardization efforts aim at making LTE the dominant connectivity technology for the Internet of Things (IoT) paradigm in the mid-term future. Recent research activities focus on the evolution of LTE across 3GPP releases to support novel use cases by extending its system capabilities in the radio access interface with additional MTC enhancements and support for direct D2D communication. LTE-M, also referred to as LTE for MTC, constitutes a standard evolution enabling the IoT by reducing the complexity, cost and power requirements of the end devices. To this end, 3GPP has recently introduced an additional User Equipment (UE) category[2], referred to as category-0, that is associated with physical-layer capabilities specifically intended for MTC support. Besides UE category-1, which is already part of early 3GPP LTE releases and can be also potentially used for MTC, the upcoming UE category-0 optimized specifications will transform LTE into a viable option for MTC and numerous IoT applications, and allows for an even less complex and cheaper modem design. In addition, a brand new narrow-band radio access technology is being promoted within 3GPP, coined Narrow-Band IoT (NB-IoT)[3], which promises to reach those vertical market applications where LTE-M cannot reach [52]. As standardization work is underway, LTE is anticipated to further evolve its technical characteristics in the short term.

C. Challenges for LTE

Despite the potential suitability of LTE for its use in the smart grid domain, it was not initially intended for smart grid applications [53]. In order to efficiently support smart grid communications within the distribution grid, LTE needs to be enhanced and extended to cope with some of the stringent requirements of smart grid NAN functionalities which cannot easily be fulfilled with today's cellular technologies [3], [15]. Some of the key design requirements for LTE technology to support the applications in the distribution domain of smart grids are summarized as follows:

- **Data traffic characteristics**. Smart grid data characteristics are not the same as those generated by broadband services originally thought for LTE [54]. The messages exchanged can be event-driven (e.g., protection and control related) or follow a periodic traffic pattern (e.g., monitoring related, measurement reports). The traffic requirements for communication within a smart grid are introduced in related literature. In [10] and [55], the major types of traffic that a smart grid communication network is anticipated to carry are studied along with their QoS requirements. The communication requirements for substation automation systems are defined in the IEC 61850-5 Standard [15], [16]. In particular, this standard describes the performance classes and transfer time upper bounds for different message types. Most control applications in the smart grid require sporadic and short but time-critical data exchange. Traditionally, cellular networks have been designed to deal with asymmetric nature of the traffic, which requires higher throughput in the downlink than in the uplink. However, in the case of metering and monitoring NAN applications, traffic is mainly uplink [50].
- **QoS differentiation for real-time and non-real-time transmissions**. Enhancing LTE with fine-grained resource allocation and traffic prioritization mechanisms would enable MNOs to provide differentiated services to end users over the existing infrastructure. Motivated by the strict performance requirements of smart grid automation services, novel LTE resource management mechanisms need to be designed to differentiate between real-time and non-real-time smart grid transmissions and ensure QoS guarantees over the shared public infrastructure. Message prioritization and resource reservation mechanisms may help mitigate network congestion and allow the most important messages to be delivered on time. Towards this end, it is necessary to support different levels of data delivery criticality depending on the application [15], while not jeopardizing HTC data traffic beyond their acceptable QoS levels.
- **Network access for a massive number of devices**. How to configure the system parameters for optimal functionality and how to dimension the network are among the most important concerns to be addressed when designing and deploying a large-scale smart grid communication network. Network connectivity for a sheer scale of grid entities is then needed. LTE radio access must support massive network deployments with high density of users/devices per connection point, i.e., per eNodeB. Efficient dynamic congestion- and overload-control mechanisms and/or techniques involving minimal exchange of signaling messages are thus required. A survey of alternative solutions for the Random Access Channel (RACH) was provided in [56]. Furthermore, the future distribution grid will be a flexible and fully dynamic environment where the number of metering devices joining the communication network will rapidly evolve, i.e., frequent entry/re-entry [13]. Therefore, network scalability should be provided to accommodate and handle the new devices and facilitate the grid operation [57].
- **Congestion control**. The integration of smart grid traffic within LTE network introduces a large data volume due to the fact that a very large number of devices will be connected to the network. LTE networks need to support and handle properly the aggregated smart grid data in order to avoid network congestion and capacity overload [7]. While meter reading requires only modest throughput per connection link, there are other use cases, such as

[2] In principle, LTE releases define various device-capability classes. UEs are categorized into categories to classify their capabilities in terms of peak rate, duplex transmission, spatial multiplexing, modulation, etc. This enables base stations to communicate effectively with them knowing their performance specifications.

[3] NB-IoT was formerly referred to as Cellular IoT (CIoT).

alarm and protection functions for substations that require considerable throughput (in the order of several megabits per second). This is the case of a power fault that affects various segments in the grid where notification alarm messages are sent simultaneously by several devices in a cascaded and redundant manner. Congestion avoidance techniques based on fusion approaches or core network virtualization are therefore required to ensure network stability and reduce the overall traffic volume. Moreover, the cloud-RAN concept is worth pointing out, where only basic communication functionalities are left to base stations and coordination of radio resources across distributed access nodes is performed in a centralized (cloud) way.

- **Latency**. The currently achievable end-to-end latency in LTE (close to 100ms, according to [58]) is not sufficient to enable delay-critical applications (e.g., control or protection related) in the distribution grid according to the IEC 61850 Standard [15], [16]. While LTE can meet the latency requirements for slow automatic interactions, fast automatic grid operations require end-to-end message delivery in the order of tens of milliseconds or, as stated in the vision of 5G, even below 5ms. Therefore, LTE needs to be optimized to meet these stringent constraints. Latency over the radio link can be lowered by reducing transmission-time intervals and spreading data over frequency rather than time. In addition, to avoid a scheduling request-grant phase prior to data transmission, which introduces an additional delay related to connection establishment handshake, the medium-access control should allow for immediate access by providing instant-access resource allocations [59]. The involvement of the LTE core network in the data transmission also affects the experienced end-to-end latency, since based on the typical network architecture, traffic is concentrated to only a few core sites from extensive geographical areas [60]. Thus, enhancing LTE with direct D2D communications among smart grid entities in close proximity with each other without routing through the core network could provide low latency figures and facilitate delay-critical grid applications where real-time transmissions are required.
- **Reliability**. Full support for critical automatic smart grid operations requires an ultra-reliable connectivity with a guaranteed availability and reliability of service. Some protection-related functionalities in the distribution grid are associated with reliability levels of at least 99.99%, which is translated into a probability that a packet is not delivered within the specified deadline below 10^{-4}. Unreliability issues in the power grid would result in more frequent power outages, voltage fluctuations and harmonic distortion. LTE needs to ensure grid reliability without adversely affecting the performance of conventional cellular users. A combination of both D2D and infrastructure-based communications can lead to increased reliability by means of multi-path diversity.
- **Energy efficiency at the device side**. As networks become denser with the introduction of smart grid entities, transmission of communication-related control signals (e.g., for medium access, synchronization) should be kept to the minimum. Communication needs to be performed only when there is data to deliver; thus, interference levels are also reduced. Allowing smart devices to sleep at every opportunity minimizes energy consumption and leads to longer lifetime [61]. LTE discontinuous reception is a key mechanism in reducing the device energy consumption and several approaches have been proposed in the literature to optimize its performance [62]. The target is to reduce the power consumption by at least a factor 10 by the year 2020.
- **Spectrum flexibility**. Traditionally, public cellular systems have been exclusively deployed in licensed spectrum. However, future cellular systems should support a higher degree of spectrum flexibility. Cognitive radio technology enables dynamic spectrum access in both licensed and unlicensed bands for NANs [63]. In addition, the 3GPP is working towards the definition of a new radio interface, coined NB-IoT, which exploits guard bands for dedicated ultra-narrow-band transmission of MTC. The use of unlicensed spectrum is also gaining momentum and ISM bands can be used to boost cellular capacity in combination with licensed spectrum dedicated for critical NAN control data. LTE-Unlicensed (LTE-U) and LTE-License Assisted Access (LTE-LAA) have been recently proposed for Release 13 of 3GPP Standards, making use of the 5 GHz unlicensed band to provide additional spectrum [64]. Several challenges therefore occur in terms of interference control within a heterogeneous communication environment while efficient and seamless usage of radio resources should be guaranteed. Thus, novel radio design approaches are required where network access often shifts from the typical cellular access to hybrid schemes that emphasize on short-range deployments [65].
- **Security**. In power systems, cyber security is of utmost importance. Message authentication is critical to ensure that the received data used in any decision-making system operation originates from the correct source. Advanced LTE mechanisms, already applied for cellular HTC, must be enhanced to prevent cyber security attacks in the smart grid, a major concern for utilities nowadays. Appropriate security solutions for each use case are required, e.g., authorized access to the real time data and control functions, as well as use of encryption algorithms for wide area communications to prevent spoofing of sensitive and private data.

The above mentioned LTE design challenges have given rise to several research initiatives over the last years for addressing the problem of integration of smart grid NAN communication traffic in cellular deployments. In the following section, a comprehensive discussion on the different alternatives is carried out, identifying strengths and weaknesses of each one of them.

V. LTE for NAN applications: Related Work

The foreseen potential of supporting NAN applications with LTE technology constitutes the main motivation behind the active research efforts currently ongoing on this topic. Technical feasibility studies have been conducted to determine the suitability of LTE technology and gain an understanding of its current limitations through performance evaluation that may involve even field measurement tests. On top of these assessments, architectural and protocol enhancements have been also proposed for evolving the functionality and capabilities of LTE standard to successfully support NAN use cases. This section constitutes one of the key contributions of this paper, by providing a classification of the existing works according to their specific approach. Their scope and limitations are thoroughly compared in Table IV.

A. *Feasibility studies*

Existing feasibility studies can be classified into two main groups; those based on studying latency[4] and those based on evaluating capacity and scalability of LTE for various smart grid NAN applications.

The stringent latency requirements of delay-critical operations in the power distribution network is the focus in [66] and [67]. Based on conducted field trials, the authors perform a latency and reliability assessment for LTE technology when used for communication among medium-voltage grid entities under various load conditions. Using the IEC 61850 standard as a guideline, the authors argue that LTE can support automatic interactions with a delay budget of 100ms, achieving small latency deviations compared with other cellular technologies. Reliability levels are high given that the coverage is adequate; however, ultra-reliable support of protection messages with virtually-zero latency lies in the future LTE developments.

Motivated by the uplink-dominant nature of metering and monitoring traffic, LTE frequency- and time-division duplexing (FDD, TDD) modes are evaluated in [68] and [69] for delay-sensitive NAN applications. Through system-level simulations, [68] describes the superiority of FDD over TDD in terms of uplink delay, while TDD achieves a better channel utilization in case of uplink data bursts, due to its flexible channel allocation configuration. In the case of LTE-TDD scheme, the possible uplink/downlink configurations are assessed from latency perspective in [69]. LTE-TDD is also considered in [50] for DA applications with 100ms and 10^{-3} latency and reliability requirements. However, the authors assume that the random access procedure has already been established; thus, no additional delay for connection setup is considered. The proposed bandwidth reservation method might also be insufficient in case of intense traffic load conditions.

While the previous works did not quantify the performance degradation of human-type traffic in shared LTE networks, the works in [70] and [71] study the impact of smart grid integration for several NAN application scenarios. The authors argue that, by applying proper LTE-QoS configuration for smart grid traffic, low network latencies and high packet delivery rates can be achieved, while the deterioration of conventional LTE services is not proved significant. However, the smart grid traffic characteristics considered in the simulation setup are associated with large packet interarrival times and modest data rates. These are opposed to the burst traffic patterns of protection-related messages and the increased aggregated data rates in large consumer conglomerations where a massive number of grid entities is considered.

In an effort to accurately characterize the impact of smart grid communication traffic, the authors in [72] develop analytical (periodic and event-based) traffic models based on a queuing system analysis. The average buffer length and queuing delay expressions are analytically derived and the accuracy of the models is validated by considering an LTE simulation scenario. A similar analytical approach for smart grid traffic characterization is proposed in [76]. After validating the derived models, the authors investigate the maximum number of smart grid entities that can be simultaneously supported in a single LTE cell. The impact on conventional LTE voice and data services is also quantified in terms of blocking service probability.

In [73], the overloaded RACH performance for LTE is studied considering a surge in initial network entries by a large number of smart meters. In particular, an analytical Markov chain model is proposed for the evaluation of network access and energy consumption, while the feasibility of overload-control mechanisms proposed in the literature is assessed through protocol-level simulations.

Capacity analyses for LTE network dimensioning in the distribution grid are given in [74] and [75]. Focusing on smart metering use cases, the number of supported devices with ensured QoS is determined through simulations. In both studies, a dedicated LTE network is considered; thus, the effect on human-type traffic is not analyzed. The congestion issue when a massive number of smart metering devices initiates network access using the random access procedure is studied in [78]. In particular, the authors discuss the preamble[5] collision problem that occurs due to the limited number of available preambles with respect to the increased access demand. In case the number of preambles available for metering data transmission increases, the impact on conventional LTE traffic is quantified in terms of latency and throughput.

A random access load analysis is performed in [77] where a smart metering scenario is considered. To overcome network congestion in radio access, an overview of enhanced random access mechanisms are proposed, e.g., access class barring schemes, separation/dynamic allocation of random access resources.

B. *LTE enhancements for NAN applications*

As it was introduced in Table IV, LTE enhancements can be categorized into three main groups:

- Radio access improvements,
- Enhancements in scheduling and resource allocation procedures,
- Other solutions.

[4]Latency in HTC often refers to the ”best” or ”average” case, whereas for power grid it is mostly about the ”worst” case.

[5]According to LTE terminology, a preamble constitutes a digital signature that a device transmits in a random access slot. 3GPP specifies in total 64 orthogonal pseudo-random preamble sequences available for random access.

TABLE IV

INTEGRATION OF NAN APPLICATIONS IN LTE NETWORKS: STATE-OF-THE-ART AND CLASSIFICATION OF EXISTING WORKS

Study/Proposal				**NAN Application**				**Performance Metrics**												**Validation**			**Traffic Flow**	
Type	Subtype	Focus/Approach	Reference	Smart metering	Distribution automation	Demand-response	Microgrid	Throughput	Latency	Channel utilization	Coverage	Capacity	Blocking probability	Access probability	Collision probability	Packet success/loss rate	Fairness	Energy consumption	Impact on HTC	Field measurements	Simulation	Theory	Uplink	Downlink
Feasibility study	Latency-based	Reliability analysis for remote control operations	[66]		✓				✓							✓				✓			✓	✓
			[67]		✓				✓		✓					✓				✓			✓	✓
		Evaluation of LTE duplexing modes in delay-sensitive operations	[68]	✓	✓				✓	✓											✓		✓	
			[69]	✓	✓				✓	✓											✓	✓	✓	
			[50]		✓				✓		✓					✓					✓		✓	✓
		Impact on HTC when supporting NAN use cases	[70]	✓	✓			✓	✓										✓		✓		✓	✓
			[71]			✓		✓	✓							✓			✓		✓		✓	✓
		Analytical traffic modeling for data volume management	[72]	✓		✓			✓			✓							✓		✓	✓	✓	
		Near-simultaneous network entry attempts	[73]	✓					✓					✓	✓			✓			✓	✓	✓	
	Capacity-based	Supported devices for network planning	[74]	✓							✓	✓								✓	✓		Not specified	
			[75]	✓				✓		✓		✓									✓		✓	✓
		Analytical traffic modeling for data volume management	[76]	✓		✓	✓	✓		✓			✓						✓		✓	✓	Not specified	
			[72]	✓		✓			✓			✓							✓		✓	✓	✓	
		Random access channel load analysis	[77]	✓	✓				✓			✓		✓	✓				✓	✓	✓		✓	
			[78]	✓				✓	✓							✓			✓		✓		✓	
LTE enhancements	Radio access improvements	Dynamic group paging	[79]	✓						✓				✓	✓						✓		✓	
		Contention-based mechanisms	[80]	✓				✓	✓	✓						✓			✓		✓		✓	
			[81]	✓	✓				✓			✓						✓	✓		✓	✓	✓	
		Access load estimation	[82]	✓	✓				✓					✓							✓	✓	✓	
			[83]	✓					✓							✓					✓	✓	✓	
		Base station assisted cascading-fault detection	[84]		✓				✓												✓		✓	
	Scheduler design & Resource allocation	Weighted round-robin algorithm	[85]	✓	✓		✓		✓											✓	✓		✓	✓
			[51]	✓			✓	✓	✓							✓			✓		✓			✓
		Proportional-fair and round-robin improvements	[86]	✓								✓	✓								✓		✓	
		Static allocation schemes	[87]	✓				✓	✓										✓		✓		✓	
			[88]	✓					✓												✓	✓	✓	
		Adaptive allocation schemes based on queuing modeling	[89]	✓	✓			✓	✓							✓	✓		✓		✓		✓	
			[90]	✓	✓			✓	✓			✓							✓		✓		✓	✓
		Game theory for bandwidth sharing	[91]	✓				✓	✓								✓				✓		Not specified	
		Relay-assisted scheduling	[92]	✓					✓										✓		✓		✓	
		Latency distribution	[93]	✓	✓				✓											✓	✓	✓	✓	
	Other	Subframe configuration	[94]	✓				✓	✓												✓		✓	
		Cell coverage planning	[95]	✓					✓		✓					✓				✓	✓		✓	
		Core network provisioning	[96]		✓				✓							✓			✓		✓		✓	
		Multicast technology	[97]			✓		✓	✓							✓		✓			✓			✓

1) Radio access techniques: A dynamic algorithm for efficient resource utilization with QoS guarantees in the group-paging[6] mechanism is proposed in [79]. The performance evaluation illustrates significant resource efficiency gains with respect to the static allocation of random access opportunities. However, this work considers a relatively small number of devices with respect to 3GPP specifications [77].

A novel contention-based access scheme based on reduced signaling message exchange is proposed in [81]. Motivated by the characteristics of smart metering traffic, the authors consider a data access scheme utilizing only the shared uplink resources in contrast with the conventional LTE access schemes that utilize the uplink control and the random access channel. Their analytical and simulation results demonstrate the improved performance in terms of latency and power consumption even for a large population of attempting devices. A similar approach where the random access procedure is replaced by direct data transmission through the control channel is described in [80]. Despite the improvements in terms of smart meter throughput/latency and the minimal effect on human users, the high packet collision problem remains unsolved.

In an effort to proactively estimate the anticipated network load (alarm reports, periodic measurements), the authors in [82] develop a reliable mechanism that can be easily incorporated in the standard LTE access mechanism. Based on the estimate, the access opportunities for granting access are determined in a network with dedicated resources for smart grid entities. In [83], a packet aggregation method that mitigates the increased packet collisions in massive smart metering deployments is introduced. However, the reduced packet losses come at the expense of increased access latency, rendering the method insufficient for delay-intolerant services. A mechanism involving cooperative communication with notification messages among peer nodes is developed for a cascading alarm scenario in [84]. The authors propose protocol enhancements in the LTE radio resource layer for rapid fault detection and isolation, to significantly mitigate the

[6]Group paging is proposed to alleviate the random access collision issue. Upon receiving a group paging message from the base station, all devices belonging to the paging group should immediately initiate the random access procedure during a specified time interval.

access latency with respect to the standard procedure.

2) Scheduling and resource allocation: The scheduler design for efficient radio resource management constitutes one of the most representative areas of research related to the integration of NAN use cases in LTE networks. In the literature, several spectrum sharing strategies between smart grid and human-type flows have been proposed. A common approach identified in most works is the traffic prioritization of smart grid operations over human-type LTE services.

A priority-weighted round-robin algorithm is discussed in [85]. Based on the consideration of a queuing model with a non-preemptive discipline, the delay gain is quantified for various types of smart grid traffic in a dedicated LTE network. A similar technique is used in [51], where the authors examine the integration of IEC 61850 Manufacturing Messaging Specification (MMS) services, such as smart metering and remote control applications, in shared LTE networks. The downlink performance in network underload conditions is investigated, while the instantaneous communication channel conditions are not taken into account in the scheduling decisions. Enhancements on default round-robin and proportional-fair scheduling algorithms for smart metering use cases are proposed in [86]. In particular, the authors argue that the accommodation of high node densities in a limited coverage area comes at the expense of increased signaling exchange. Therefore, in order to reduce the extensive signaling load, their proposed algorithms exploit the cumulative metering traffic characteristics to adjust the default scheduling granularity.

The previous approaches are based on simple modifications of existing scheduling policies and do not consider the stringent requirements imposed by distribution automation services. Novel resource management strategies based on static allocation schemes are discussed in [87] and [88]. In particular, the authors in [87] propose spectrum reservation (two consecutive resource blocks) for guaranteeing smart meter connection while in [88], a queue-aware mechanism allocates fixed access grants to devices over periodic time-intervals. Both works aim at the minimization of the required signaling load due to excessive number of devices while guaranteeing QoS for smart metering services.

An adaptive LTE resource allocation scheme for the integration of IEC 61850 MMS and Generic Object Oriented Substation Event (GOOSE) services related with wide-area substation automation tasks is covered in [90]. Based on an analytical characterization of the performance constraints that energy automation tasks introduce in the LTE scheduling process, a novel scheduling discipline is designed. The simulation results illustrate that demanding automation services with a 60ms delay budget, packet loss rate requirement 10^{-6} and data rates in the order of tens of Kbps can be successfully supported with minimum impact on background real-time LTE traffic. The maximum delay tolerance of smart grid messages constitutes the main criterion of the adaptive allocation scheme proposed in [89]. A queuing model is developed for the analysis and the authors illustrate through simulations the superiority of the proposed scheme with respect to the legacy proportional fair scheduler.

A two-stage scheduling scheme based on cooperative game theory and multi-criteria decision making is proposed in [91] for different smart grid traffic classes. In particular, the authors first formulate a cooperative bargaining approach to ensure a fair resource sharing among the traffic classes and, at a second level, the resources are allocated according to delay, channel status, queue length, and past average throughput criteria. An uplink scheduling mechanism based on cooperative communications is discussed in [92] and a set of relays is considered to provide the link among the base station and the smart meters. The authors argue that the proposed mechanism outperforms the LTE legacy schemes after computing the percentage of served devices and users with guaranteed QoS requirements.

In [93], a novel scheduler is analytically designed based on the latency distribution of phasor measurement messages exchanged in the distribution grid. The scheduler is aimed to maximize the achieved rate of smart grid traffic, however without quantifying the performance degradation of human-type flows.

3) Other: There can be found in the literature several LTE enhancements for smart grid traffic integration that cannot be clustered into any specific category since they propose techniques that hold nothing in common with other proposals. The work in [94] proposes a novel frame structure to mitigate heavy uplink metering traffic and achieve better spectrum utilization. Allocated subframes can be flexibly configured to adapt to different traffic loads. Numerical results demonstrate an improvement in terms of delay and throughput without considering possible effects on HTC.

A semi-analytical approach for cell coverage planning with uplink delay constraints for smart grid applications is proposed in [95], using theoretical outputs from analytical mathematical models combined with real measurements. The authors argue that cell planning algorithms for future LTE-NAN networks need to incorporate latency constraints for coverage range computations. Architectural enhancements in the core domain of LTE networks for QoS provisioning of smart grid services are discussed in [96]. Motivated by the strict requirements of distribution automation traffic, the authors employ QoS differentiation mechanisms related with the assignment of dedicated bearers[7] to smart grid traffic types. The simulation results reveal a significant reduction in delay and packet loss rate.

The authors in [97] exploit the LTE multicast technique to design an efficient communication framework between the aggregator and the consumers in demand-response use cases. Multicast technology, already applied for content distribution related to human-oriented services, can provide an efficient point-to-multipoint communication platform for metering information exchange, since demand-response programs are inherently designed for a large set of energy consumers. Through a performance analysis, the authors illustrate the effectiveness of different LTE multicast schemes over the LTE unicast service, in terms of latency, throughput and packet loss.

[7] The class-based QoS mechanism for LTE relies on the concepts of data flows and bearers. Data flows are mapped to bearers which are considered as a set of multiple QoS requirements and are associated with different packet treatment (i.e., scheduling and queue management policy, resource allocation) among the network nodes in the core domain.

C. Conclusions

A comprehensive survey and comparison of the existing works related to the feasibility study and enhancements of LTE for smart grid NAN services has been presented in this subsection. Main strengths and weaknesses among the proposed studies/proposals have been identified and one of the basic conclusions that can be drawn is the necessity for radical shifts on the way that cellular systems are currently designed. The basic areas of research reside in: *i)* the improvement of LTE radio access considering the sheer scale of NAN entities requesting connectivity, *ii)* the development of resource sharing strategies for the accommodation of NAN traffic in shared LTE networks, and *iii)* architectural improvements aiming at latency and reliability guarantees for NAN traffic. In addition, any proposed technical solution for LTE-NAN integration should be evaluated by means of the key performance metrics described in Table IV, which have been pointed out by the different techniques that can be found in the literature.

Among the different alternatives for enhancement of LTE to support the demanding NAN applications, the option of direct communications between end-devices, the so called D2D communications, is one of the most promising towards achieving extremely low end-to-end latencies and boost reliability. As it has been already discussed, these constitute major challenges for turning LTE into a suitable technology for smart grid NAN use cases. For this reason, D2D communications are being further developed in future releases of LTE and constitute today focus of intense research activities worldwide. The following section is devoted to discuss the applicability of D2D communications technology in the context of LTE networks, as an enabler for advanced smart grid NAN functionalities in the power distribution grid.

VI. A Promising Approach: LTE Device-to-Device Communications for the Smart Grid NAN

One of the highlights of 3GPP Release 12 was the introduction of D2D discovery and communication [98], where devices can utilize cellular resources and directly exchange data bypassing the cellular infrastructure. This introduces a diversified architecture in the radio access domain, characterized by the coexistence of cellular links that communicate via the base station and relay their traffic through the core network, and D2D links that communicate directly in a rather autonomous way. In network-assisted D2D, control remains in the responsibility of the eNodeB, i.e., the base station. This approach yields a significantly better performance compared to the non-assisted scheme, as a result of the superior resource allocation and interference management that can be achieved by means of a central entity (i.e., the base station) [99].

In the following subsections, the benefits of LTE-D2D communications as the enabling technology for smart grid NAN operations are first highlighted. Then, the focus is set on basic case studies relevant for NANs. In particular, we examine how LTE-D2D technology can be efficiently applied to fundamental NAN application scenarios, by enabling unprecedented functionalities and diffusing distributed intelligence in the distribution grid components.

A. Benefits of LTE-D2D in the distribution grid

Some of the key potential benefits of supporting direct communication between devices in the distribution grid using LTE-D2D enabled networks include:

- **Radio resource management**. Unlike the majority of short-range radio network technologies using license-free bands, LTE operates in licensed spectrum. Therefore, since radio resources can be properly managed by the network, it is possible to minimize interference and maximize the overall system performance [59]. Communication among smart grid entities can thus benefit from the network control in terms of energy consumption, node synchronization, and efficient cellular spectrum utilization. The localized nature of the D2D transmissions also allows for the reuse of cellular radio resources while maintaining acceptable interference levels outside a certain spatially limited area around each transmitting node in the system. A tighter reuse of the scarce spectrum can also be achieved by LTE small-cells, by restricting radio transmissions to the point-to-point connection between two devices.
- **Throughput and Latency**. Direct communication between IEDs may yield higher throughput and lower latency than communication through an LTE base station. This feature is of utmost importance especially for time-critical protection and control applications in the distribution grid. The additional latency imposed by the transmission through the LTE core network may be fatal for delay-sensitive protection functionalities where every millisecond matters. Via D2D communications, the network can still exert control over the radio resources used for these connections, to maximize the range, throughput, and overall system capacity.
- **Network offloading**. By offloading traffic onto direct D2D links, base stations and other LTE network components are relieved from the extensive infrastructure network load. Direct communication bypasses the cellular infrastructure and avoids routing the traffic through LTE network which, in turn, leads to efficient and real-time load balancing.
- **Energy efficiency**. D2D communication allows for lower energy consumption due to the shorter distance between communicating devices as compared to the distance between devices and their serving base stations [5]. Energy efficient device discovery[8] is also achieved since the eNodeB assists the discovery process by identifying potential D2D links through control messages. This feature applies in metering use cases where AMI systems span long distances and multi-hop communication appears as a necessity.
- **Reliability**. A combination of both D2D and infrastructure-based communications can lead to increased reliability by means of multi-path diversity. In addition, shorter links are associated to lower packet error rates, thus yielding higher reliability figures. This

[8]Several works in the literature deal with peer discovery techniques in cellular networks [100] [101] [102].

feature becomes important in protection-relevant NAN functions where self-healing and configurability need to be ensured in a timely manner.

B. Applicability of LTE-D2D in NAN use cases

LTE-D2D technology allows for a decentralized structure of the power distribution grid. Via D2D communications, large-scale NAN functionalities could be delegated and performed autonomously (in a distributed manner) rather than centralizing all operations in a management unit. Decision making and intelligence could be pushed closer to the grid to achieve faster response times and resource utilization [103], leading to the concept of edge-computing. This goes against the traditional model of NAN architecture, in which non-cooperative and disparate systems are deployed and managed independently of one another in a hierarchical manner. Today, NANs are currently associated with massive amount of raw data exchange that are aggregated in centralized management units.

In the new scheme facilitated by D2D communications, smaller amounts of manageable data are transmitted in multiple communication flows among the endpoints at the edge of the network; thus, costs related to data storage systems are optimized. By exploiting LTE wide-area capabilities, access to many streams of available information is possible at a node level, eliminating the occurrence of bottleneck links and enabling prompt actions within the NAN [104]. Likewise, the distributed system management allows for more targeted operational decisions and ultimately leads to a more efficient operation of the distribution grid. The need for decentralized D2D communication in an agent-based energy management system is described in [105]. In [106], a D2D-assisted relaying framework based on cellular technology is proposed for the energy management in the distribution grid. In particular, the authors formulate the data scheduling as a two-stage stochastic programming problem that aims at the minimization of the information loss rate and analytically derive the solution based on the latency uncertainties.

The fundamental advancements that LTE-D2D networks bring to the current aging distribution grid is summarized in Table V. In the following subsections, the beneficial effects of LTE-D2D networks, as the communication technology applied in representative NAN use cases, are identified.

1) Microgrid distributed management and control: A microgrid is defined as a geographically-limited and autonomously operated power system that includes low- and medium-voltage networks and is connected with the main distribution grid through a coupling substation. The microgrid concept substantially contributes to the transition from passive to active distribution networks which are characterized by a bidirectional electricity and information transmission. The islanding capabilities of a microgrid, through its operation in *grid-connected* or *stand-alone* mode, optimize the power quality and ensure system stability and reliability. One of the possible locations of microgrids is in remote areas (e.g., rural areas with no access to utility grids, military camps) where there is no pre-existing communication infrastructure; therefore, the flexible deployment and ubiquitous coverage of LTE networks render them a suitable technology to support reliable communication for their interconnection with the main utility grid. In addition, D2D mechanism could be an efficient way to extend network connectivity in case of poor radio coverage in these isolated areas.

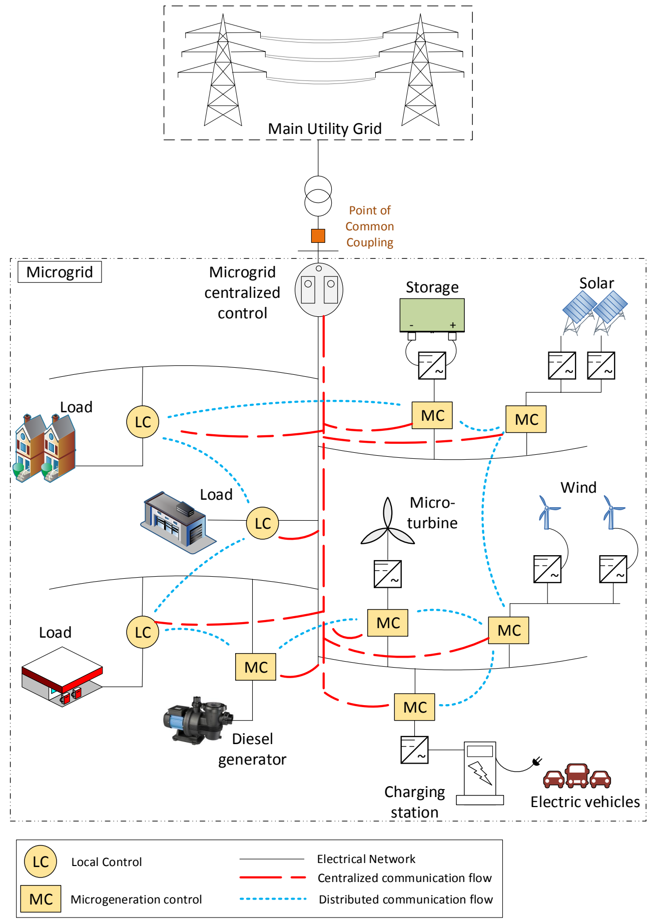

Fig. 2. A typical microgrid architecture. Distributed communication among microgrid entities can be facilitated by LTE-D2D technology with substantial benefits for efficient power grid control. This scheme enhances reliability through decentralized coordination instead of imposing hierarchical control via a central controller.

As illustrated in Figure 2, a typical microgrid system consists of DERs (e.g., wind turbines, solar photovoltaic arrays), energy storage devices, industrial/residential loads and distribution feeders. In a distributed system approach, all these individual devices need to efficiently communicate with each other in order to formulate an integrated and solid power system. Utilizing the performance benefits of LTE-D2D technology, this decentralized coordination can be performed in a fast, secure, and reliable context. With direct message exchange, localized decisions for voltage regulation can be taken in order to avoid turbulence in voltage caused by the randomness of the amount of power that DERs inject to the main distribution grid [107]. A comprehensive review of microgrid decentralized control techniques is provided in [108]. In [109], a NAN architecture based on a multi-agent system technology is proposed to achieve microgrid control.

TABLE V

POWER DISTRIBUTION GRID EVOLUTION WITH D2D TECHNOLOGY. DIRECT COMMUNICATION AMONG SMART GRID ENTITIES ALLOWS FOR A MODERNIZED VISION AND FULLY-INTERCONNECTED STRUCTURE OF THE DISTRIBUTION NETWORK.

Current distribution grid	Distribution grid with enhanced D2D capabilities
Radial topology with centralized power generation units and unidirectional power flows	Fully interconnected topology with DER integration and bidirectional dynamic power flows
Passive system management often requiring extensive human intervention in case of failures	Automated and intelligent system management to efficiently coordinate the diversified functions across the distributed network components
Small-scale and localized status supervision of secondary substations within their LANs	Control and real-time status monitoring of most devices, e.g., IEDs, breakers, transformers, in the secondary substations
Inter-substation communication is limited to only the adjacent substation	Support of multi-substation communications
Wide-area monitoring and control interactions related to mission-critical functions are not supported and affect reliability and power quality	Fine-grained fault detection/isolation which prevents large-scale cascading failures and drastically reduces system response times
Currently consumers have no means of receiving information that would reflect the grid state; thus cannot react to reach the balance and increase efficiency.	Consumer-interactive approach for dynamic electricity consumption and detailed pricing information (demand side management)

Each microgrid component is represented as an autonomous intelligent agent that is able to communicate with neighboring agents for localized decision-making.

Besides the communication within the microgrid, interaction with the main distribution grid is of paramount importance. The operation and management of a microgrid in different modes requires extensive and fast wide-area control and monitoring of system diagnostics by gathering, aggregating and analyzing data from the micro-sources and loads. The impact of latency in load sharing for wireless-enabled microgrids with power inverters at different geographical locations is studied in [110]. Enabled by D2D scheme, control signaling among peers on a short-term basis ensures dynamic interactions between the operation modes and rapid response to grid changes. For example, in the case of a system disturbance, e.g., power outage or load change in the microgrid, a circuit breaker in the coupling substation is triggered to synchronously connect the microgrid to the main grid, ensuring its seamless operation and service continuity. Another control action would initiate the use of distributed local power storage or other local generation instead, depending on the pricing of power and its forecast. These protection operations are associated with stringent (in the order of few milliseconds) latency requirements for message delivery. LTE-D2D networks support the transmission of time-critical information among the peers offering low latencies in the access domain. Direct message exchange among neighboring controllable units equipped with LTE interfaces maintains stable voltage and frequency at load ends. In addition, communication redundancy is easy to be achieved and the absence of a central master controller eliminates the potential risk of a system failure/shutdown.

Microgrid systems constitute an important driving force that pushes to a different design paradigm for the architecture of the future power systems. As the main utility grid continues to be partitioned into manageable and autonomous microgrid systems, LTE-D2D networks are foreseen to contribute substantially to enhanced levels of reliability, resilience, and robustness by enabling a wide-area grid synchronization among regional microgrids.

2) Smart substation automation: Substation automation constitutes one of the key modules in the overall power system operation providing integral functions to the distribution grid automation, e.g., fault management, maintenance and analysis. As smart grid capabilities expand dramatically, the automation of distribution systems is a growing imperative for the efficient grid performance with increased control of relays, capacitor banks and transformers along the feeders. New requirements subsequently arise for monitoring, control and protection of distribution substations and remote monitoring units, often associated with short reaction times [27].

Highly reliable LTE-D2D networks can potentially support these demanding requirements while guaranteeing the quality of electric service. D2D networks can be easily formulated by taking advantage of the close proximity among the grid entities. This results in a well designed substation automation architecture that provides a scaled approach for adding new automation functions. Through direct control signaling among IEDs attached on the distribution feeders and transformers, real-time situational awareness and supervision of all power equipment is possible [14]. The time-sensitive nature of substation automation services constitutes a major challenge for current LTE deployments where communication is supported through a central entity (base station). The LTE backhaul network can act as a communication bottleneck not only due to the additional delay but also due to congestion issues; substation automation in future distribution grids requires a massive deployment of IEDs within the substation local area networks to improve observability and controllability. By avoiding relaying traffic via the base station, LTE-D2D deployments eliminate the occurrence of these issues.

In case of communication within a substation local area network (intra-substation), GOOSE messages are used for fast horizontal communication between the IEDs. According to the IEC 61850-8-1 standard, GOOSE messages can be used for direct data exchange, for example, of interlocking and blocking information between IEDs [15], [111]. In particular, the IEDs execute their control and protection algorithms using the received sensor input data, e.g., from voltage and current transformers. The resulting commands and status signals are then sent to the relevant circuit breaker, as well as other IEDs, using IEC 61850-8-1 GOOSE. Under stable operating conditions, each IED periodically reports its applications states via GOOSE messages to other IEDs, as a *heart-beat* function. Once a status change is detected, the retransmission period of GOOSE messages is shortened (burst traffic) to ensure the timeliness of their delivery [111].

Substation automation is conventionally mainly limited within the substation fence due to the scalable limitations of the wired communication technologies. However, with the introduction of LTE-D2D networks, inter-substation communication can be achieved extending the automation scope [16]. GOOSE messages can be transferred along neighboring substation local area networks, thus contributing to an improved wide-area monitoring, control and protection operation assisted by LTE coverage. Differential fault detection is then achieved since IEDs, using the input from current transformers on each end of a line, communicate with one another and actuate their own breaker if there is a significant deviation in current flow. In addition, the fast exchange of GOOSE messages in case of a system failure can be successfully supported by LTE high data rate; thus, the cascading effects of the power fault can be timely prevented and limited to a local level avoiding a widespread grid fault.

Figure 3 illustrates an envisaged NAN architecture with a substation automation deployment scenario where remote monitoring units, equipped with advanced feeder automation devices and integrated cellular communication interfaces, offer monitoring, protection, control, diagnostic and supervision functionalities. When an event occurs, the IEDs exchange GOOSE messages to notify each other about the grid status and/or initiate control actions. Communication among the remote monitoring units is performed in a direct D2D manner over the shared cellular resources with conventional mobile LTE devices that generate HTC. Both smart grid entities and human users compete for the available cellular resources; thus, network control is required for efficient spectrum sharing.

LTE-D2D networks enhance power systems with advanced control schemes for remote operations in substation automation. The advantages of low end-to-end latency and license-assisted network access achieved with LTE-D2D technology improve grid reliability and actions to balance power supply can be initiated based on an automated data acquisition platform. By bypassing the LTE core network and allowing IEDs to autonomously communicate their status, power faults are rapidly detected, isolated and finally repaired, minimizing their impact in the overall power grid. The time-critical nature of substation automation services introduces several challenges for current communication technologies and the support of these services constitutes an open research issue, and hence, motivates the research community to further explore recent developments in LTE releases. In this direction, LTE-D2D technology appears as a promising solution to deal with the stringent -virtually zero- latency requirements for mission-critical message delivery.

3) Active demand-response: Demand-response generally refers to the flexible management of energy consumption at consumer ends in response to supply conditions regulated by the utility providers. In future smart grid vision, energy consumers are transformed to *prosumers* who could interact and collaborate, by producing, consuming, storing, and also transacting energy on a peer-to-peer basis. This interaction involves the periodic exchange of simple pricing signals among interconnected smart meters, load controllers, or grid agents to achieve more efficient energy management. These decentralized energy optimization strategies, performed on a local level, lead to the creation of more energy efficient *prosumer* hubs and clusters that actively contribute to the overall grid performance.

LTE-D2D communications play therefore a pivotal role in the realization of active demand-response systems. By exploiting D2D proximity mechanisms, devices are able to discover the presence of other D2D-capable devices in their vicinity and formulate mesh networking topologies for energy data exchange. LTE-D2D networks then provide a bidirectional communication system between smart meters and, in general, between loads and generators, enabling customers to monitor electricity usage in real-time. They can further make sophisticated decisions about their instantaneous energy consumption, adjusting both the timing and quantity of their electricity use. In particular, they can take advantage of fluctuating energy prices to achieve significant savings or shift their demand for electricity during peak load periods to off-peak times. In addition, the enhanced coverage characteristics of LTE allow spatially distributed smart metering deployments to cover long distances using D2D relaying features. In [104], a novel data delivery framework based on D2D-enabled cellular networks is proposed to offload smart grid data from the core network and reduce the cost for utilities.

The wide adoption of LTE allows its use for active demand-response as it offers improved availability and responsiveness over AMI and eliminates much of the cost and complexity with respect to other communication technologies. LTE-D2D networks not only enable direct load control at customer side but also encourage the development of dynamic pricing programs which constitutes a fundamentally lacking feature in current AMI architecture. By receiving a more accurate view of the energy consumption status, utilities establish varying energy pricing levels in response to customers' demands. With the high speed connectivity offered by LTE-D2D, users' satisfaction is improved since price tiers are available shortly after the initiation of demand-response events. LTE-D2D therefore provides the required mechanisms for active demand-response by introducing a new cost-aware communication cooperation paradigm.

As thoroughly discussed in the previous use cases, LTE-D2D constitutes a promising network approach with large potential gains when applied in a modernized power grid. However, besides the intrinsic challenges of enabling D2D communications in a network originally designed to be centralized, many research efforts are still required before LTE

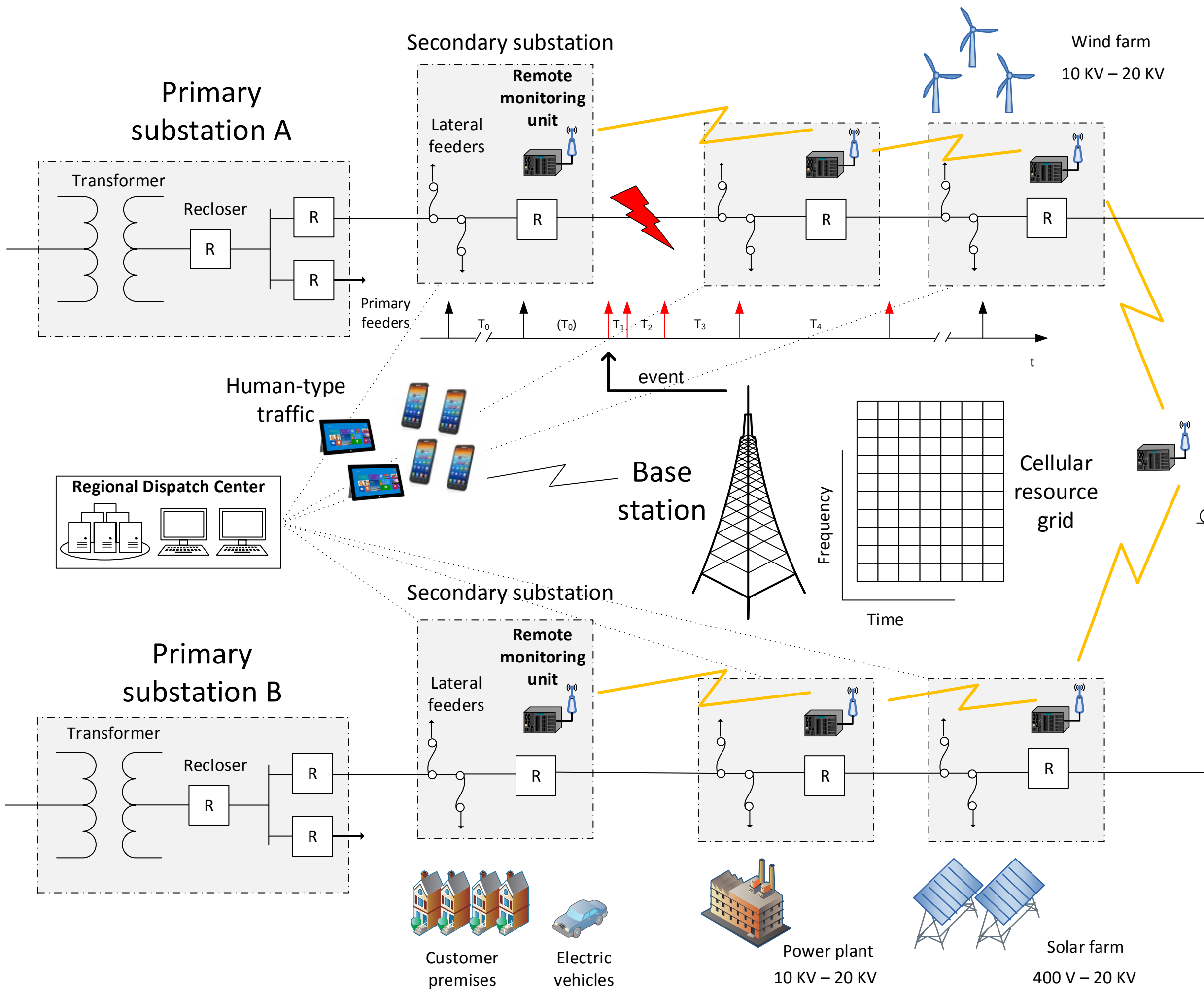

Fig. 3. Illustration of a simple-loop[10] distribution network topology with its system components. Self-healing and protection characteristics, evident in all stages of the network, are achieved through inter-substation communications. Local sensing and control of fault conditions are performed via an underlying reliable D2D communication among remote monitoring units that compete for the shared cellular resources with LTE users.

technology successively supports D2D communication between devices in the distribution grid. Therefore, we foresee that research groups around the globe will steer their efforts towards the design of optimized LTE-D2D networks to support advanced distribution grid services. Over the next years, utility operators are expected to implement cellular-enabled D2D applications effectively in the distribution domain of smart grid, where assets in the field can be in remote locations and spread across large geographical areas.

VII. Open Issues and Future Research Directions

This survey has focused on cellular technology as the communication enabler of demanding operations in the distribution domain of the future power grid. A close look at the technical enhancements of LTE networks to realize the smart grid vision has been taken. In this section, we summarize the lessons learned and point out the open research issues in this particular area.

A. Lessons Learned

Among various communication technologies proposed for the support of demanding NAN applications, cellular LTE technology based on its innate performance characteristics constitutes a promising option. Although cellular networks are considered mature for traditional HTC with well-established ecosystems, the 3GPP has already raised the need to revisit the design of next generations of cellular networks in order to make them capable and efficient to provide support for MTC, which is the case of smart grid NAN use cases. To this end, there is an increasing interest from both academia and industry to develop enhancements for cellular operation over the recent years.

Various works have covered the applicability of cellular networks in NANs; thus, the understanding of the occurring performance limitations can be considered well-known at this

[10] In a simple loop topology, a closed tie switch can be used to allow power flow across the upper and lower segments of a radial (tree-structured) distribution system providing enhanced backup capability.

point in time. Besides the existing feasibility studies that investigate the suitability of cellular networks in various NAN application scenarios in terms of latency and capacity, several research initiatives aimed at LTE architectural and protocol enhancements have been recently proposed, while some are still underway. In particular, some works have focused on the random access procedure of LTE and its performance limitations in case of a traffic surge of smart grid entities. In turn, they propose radio access improvements to alleviate the massive number of channel access attempts and avoid network congestion and intolerant latencies. Other works have evolved around the design of efficient scheduling and resource allocation policies for smart grid traffic while attempting to keep the degradation on conventional HTC in the shared LTE networks at a minimum level. This paper constitutes the first effort to provide a comprehensive survey and qualitative comparison of the existing research proposals.

The envisioned distributed network structure and operation of the future distribution grid calls for a further evolution of cellular networks with enhanced D2D communication capabilities. This network scheme proposes a shift on the traditional cellular architecture by avoiding routing traffic through the base station. It constitutes a less explored research direction; however, it is considered by the community as a promising approach to overcome the performance limitations of current cellular technology and address the demanding QoS requirements of some NAN applications that are not currently supported. In this paper, the applicability of D2D-enabled LTE networks in the future distribution grid has been thoroughly discussed considering three representative NAN use cases, namely: microgrid distributed management and control, smart substation automation, and active demand-response.

The exploration of D2D communications in cellular networks has received intense attention over the last recent years. This is reflected in the latest advancements of the 3GPP consortium, which already integrate D2D communications in new releases of LTE standard. The ultimate goal resides in enabling a broad range of new services and connectivity paradigms.

B. Open Challenges in Cellular Technology for Smart Grid NANs

A number of open issues and technical challenges need to be addressed before cellular technology constitutes the key enabler for smart grid NANs.

1) Time-critical and reliable NAN operations: In order to support emerging smart grid applications in the distribution domain, future cellular networks need to evolve to ensure the performance requirements imposed by the communication between IEDs in NANs. The transmission of protection messages related to energy-automation tasks still represents an open issue in current cellular networks; effective solutions are thus required to guarantee reduced (and deterministic) latency when several grid devices access the network in a highly synchronized manner, e.g., after a power outage. Time-critical applications, currently not viable with existing wireless technology, involve real-time communication of protection/alarm information between substations. In order to avoid the quick propagation of a fault in the electrical grid, it is of key importance to ensure that critical data can be exchanged between substations in real time with ultra-low latencies to isolate the fault.

The 3GPP has already started to study latency reduction techniques for Release 13 in order to keep LTE latency performance closer to the requirements that will come from future delay-critical use cases, such as the protection and control of the smart grid [112]. These techniques include solutions for fast uplink access, shortening of the scheduling time interval of LTE and reduced processing time. Semi-persistent scheduling constitutes also a latency-reduction mechanism, that is currently under discussion for standardization as part of Release 14, and is based on conditional transmission depending on data availability [113]. The current LTE scheduling time granularity of 1ms is rendered insufficient for the fast data transmission of alarm messages [27]. Scheduling decisions need to be taken in shorter transmission time intervals, e.g., 0.5ms or less, by simultaneously adjusting the size of the Orthogonal Frequency Division Multiplexing (OFDM) symbols in the LTE subframe. This may necessitate the design of novel multi-carrier modulation techniques in the physical layer that allow rapid channel estimation.

Future research should also consider the design of a physical subframe structure with potentially more frequent TDD switching within a scheduling interval. TDD parameters, such as guard period and cyclic prefix, should be thoroughly examined and optimized for time-critical NAN information delivery. Since the successful delivery of mission-critical NAN data has to be guaranteed within a predefined delay bound, advanced Hybrid Automatic Repeat reQuest (HARQ) retransmission schemes need to be applied to compensate for incorrect link adaptation [114].

Aligned with the vision of 5G networks, NAN integration with cellular technology could benefit from the heterogeneity in terms of network types and capabilities, a key characteristic of the emerging wireless networks. In order to support the demanding NAN QoS requirements, LTE-based systems could be extended or assisted by short-range technologies already present in our day-to-day lives, e.g., WiFi [115]. Among others, reliability and availability could be improved if simultaneous radios are used for the same purpose enabling the exploitation of diversity in transmission. Consider the example of a critical message that needs to be sent between two substations in a smart grid to avoid a cascade effect and thus a blackout in a given region. The use of simultaneous radio interfaces for the transmission of the same critical message could maximize the probability of successful delivery.

Future research needs to examine the use of direct D2D communication to further reduce the end-to-end latency by avoiding routing NAN traffic through the core network. As discussed in Section VI, LTE-D2D scheme would be a clear beneficiary of the high performance and is harmonized with the ongoing evolution of the power grid into a self-healing grid, supporting a much more distributed generation and storage of power as well as microgrids.

2) Connectivity for a sheer scale of NAN entities: Current cellular systems were not designed to handle efficiently the simultaneous access of thousands of smart grid NAN entities. Even in the case where the aggregated traffic demand is within the system capacity, the signaling overhead related to the initial network entries results in uncontrolled congestion in the random access channel.

The limited random access opportunities compared with the increased resource demand render the current access mechanism highly susceptible to congestion due to its limited capacity. The 3GPP defines a number of potential improvements in the physical random access procedure for the initial network entry of a massive number of devices in a single LTE cell [77]. However, extended access class barring mechanisms are only applicable to delay-tolerant smart grid services.

To efficiently handle the massive contention access, dynamic allocation techniques based on the peculiar traffic nature of smart grid NANs need to be developed upon detection of random access channel overload. Dynamic configuration of the contention resources results in a trade-off with the resources available for actual communication [56]. A potential future research area lies in the development of traffic-aware adaptive contention and load control schemes [116]. The analytical modeling of periodic and event-based smart grid NAN traffic activation patterns (i.e., described by the time-limited uniform and beta distribution respectively) allows the base station to timely detect/predict potential network congestion through reinforcement learning methods. Long-term NAN traffic characteristics can be exploited in hybrid access schemes, where periodically activated metering devices are scheduled on a quasi-static basis, whereas access for sporadically activated protection devices is contention-based. To this end, compressive sensing theory can provide theoretical bounds and schemes to jointly detect active smart grid devices and their potential data transmissions [117].

The current limitations of LTE random access procedure to meet the growing traffic demand has triggered the research community to identify the case of opportunistic spectrum use based on the optimization of multi-channel random-access protocols [63]. Another possible strategy refers to device-priority classification which allows for the definition of different back-off window size values to alleviate congestion. This configuration needs to be broadcasted by the base station via a paging procedure that involves short paging cycles. Resource partitioning with dedicated resources for alarm and protection messages constitutes also a promising approach that avoids periodic random access allocations and receives increasing attention nowadays [81].

In addition to protocol improvements, architectural enhancements of cellular networks should be extensively investigated in order to address the arising problems of extensive and dense smart metering deployments in NANs. Network densification through the use of infrastructure-deployed relays and techniques for wireless backhauling are potential strategies to increase capacity, energy efficiency of radio links and enable a better spectrum exploitation [118]. In particular, wireless network coding, buffer-aided relaying and adaptive link selection are promising research directions to make wireless relaying a viable option for efficient in-band backhauling [119], [120].

The opportunity raised by direct D2D communication to decentralize and offload NAN traffic with the use of local relay links should be investigated in detail in future research. The exploration of D2D communication exploiting the availability of secondary radio technologies, such as those based on the IEEE 802.11 and IEEE 802.15.4 Standards, constitutes a related promising research topic [121], [122]. Network discovery, optimal and dynamic mode selection, heterogeneous scheduling, and traffic flow management techniques are some of the areas that deserve further attention.

3) QoS provisioning for cellular users: As indicated in the literature review, QoS provisioning through the definition of new QoS classes beyond current cellular standardization is required for differentiated data handling in shared networks. On top of the high data rate traffic patterns of human-oriented services, the shared cellular network should accommodate a wide range of smart grid NAN traffic characteristics from low-rate sporadic metering data to bursty protection information exchange. Traffic prioritization is therefore essential for resolving the contention among the NAN and cellular entities competing for radio resources.

The effectiveness of novel cellular network mechanisms that enable delay-critical, ultra-reliable, and massive deployments in smart grid NANs needs to be evaluated while keeping the performance of cellular users at a guaranteed level. On the other hand, radio resource management strategies need to rigorously consider the stringent performance constraints imposed by smart grid messages and thus guarantee the smooth and seamless operation of the power grid [90]. Game-theoretic frameworks can be applied to model the competing behaviors of the network entities. To this end, future research works in the field should further elaborate the effects of NAN traffic into human subscribers' perceived quality of experience, especially for real-time applications. This necessitates the consideration of accurate traffic models while queuing theory can be seen as an effective analytical tool for performance evaluation.

QoS traffic differentiation must involve minimal and simplified signaling procedures for radio bearer establishment in the core network. In addition, since global knowledge of channel state information for every potential communication is infeasible, localized methods need to be developed to allow for a timely acquisition of this information in a practical network deployment. In this context, the exploitation of D2D communications with direct message exchange among peer devices can play a pivotal role in relieving the core network from extensive signaling [123]. In the case of LTE-D2D communication in NANs, radio resource management in the shared spectrum should be carefully performed without significantly degrading the regular cellular system performance. Proper sensing, scheduling and handling of the interference caused by the D2D links are currently subject of extensive research [124], [125].

4) Spectrum flexibility: In cellular-enabled NANs, the dynamic spectrum usage and the utilization of new spectrum bands are essential for the accommodation of dense deployments. Non-orthogonal design of multiple access schemes should be further pursued in future research as a means to increase system capacity and spectrum efficiency. Although the widely used OFDMA scheme presents significant advantages, the idea of relaxing the orthogonality constraint would enable a better handling of the increased NAN demand for the scarce resources, since the number of supported devices would be no longer limited by the orthogonal resources. The challenge here mainly resides in the development of efficient successive interference cancellation techniques.

Opportunistic multiple access could be also achieved with a cognitive architecture in order to meet the growing NAN traffic demand [126]. Cognitive radio can essentially sense the unused portion of the spectrum and the basic challenge resides in the efficient spectrum sharing to minimize the multi-user collisions in dense NAN deployments [63].

Recent developments in self-interference mitigation techniques render full duplex communication, i.e., the simultaneous transmission and reception in the same frequency band, a promising option for efficient spectrum usage. However, LTE standard currently supports only half duplex schemes (TDD or FDD). To this end, there is currently growing research interest on the development of self-interference cancellation techniques and the design of appropriate transceivers for full duplex systems [127]. Since protection-related NAN message exchange is usually performed in short communication links, the use of short-range millimeter wave (mmWave) technology could also offer extremely high data rates and support of massive uncoordinated access in NANs, which otherwise would easily impose a burden on the current access network. The challenges in this case reside mainly on the development of collision-aware hybrid resource allocation schemes and efficient retransmission policies [128].

Finally, as discussed in Section VI, LTE-D2D communication scheme, involving message exchange in short transmission distances, could enable dense spectrum reuse and requires half of the resources as compared with regular cellular communication mode.

5) Security: Information exchange in smart grid NANs often involves the transmission of sensitive and confidential metering data related to energy consumption. Security threats involve disclosure of private data, unauthorized access and injection of false information that affects the normal power system operation [7]. In addition, IEDs have limited cryptographic capabilities due to the overhead induced by the extra payload that would cause unacceptable delays in time-sensitive applications. Therefore, detection and mitigation of possible cyber attacks across the entire NAN infrastructure constitutes a major concern for the legacy cellular systems. In particular, encryption mechanisms need to be developed to ensure the confidentiality and authenticity of the data transmitted [129]. The encryption schemes should be computationally efficient to keep hardware complexity at low levels and induce minimum additional latency. Increased data privacy through anonymization of metering data constitutes another method to achieve security in NANs [130].

VIII. Conclusion

Cellular communications within NANs constitute a promising communication paradigm for the realization of the smart grid vision among other alternatives. Smart grid NANs formulate the communication facility of a power distribution system and often involve demanding operations that are not currently realizable. In turn, the modernization of the legacy power grid requires advanced communication and control functionalities that necessitate radical enhancements in current cellular technology. In this survey paper, the focus has been on the studies that investigate the challenges and propose architectural and protocol improvements of cellular technology to support NAN applications. A comprehensive survey of recent works in the field and a classification of existing approaches has been presented, leading to the identification of potential gaps for research contributions.

As a promising extension of LTE capabilities, D2D communications, which can offload the main cellular networks and boost the performance of wireless communications from various perspectives, have been identified as a promising solution for the future operation of NANs via public cellular networks. LTE-D2D will enable applications not currently realizable with today's cellular technology, such as the efficient automatic operation of the future distribution grid that involves microgrid distributed management, smart substation automation, or active demand-response services, as it has been discussed in this paper. We have outlined the lessons learned and identified the open research challenges in cellular technology for smart grid NANs to motivate and foster further research activities. A redesign of current LTE cellular networks is still needed to enable autonomous and automatic interactions for smart energy systems, putting particular emphasis on enabling mission-critical applications.

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