

From 2G to 5G: A comprehensive review of mobile network technologies for smart grid communications

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Abstract

Their wide coverage, scalability and cost-effective infrastructure have made mobile cellular networks key enablers of smart grid modernization. This review systematically traces how mobile network technology has evolved from second-generation (2G) through fifth-generation (5G) systems, looks at how each generation has been applied in smart grid settings, and sets out what each generation could and could not do.

Early on, second-generation GSM and GPRS supported basic Automatic Meter Reading (AMR) and simple SCADA polling, but high latency and unidirectional communication constrained what these networks could realistically support. Third-generation UMTS and HSPA improved on this by introducing bidirectional Advanced Metering Infrastructure (AMI), including remote connect and disconnect capability, which in turn made large-scale smart meter rollouts practical. With fourth-generation latency dropped to 20–50 ms, enabling real-time distribution automation and Phasor Measurement Unit (PMU) streaming. Fifth-generation NR takes this further still, introducing Ultra-Reliable Low-Latency Communication (URLLC) with latency as low as 1–5 ms, along with network slicing and Massive Machine-Type Communication (mMTC), which together address most of the remaining barriers to wireless grid protection.

Global pilot projects across Europe, China, and North America have validated these capabilities in live grid environments. Still Mobile communications for Smart Grids are facing challenges, including rural coverage economics, cybersecurity threats and legacy system migration. Each generation has systematically resolved the critical limitations of its predecessor, with 5G representing the most comprehensive wireless solution for smart grid applications to date.

Keywords: Smart grid; Mobile networks; 4G LTE; 5G; Advanced metering infrastructure; Communication evolution

1. Introduction

Renewable energy integration, Electric Vehicles growth, and Distributed Energy Resources (DER) deployment are making the global electric power industry undergo a transformation [1]. Solar and wind generation capacity has grown exponentially, introducing variability that traditional centralized grids struggle to manage [2]. Electric vehicles function as both loads and potential distributed storage resources that require sophisticated coordination mechanisms [3]; these drivers necessitate bidirectional communication capabilities that traditional centralized grids cannot provide [4].

Smart grid architecture addresses this challenge through hierarchical communication layers with distinct functional roles [3]. Consumer devices, smart appliances and smart meters within residential or commercial buildings are connected by Home Area Networks (HAN). Data from multiple HANs is then aggregated by Neighborhood Area Networks (NAN), which typically cover several thousand meters within a geographic area. Sitting above both, Wide Area Networks (WAN) link substations, control centers, and distributed generation facilities across utility service territories

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[3]. This layered structure underpins real-time monitoring, control and coordination across the entire power system [1]. The architecture supports two way power flows and information exchange between utilities and consumers. This enables Demand Response (DR) and DERs integration [4].

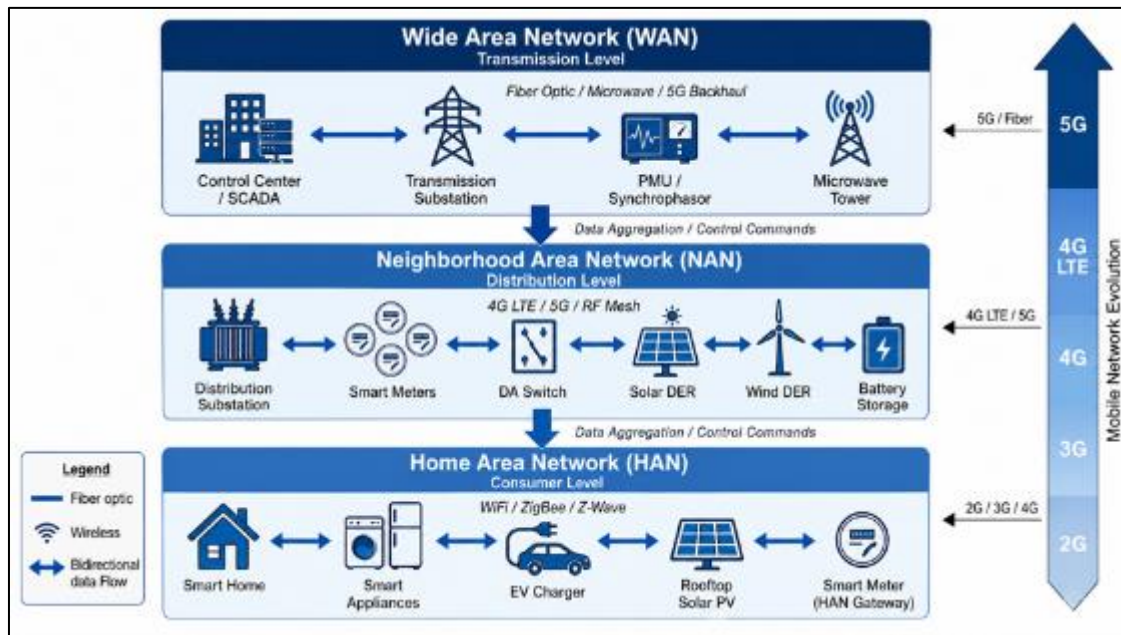


Figure 1 Smart grid communication architecture showing HAN, NAN, and WAN layers with corresponding mobile network generations

Cellular networks are critical enablers for grid modernization as they provide flexibility, scalability and widespread coverage [5]. These technologies support rapid deployment across geographically distributed assets. Unlike wired infrastructure which require trenching and physical installation [2]. Cellular networks meet diverse connectivity requirements ranging from remote sensor data transmission with low-bandwidth to video surveillance with high-bandwidth [5]. The investment in infrastructure is shared across multiple industries, which reduces costs compared to utility-specific wired networks [6]. Coverage extends to remote and rural areas where dedicated fiber deployment proves economically infeasible [7].

Early Supervisory Control and Data Acquisition (SCADA) implementations used dedicated wired infrastructure including leased telephone lines, microwave links and power line carrier systems [9]. However, the transition toward decentralized renewable-oriented systems demands communication solutions capable of handling massive device connectivity, ultra-reliable low-latency transmissions, and enhanced mobile broadband simultaneously [8]. The development of cellular communication technologies from the basic data services to advanced Machine Type Communications (MTC) has helped achieve this objective [5]. The change from the circuit switching voice network to the packet switching data network made it possible for the development of various smart grid applications in each generation [7].

Previous research has examined smart grid telecommunications infrastructure comprehensively and identified cellular technologies as optimal for wide-area connectivity between remote nodes, infrastructure, and intelligent meters [5]. The research analyzed telecommunications infrastructure for smart grids, evaluating fiber optics, MPLS-TP, microwave, DMR, LTE/4G, and 5G technologies across protection systems, SCADA, AMI, distribution automation, DERs, and outage management applications [5]. The use of satellite communications as complementary solutions for remote or disaster-stricken areas where terrestrial networks face limitations was also discussed [10]. European utilities have adopted various telecommunication technologies for smart meter national roll-outs, with cellular networks increasingly preferred for Low Voltage applications [6]. The energy sector requires diverse performance characteristics from 5G technologies ranging from high-capacity smart metering systems to ultra-low latency systems like supervisory control and fault-location [8].

Despite extensive literature on individual cellular generations and specific smart grid applications, no comprehensive review traces how mobile networks have evolved from second-generation (2G) through 5G within the smart grid context. Existing surveys focus on single-generation capabilities [7] or specific applications like Advanced Metering

Infrastructure [9] leaving a gap in understanding how successive cellular generations have progressively addressed evolving grid communication requirements. As carriers decommission legacy 2G/3G networks, utilities planning network upgrades and technology transitions must understand this evolution. The historical perspective reveals patterns in technology adoption and identifies persistent challenges, insights that inform future deployment strategies.

This review systematically analyzes mobile network evolution and its applications in smart grids across four cellular generations. The paper examines communication requirements for grid applications and analyzes the technical capabilities of 2G through 5G networks. It then evaluates generation-specific implementations through case studies and compares performance across generations, before turning to deployment challenges and future directions. Section 2 establishes the requirements framework for smart grid communication. Sections 3 to 6 analyze mobile cellular networks technologies and address their technical specifications, applications and limitations. Section 7 presents comparative analysis identifying three paradigm shifts across generations. Section 8 discusses challenges including spectrum allocation, cybersecurity, legacy integration, rural economics, standardization gaps and 6G outlook. Section 9 concludes with synthesis of the evolutionary trajectory and future research directions. This evolutionary perspective clarifies how cellular technologies have matured alongside smart grid development and informs future network planning and deployment strategies.

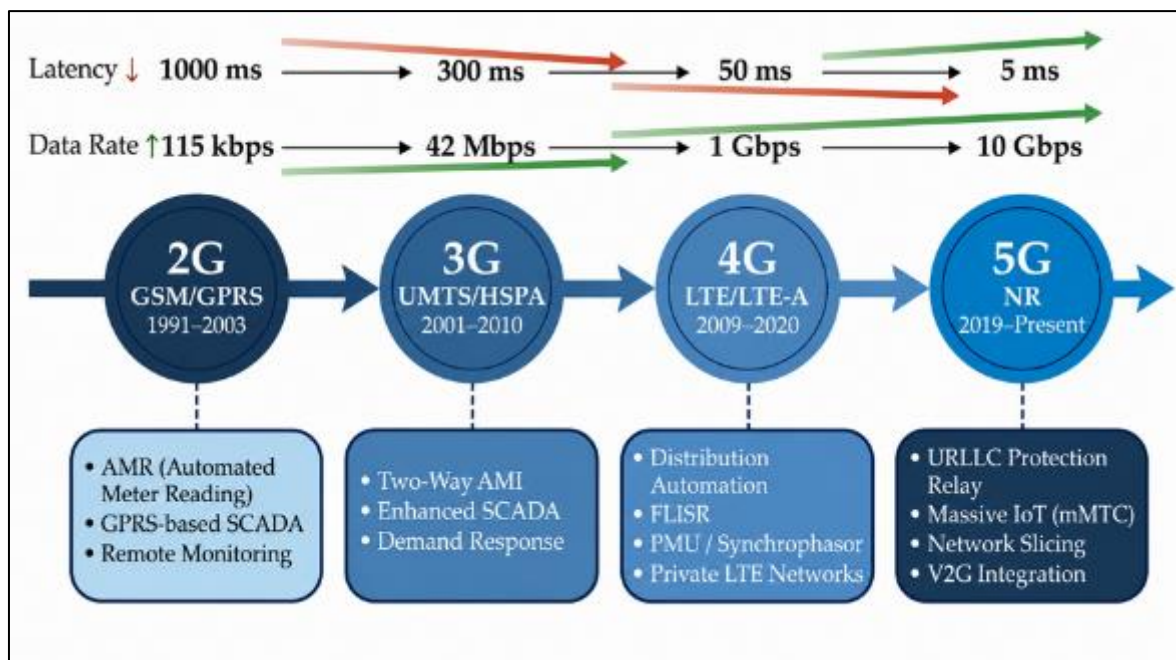


Figure 2 Timeline of mobile network generations (2G–5G) and key smart grid milestones

2. Communication Requirements of Smart Grids

Communication requirements of smart grid applications impose demands that span multiple orders of magnitude in latency, bandwidth and reliability. Protection systems require sub-millisecond response times with near-perfect reliability, while advanced metering infrastructure operates on minute-scale intervals with moderate reliability constraints. This heterogeneity necessitates a comprehensive requirements framework to evaluate communication technology suitability across application domains.

2.1. Protection Systems

Protection systems impose the most stringent communication requirements in smart grid operations. Line differential protection demands 1 ms latency with 99.999% reliability [11]. Tele-protection systems exhibit varying latency requirements depending on protection scheme: blocking operations require 3–5 ms, direct transfer trip systems operate within 12 ms, and permissive transfer trip systems function at 12–15 ms [13]. These systems demand deterministic delivery with minimal jitter to ensure coordinated fault isolation. Wide-area protection applications require ultra reliable and low latency communications with event based traffic patterns [15]. Protection systems also require near real-time data interchange with high reliability [16].

2.2. SCADA and Distribution Automation

Supervisory Control and Data Acquisition systems require 10–100 ms latency for monitoring and control operations [10]. Distribution automation applications demand specific latency constraints coupled with reliability requirements [20]. SCADA systems historically operated with limited bandwidth [17]. Modern distribution automation requires higher data rates with real-time support for control actions and bidirectional traffic flows [13]. These systems maintain constant connectivity and network observability, and facilitates coordination between distribution system operators and prosumers [10].

2.3. PMU and Synchrophasor Systems

Phasor measurement units generate streaming data at 30–60 samples per second and require 20–100 ms end-to-end latency [14]. PMU systems operating at 50 Hz produce synchronized immediate measurements [18]. The telecommunication network delay constraint is 20 ms at 50 Hz reporting rate [14]. Each PMU flow consumes 64.8 Kb/s bandwidth at 50 Hz sampling frequency [14]. Phasor data concentrators process these streams with 10–100 ms decision latency [18]. Near real-time data interchange with high reliability is also required for wide-area monitoring systems using PMUs [16].

2.4. Advanced Metering Infrastructure

Advanced Metering Infrastructure operates on 1–15-minute data collection intervals with massive device connectivity requirements [13]. AMI systems use thousands of resource-constrained devices which require reliable data delivery at lower latencies [12]. Smart meters transmit daily readings with fine granularity, validated by distribution system operators over many hours [19]. Neighborhood area networks support transmission rates between 100 kbps and 10 Mbps across coverage areas up to 10 km [13], [18].

2.5. Demand Response

DR systems require 1–10 second response times for power balancing applications [16]. These systems coordinate changes in consumer energy consumption which respond to price variations or incentive based programs [13]. DR for grid balancing also requires near real-time data interchange, but with moderate reliability [16].

2.6. Electric Vehicle and Vehicle-to-Grid

Electric vehicle coordination requires 100 ms to 1 second latency for charge and discharge management [13], [18]. Vehicle-to-grid systems exchange messages between the grid and electric vehicles, and transmit battery status including temperature, charge level and capacity [13]. These systems must support ISO 15118 protocol for standardized communication. Connection and disconnection events occur dynamically based on time and location without predetermined patterns [18].

2.7. Distributed Energy Resources Integration

DERs require real time monitoring and control with bidirectional communication capabilities [13]. DER integration systems must accommodate dynamic connection and disconnection of distributed generators and loads [18]. Increased number of deployed DERs is pushing power grid infrastructure toward its maximum operational limits [14]. IEC 61850 standardizes communication networks within substations and extends to distributed sources [17].

2.8. IoT Sensors and Massive Connectivity

IoT sensor networks require low-power operation with a 10-year battery life and massive connectivity across millions of devices [13]. These systems transmit periodic and intermittent small data packets [19]. Wireless and wired sensors enable remote monitoring of grid assets [17]. Power-over-fiber technology can also remotely power sensors and control electronics [13].

Table 1 Communication Requirements by Application Domain [1,3,9,10]

Application Domain	Latency Requirement	Bandwidth	Reliability	Traffic Pattern
Protection Systems	1–15 ms	Low	99.999%	Event-driven, deterministic
SCADA/DA	10–100 ms	75 bits/s–100 Mbps	High	Continuous bidirectional
PMU/Synchrophasor	20–100 ms	64.8 Kb/s per flow	High	Streaming, 30–60 samples/s
AMI	1–15 minutes	100 kbps–10 Mbps	Moderate	Periodic daily readings
Demand Response	1–10 seconds	Moderate	Moderate	Event-driven price/incentive
EV/V2G	100 ms–1 second	Moderate	Moderate	Dynamic charge/discharge
DER Integration	Real-time	Variable	High	Bidirectional, dynamic
IoT Sensors	Minutes–hours	Very low	Low–moderate	Periodic intermittent

These requirements cover a range of six orders of magnitude regarding latency starting from one millisecond required by protection systems to 15 minutes required by metering applications. There is no such communications technology that can serve perfectly in meeting requirements for all application areas at once; hence, in choosing technologies and planning communications technologies, network architecture, requirements of individual applications must be strictly matched to corresponding to communications technologies.

3. 2G (GSM/GPRS/EDGE) in Smart Grids

Second-generation cellular technologies brought the first widespread adoption of wireless communications to utility operations. GSM networks that deployed commercially since 1991, provided initially circuit-switched voice and 9.6 kbps data via Circuit-Switched Data [23]. GPRS, introduced in 2000, overlaid packet-switched capabilities onto existing GSM infrastructure, delivering 20–115 kbps theoretical throughput with always-on connectivity [22]. EDGE, standardized in 2003, enhanced modulation schemes using 8PSK to achieve up to 384 kbps theoretical rates [22]. These technologies operated primarily in the 900 and 1800 MHz bands offering excellent propagation characteristics and wide geographic coverage [23].

Latency in GPRS technology ranged 500 to 1,000 ms, while EDGE technology reduced this time to 300 and 400 ms [27]. The packet-switched architecture of GPRS enabled more efficient spectrum utilization compared to circuit-switched GSM for bursty data applications [22]. Both technologies leveraged existing GSM base station infrastructure, which minimized deployment costs for utilities. Security relied on A5/1 and A5/2 encryption algorithms which provided minimal protection against sophisticated interception. Availability of 95–98% was normally attained for network reliability.

3.1. Smart Grid Applications

Early utility deployments focused on Automated Meter Reading, where one-way communication sufficed for scheduled meter reads with low data volumes. Meters transmitted consumption data on fixed schedules, typically daily or monthly without requiring real-time responsiveness. A GPRS-based distribution automation system using SCADA with Advanced Metering Infrastructure has been proposed for rural distribution systems [21]. GPRS enabled remote monitoring of distribution assets including transformer monitoring and fault indicators through dedicated modems installed at field locations. These modems provided cost effective connectivity for assets in remote areas where deployment fiber optic networks was economically not applicable.

SCADA systems adopted GPRS for alarm reporting and status polling at remote substations, particularly in developing countries where wired infrastructure was limited, while distribution automation systems used GSM technology to control and monitor relays remotely [13]. A telemetry solution deployed for Islamabad Electric Supply Company and Peshawar Electric Supply Company in Pakistan utilized GPRS to transmit energy data from grid stations to remote

power control centers [24]. The system measured active and reactive energies, active and apparent powers, current, voltage and power factor at selected grid stations. Data transmission occurred at scheduled intervals, and alarm conditions triggered immediate notifications to operators.

European utilities conducted meter-reading pilots using GPRS technology between 2003 and 2008 to evaluate cellular connectivity as an alternative to drive-by AMR systems. These pilots demonstrated technical feasibility but revealed cost and reliability constraints that limited widespread adoption. Italy's Enel deployed one of the earliest large-scale AMR systems using power line carrier technology, while other European utilities experimented with GPRS for rural areas. The pilots established baseline performance metrics and identified requirements for next-generation cellular technologies.

Mobile workforce management was another early application that provided field crews with voice communications and basic data connectivity. GSM modules enabled spontaneous messaging to authorities for power theft detection and energy consumption notifications to consumers [25]. Field technicians used handheld devices connected by GSM to access work orders, asset information and outage data while in the field. This became possible because of the extensive coverage that had already been accomplished through the use of GSM technology by the early 2000s. Mobility features that existed in cellular networks were better suited compared to fixed wireless or wireline services in workforce applications.

3.2. Fundamental Limitations

Protection systems require very low latency (milliseconds) and extremely high reliability, but 2G GPRS latency of 500–1000 ms made real-time control infeasible. EDGE latency of 300–400 ms, while improved, remained orders of magnitude above protection system requirements. 2G networks reliability ranging from 95% to 98% was below the requirements for mission-critical protection applications.

Low data rates constrained application scope significantly. GSM/GPRS performance with current smart meter traffic was characterized, and the results revealed that PMU data would seriously challenge these wireless systems [22]. Theoretical GPRS rates of 20–115 kbps proved insufficient for video surveillance or synchrophasor streaming, which requires significant bandwidth per PMU flow. EDGE's 384 kbps theoretical maximum could support only a handful of simultaneous PMU streams.

AMR systems using 2G provided one-way communication only and lacked remote connect/disconnect capability required for Advanced Metering Infrastructure. This fundamental architectural constraint prevented utilities from implementing DR programs or remote service management. Security vulnerabilities in the A5/1 and A5/2 encryption algorithms exposed communications to the risk of interception, creating unacceptable risks regarding control commands. Limited device density support constrained scalability as smart grid deployments expanded to millions of endpoints.

The requirements of smart grid networks differed from traditional wireless networks designed for mobile voice and broadband data users [23]. 2G cellular lacked application awareness and struggled to support thousands of simultaneously communicating devices within single cells. Due to these limitations the use of private wireless networks was considered by energy firms instead of using the public cellular network. The gap between 2G capabilities and smart grid requirements established the imperative for next-generation cellular technologies.

4. 3G (UMTS/HSPA/CDMA2000) in Smart Grids

Third-generation cellular technologies marked a pivotal transition from one-way automated meter reading to bidirectional Advanced Metering Infrastructure. 3G UMTS enabled bidirectional AMI with remote connect/disconnect capabilities [3]. UMTS that commercially deployed from 2001, introduced Wideband Code Division Multiple Access air interface delivering 384 kbps data rates [23]. High-Speed Downlink Packet Access standardized in 2005, enhanced downlink performance to 7.2–14.4 Mbps [23]. High-Speed Uplink Packet Access followed in 2006, providing 5.76 Mbps uplink capacity. HSPA+ evolution in 2008 achieved up to 42 Mbps downlink and 11 Mbps uplink through advanced modulation and multiple-input multiple-output techniques [23]. These technologies operated across the 850, 900, 1900 and 2100 MHz frequency bands offering improved propagation characteristics compared to higher-frequency alternatives.

4.1. Technical Characteristics

UMTS latency ranged from 100–300 ms, while HSPA+ reduced this to 50–100 ms through optimized packet scheduling and reduced transmission time intervals [17]. Unlike 2G GSM 3G technologies supported simultaneous voice and data transmission and enabled field personnel to maintain voice communications while accessing grid data. UMTS was IP-based and packet-oriented, which made it suitable for metering applications [26]. The W-CDMA air interface was spectrally efficient than narrowband CDMA technology enabling greater user capacity within the coverage areas. Security mechanisms evolved beyond 2G A5 encryption to incorporate mutual authentication and stronger cipher algorithms. Network reliability typically achieved 98–99.5% availability under normal operating conditions — an improvement over 2G, though still below mission-critical thresholds [11].

4.2. Smart Grid Applications

Advanced Metering Infrastructure represented the primary application domain for 3G technologies in smart grid deployments [11]. Two-Way communication enabled 15-minute interval meter reads with bidirectional data exchange, supporting time-of-use pricing and load profiling. Remote connect/disconnect capability allowed utilities reduce operational costs by managing service activation and disconnection without field visits. European utilities deployed smart metering projects with various telecommunication technologies [6]. UMTS was identified suitable for metering applications due to its IP based packet-oriented architecture [26].

SCADA systems benefited from 3G's enhanced data rates by enabling faster polling rates and larger data payloads than 2G networks. Enhanced SCADA implementations supported more frequent status updates from remote substations and distribution automation equipment. DR systems used LTE to transmit near-real-time price signals to controllable loads, which enabled consumer participation in grid balancing. Mobile workforce management systems deployed tablet-based field management applications with real-time data access, improving. Operational efficiency for maintenance and emergency response crews.

Distributed energy resource monitoring also emerged as an application domain particularly in early solar photovoltaic monitoring systems. These systems used 3G connectivity to transmit generation data, inverter status and environmental parameters to centralized monitoring platforms. GSM 3G/4G cellular technologies were discussed as major communication technologies for smart grid environments. Including home area automation, substation automation and vehicle-to-grid communications [3].

4.3. Limitations and Constraints

Despite improvements over 2G, 3G latency of 50–100 ms remained insufficient for distribution automation requiring less than 50 ms response times [13]. Protection systems demanding 1–15 ms latency could not be supported by 3G technologies. Which exceeded requirements by two orders of magnitude. PMU data streaming applications that require latency less than 20 milliseconds for real-time data transmission have always been out of reach of the 3G network. The 98–99.5% reliability of 3G networks fell short of the 99.999% threshold demanded by mission-critical protection applications.

High cost per connection compared to wireline alternatives constrained economic viability for large-scale deployments. Rural coverage gaps limited applicability, as 3G rollout prioritized urban and suburban areas where subscriber density justified infrastructure investment. Battery life constraints emerged for IoT sensor deployments, as 3G modems consumed significantly more power than low-power wide-area alternatives. This high power consumption made 3G unsuitable for long-term battery-operated sensor networks requiring 10-year operational lifespans. Quality of service guarantees remained elusive on public cellular networks.

The gap between 3G capabilities and real-time control requirements created the need for 4G technologies. Although 3G enabled the transition from one-way AMR to two-way AMI, it could not support latency-sensitive distribution automation or protection applications. This limitation drove utilities to maintain parallel communication infrastructures: 3G for metering. And monitoring applications, and dedicated fiber or microwave networks for time-critical control functions.

5. 4G LTE in Smart Grids

While 3G latency of 50–100 ms prevented real-time distribution automation, 4G LTE latency of 20–50 ms enabled automated fault isolation and service restoration. Fourth-generation cellular technologies introduced an all-IP architecture and flat network design, transforming smart grid communications from periodic monitoring to real-time

control. LTE met the SCADA requirements of 10–100 ms latency established earlier, enabling most smart grid applications except ultra-low-latency protection systems.

5.1. Technical Overview

LTE technology, standardized under Release 8 of 3GPP in 2009 introduced Orthogonal Frequency Division Multiple Access for the downlink and Single-Carrier Frequency Division Multiple Access for uplink [29]. LTE succeeded in obtaining low latency with peak data rates compatible with Smart Grid [27]. The LTE-Advanced that came into existence with Release 10 employed carrier aggregation and MIMO techniques to achieve a peak rate of data transfer at 1 Gbps [29]. Operating with licensed frequencies ranging from 700 MHz to 2.6 GHz, these technologies managed to have improved propagation qualities [33].

Narrowband IoT was introduced in Release 13 in 2016 to support massive connectivity for low-power sensors, with long battery life and deep indoor coverage. NB-IoT achieved close to 100% reliability for outage restoration management in rural and dense urban environments [33]. LTE-M, also standardized in Release 13, provided 1 Mbps data rates with mobility support and voice capability for mobile IoT applications. The use of an all-IP architecture and flat network design have reduced protocol overhead and simplified network management compared with the hierarchical architectures of 3G networks.

5.2. AMI and Metering Applications

LTE enabled real-time meter reads at 1-minute to 15-minute intervals, supporting time-of-use pricing and load profiling with bidirectional data exchange. LTE technology is capable of handling many smart meters within limited coverage areas and transmit measurement data in real-time [30]. Remote connect/disconnect capabilities achieved response times under 5 seconds, enabling utilities to manage service activation without field visits. The DR system used the LTE technology for sending price signals to the controllable loads through near real-time communication in order to allow customers to contribute in grid balancing. NB-IoT technology supported mass implementation of the low power sensors for gas, water and electricity metering applications. Device-to-Device communications underlaying LTE networks enabled efficient spectrum utilization for advanced metering infrastructure by reusing cellular radio resources [31]. Duke Energy deployed LTE-based AMI networks across its service territory in the United States, leveraging public cellular infrastructure for meter data collection. Deployment explained the economic viability of cellular AMI technology compared to private mesh networks in urban and suburban environments [29].

5.3. SCADA and Distribution Automation

LTE latency of 20–50 ms enabled real-time SCADA polling and control operations for distribution automation applications. LTE was investigated for distribution automation applications including automated switching, voltage regulation and capacitor bank control [27]. Fault Location, Isolation and Service Restoration systems achieved sub-second fault isolation using LTE as the communication medium. It was demonstrated by co-simulation studies that the FLISR with LTE reduced outage duration considerably than the conventional manual procedures.

LTE can be used for advanced fault location, extinction and network reconfiguration in distribution networks [34]. Performance degradation caused by mobile background traffic did not increase delays beyond 100 ms, which is the maximum allowable value for these protection-related applications. [34]. China Southern Grid deployed 4G LTE for integrated protection and control systems in 10 kV distribution networks. The system located and isolated faults within 900 ms, assuming a 700 ms load-switch operating time, compared with minutes or hours for manual fault location.

5.4. Synchrophasor and PMU Applications

LTE enabled PMU data streaming at 30–60 samples per second for wide-area monitoring applications. A synchrophasor network deployed in a 10 kV medium voltage distribution grid in Huissen. The Netherlands, achieved median communication latency lower than 37 ms [32]. More than 90% of synchrophasor data could be obtained within 45 ms utilizing publicly available 4G LTE infrastructure [32]. An end-to-end delay between 30 and 80 ms was enough for monitoring purposes, but inadequate for control tasks.

IEEE C37.118.2 protocol over LTE was demonstrated in medium-voltage distribution grids for real-time state estimation applications [32]. Extensive simulations based on LTE communications confirmed performance improvement in terms of data loss for synchrophasor transmission [29]. The Netherlands distribution grid validation demonstrated the feasibility of exploiting 4G LTE technology for PMU-based applications in real-scale deployments [32].

However, public shared infrastructure designed for best-effort service introduced non-deterministic latency variations and packet reordering risks [32].

5.5. Demand Response and EV Charging

LTE supported direct load control with response times under 1 second for DR applications [16]. DR applications used LTE connectivity to aggregate thousands of controllable loads such as HVAC units and hot water heaters. Electric vehicle charging coordination utilized LTE to enable ISO 15118 communication protocol for standardized vehicle-to-grid interactions. Assessment of the UK's 4G network for electric vehicle grid integration revealed that both TCP and UDP protocols achieved latencies less than 1 second for single vehicle cases [35].

However, high penetration of electric vehicles introduced pronounced latency due to queuing delays in network routers and base station servers [35]. This highlighted challenge associated with maintaining efficient coordination as vehicle density increased. LTE proved adequate for vehicle-to-grid coordination at moderate penetration levels but faced scalability constraints under massive deployment scenarios. The findings revealed that 4G TCP often outperformed 4G UDP for vehicle charging coordination applications [35].

5.6. Private LTE Networks

Utilities deployed private LTE networks using licensed spectrum including the 700 MHz and 800 MHz bands, as well as Citizens Broadband Radio Service at 3.5 GHz [11]. Private LTE networks offered dedicated quality of service, increased security, coverage control and independence from public carriers. FirstNet in the United States established a nationwide public safety LTE network with priority. Access for emergency responders and critical infrastructure operators [34]. European utilities deployed private LTE networks for distribution automation and substation monitoring applications.

Private LTE networks enabled utilities to guarantee latency and reliability requirements without dependence on commercial carrier service level agreements [36]. Dedicated spectrum allocation eliminated congestion from consumer traffic and provided deterministic performance for mission-critical applications. Network slicing capabilities in LTE technology were limited compared to 5G, requiring separate physical infrastructure for different application classes. Private LTE deployments required substantial capital investment but provided long-term operational control and security benefits.

5.7. Limitations

LTE latency of 20–50 ms remained insufficient for differential protection requiring sub-5 ms response times. Public LTE networks provided no formal quality of service guarantees, operating on best-effort service principles [32]. Congestion problems arose in LTE random access channels during large-scale smart grid deployments with simultaneous device access [27]. Limited device density constrained support for million-sensor deployments per square kilometer required for comprehensive grid monitoring.

LTE limitation in network slicing forced all traffic to share the same quality of service tier regardless of application criticality [11]. Reliability of 98–99.5% on public networks fell short of 99.999% requirements for protection applications [17]. High power consumption of LTE modems limited applicability for battery-operated sensors requiring 10-year operational lifespans. These limitations established the imperative for fifth-generation technologies with enhanced capabilities for ultra-reliable low-latency communications and massive machine-type connectivity.

6. 5G in Smart Grids

While 4G LTE latency limitations prevented wireless protection, 5G URLLC latency of 1–5 ms enables differential protection applications. Fifth-generation (5G) cellular communication technology represents a fundamental shift from a "best-effort service" model to a "guaranteed Quality of Service" model, enabled by network slicing and ultra-reliable, low-latency 5G communication technologies targets protection system requirements of sub-5 ms latency and 99.999% reliability, addressing key 4G limitations [44].

6.1. Technical Overview and Service Categories

5G New Radio defines three service pillars for heterogeneous smart grid applications. Ultra-Reliable Low-Latency Communications targets 1–5 ms latency with 99.999% reliability for mission-critical protection and control [8]. Massive Machine-Type Communication offers connectivity for the large numbers of devices with very little power consumption [8]. Enhanced Mobile Broadband provides high throughput for applications including video surveillance and advanced analytics [8]. 5G operates across two frequency ranges, the sub-6 GHz spectrum for wide-area coverage and millimeter-

wave bands for high capacity. The energy sector serves as a significant testbed for 5G enabling technologies due to its diverse requirements [8]; the characteristics of 5G—namely wide bandwidth, low latency, high reliability and massive connectivity meet the demands of smart grids.

6.2. Network Slicing

Network slicing allows having multiple virtual networks on a shared physical network infrastructure that are suited for the requirements of particular applications [36]. Protection applications can leverage network slicing to achieve low latency with traffic isolation [8]. AMI applications can utilize massive connectivity capabilities for meter reading [8]. SCADA slices provide dedicated quality of service for control traffic [36].

Network slicing enables simultaneous support to all smart grid application classes with tailored quality of service [36]. 5G technology provides utilities with dedicated virtual slices of network resources to maximize service availability during network congestion time [37]. Network slicing logic architectures span access network, transmission network, and core network matched with power services [36]. This capability addresses a fundamental limitation with 4G that was the need to share one Quality of Service level for all traffic.

6.3. Private 5G and Multi-Access Edge Computing

Private 5G networks utilize utility-owned radio access network and core infrastructure on licensed or shared spectrum [8]. Multi access Edge Computing technology enables the deployment of computational resources in the edge sites of the network [8]. This technology supports local fault detection and edge analytics to facilitate autonomous control without the latency associated with data exchange with the cloud [8]. Extended MEC micro-clouds reduce backhaul load, increase overall network capacity and reduce delays while facilitating the deployment of utility-centric virtual network functions [8]. MEC reduces backhaul dependency for time-critical applications by processing data locally at the network edge [42]. Such architecture allows the use of distributed state estimation techniques for monitoring and control of smart grids [42].

6.4. Grid Protection Applications

5G URLLC targets 1 ms latency with 99.999% reliability, enabling wireless differential protection to replace dedicated fiber in some deployment scenarios [11]. An integrated distribution grid protection system using 5G URLLC demonstrated promising throughput, delay, packet-loss and jitter performance for differential protection. [11]. Evaluation of R-GOOSE messaging latency over public and private 5G networks in Sweden indicated acceptable Local Break Out latency for distributed protection and control schemes [38].

Based on preliminary results from Swedish pilots, 5G successfully handled fault location, isolation, service restoration and PMU-based selectivity [38]. Line differential protection can be supported by wireless ultra-reliable low latency communication on the same band used by mobile broadband traffic [45]. However, 5G Standalone achieved 12–15 ms latency, while Non-Standalone achieved 20–45 ms latency for R-GOOSE and R-SV packets, indicating that deployment mode significantly affects protection performance [44].

6.5. AMI, IoT and Sensor Networks

Massive Machine-Type Communications supports mass deployment of grid sensors including millions of devices per square kilometer [8].

The NRG-5 project validated remote DERs monitoring in Bulgaria using 5G connectivity [37]. 5G enables device auto-configuration procedures and preventive maintenance of electrical networks through continuous sensor data streams [43].

6.6. Distribution Automation and FLISR

5G URLLC enables automated fault isolation and service restoration for self-healing grid applications [40]. Fault Detection, Isolation and Service Restoration systems utilizing real-time data exchange from intelligent electronic devices require low-latency communication infrastructure [40]. A flexible communication architecture based on 5G provides highly customized communication services for future FLISR schemes [40].

5G MEC enables local FLISR logic without cloud round-trip latency by processing fault detection algorithms at the network edge [8]. The Smart5Grid project demonstrated automatic fault detection in a medium voltage grid in Italy

using 5G-enabled infrastructure [37]. Real-time safety monitoring for operators in high voltage substations in Spain was showcased as a 5G-enabled demonstrator [37].

6.7. EV and V2G Integration

5G supports vehicle-to-grid frequency regulation with response times below 100 ms for power balancing applications [16]. The large number of electric vehicles can be managed to act as virtual power plants providing the services of grid management using the advanced technology of connectivity provided by 5G network [46]. Smart charging systems send real time grid signals to EV chargers for demand management and load balancing [46]. 5G latency enables dynamic tariff response in near-real-time for DR applications [16].

Fog-based and cloud-based hybrid computing models applied to V2G networks in 5G provide flexible and timely on- DR services [46]. 5G communications support various connectivity and faster transmission for V2G systems managing and monitoring power usage [46]. However, the inherent high mobility of electric vehicles requires flexible service provisioning to maintain connectivity during vehicle movement [46].

6.8. Global Pilot Projects

The Smart5Grid EU Horizon 2020 project demonstrated 5G for distribution grid management across multiple European sites [37]. Four real-life 5G-enabled demonstrators showcased automatic fault detection in Italy, real-time safety monitoring in Spain, remote DER monitoring in Bulgaria, and wide-area monitoring between Greece and Bulgaria [37]. The NRG-5 project validated enabling solutions for the smart energy vertical at two test sites over real energy infrastructures [43].

China State Grid deployed 5G slicing for protection, AMI and distribution automation applications in 10 kV distribution networks [41]. Ericsson and Vattenfall piloted wireless protection over commercial 5G networks in Sweden, evaluating R-GOOSE latency performance [38]. These pilot projects explain the transition from laboratory validation stage to actual deployment of 5G smart grid applications [41].

Table 2 Summary of 5G Pilot Projects in Smart Grid Applications [33,34,35,36,37,38,40,41]

Project / Pilot	Location	5G Feature Used	Smart Grid Application	Key Results
Smart5Grid (EU Horizon 2020)	Italy, Spain, Bulgaria, Greece	Network slicing, MEC	Fault detection, DER monitoring, wide-area monitoring	4 live demonstrators; automated fault detection validated
NRG-5	Italy, Greece	URLLC, eMBB	Smart energy management, grid monitoring	5G enabling solutions validated over real energy infrastructure
Ericsson / Vattenfall	Sweden	URLLC, commercial 5G	Wireless differential protection (R-GOOSE)	Latency 3–8 ms; protection feasibility over public 5G confirmed
China State Grid	China	Network slicing	Protection + AMI + distribution automation (10 kV)	Sub-100 ms fault isolation; 99.9% automation success rate
Improving Reliability in 5G Slice	Europe	Network slicing, URLLC	Protection communication reliability	Slice isolation improved protection message delivery reliability
5G Distribution Grid Protection	France (RTE)	URLLC	Distribution grid protection system design	5G architecture validated for IEC 61850 GOOSE protection
5G PMU Synchrophasor	China	eMBB, 5G NR	High-precision synchrophasor measurement	Sub-microsecond GPS-synchronized PMU data over 5G validated
URLLC Distribution Protection	USA (NC State)	URLLC	System protection in distribution networks	URLLC latency bounds validated for differential protection schemes

6.9. Cybersecurity in 5G Smart Grids

5G introduces improved security through mutual authentication and encrypted user plane at the PDCP layer [39]. Network slicing isolation separates protection traffic from AMI traffic at the network level, reducing attack surface [36]. Multi-access Edge Computing security requires hardening edge access points against physical and cyber threats due to the distributed deployment [8].

Challenges include an expanded attack surface resulting from massive device connectivity, supply chain risks associated with equipment vendors and protocol vulnerabilities [39]. The most urgent issues are confidentiality of critical data, network anti-attack capability, and other security guarantees [39]. Risk mitigation strategies include Zero-Trust Architecture, end-to-end encryption and intrusion detection systems implemented at the network edge [39]. Intent-based networking provides closed-loop mechanisms for dynamic security policy enforcement across network slices [47].

7. Comparative Analysis

Table 3 synthesizes the evolutionary progression across four cellular generations, revealing systematic advancement in capabilities aligned with smart grid requirements.

Table 3 Cross-Generation Comparison of Mobile Network Generations [1,2,5,11,12]

Feature	2G (GSM/GPRS)	3G (UMTS/HSPA)	4G LTE	5G NR
Peak Data Rate	20–115 kbps (GPRS); 384 kbps (EDGE)	384 kbps (UMTS); 42 Mbps (HSPA+)	Up to 1 Gbps (LTE-Advanced)	Multi-Gbps (mmWave)
Typical Latency	500–1000 ms (GPRS); 300–400 ms (EDGE)	100–300 ms (UMTS); 50–100 ms (HSPA+)	20–50 ms	1–5 ms (URLLC)
Reliability	95–98%	98–99.5%	98–99.5%	99.999% (URLLC)
Device Density	Limited	Moderate	Enhanced (NB-IoT: 50k/km ²)	Massive (1M devices/km ²)
Key Applications	One-way AMR; basic SCADA polling; mobile workforce	Two-way AMI; remote connect/disconnect; enhanced SCADA; early DR	Real-time SCADA; FLISR; PMU streaming; EV coordination; DR	Wireless protection; network slicing; MEC-enabled automation; massive IoT
Key Limitations	High latency; one-way only; low data rates; weak security	Insufficient for real-time control; high power consumption; no QoS guarantees	Cannot support protection; no network slicing; best-effort service only	Deployment complexity; spectrum cost; limited geographic coverage
Smart Grid Suitability	Basic monitoring only	Bidirectional monitoring and control	Real-time control (non-critical)	Mission-critical applications

7.1. Paradigm Shift 1: 2G→3G (One-Way to Bidirectional)

The transition from 2G to 3G fundamentally transformed utility operations from passive data collection to active grid management. 2G technologies supported only one-way Automated Meter Reading, which prevented remote service management and DR programs [22]. 3G UMTS introduced bidirectional Advanced Metering Infrastructure with remote connect/disconnect capabilities, which enabled utilities to manage service activation without field visits [3]. This architectural shift from unidirectional to bidirectional communication established the foundation for interactive DR and DERs coordination. The 50–100 ms latency of HSPA+, while insufficient for real-time control, enabled enhanced SCADA polling rates and larger data payloads. Security mechanisms evolved beyond 2G A5 encryption to incorporate mutual authentication and stronger cipher algorithms. Nevertheless, 3G lacked quality of service provisions; therefore, its application was not very effective with regard to time-sensitive services.

7.2. Paradigm Shift 2: 3G→4G (Periodic Monitoring to Real-Time Control)

Fourth-generation technologies reduced latency from 50–100 ms to 20–50 ms, crossing the threshold for distribution automation applications [29]. Such reduction in latency made it possible for Fault Location, Fault Isolation and Service Restoration system to provide sub second fault isolation compared to minutes or hours for manual restoration. LTE met SCADA requirements of 10–100 ms latency, enabling automated switching, voltage regulation and capacitor bank control. PMU data streaming at 30–60 samples per second became viable over public cellular infrastructure. With median latency below 37 ms demonstrated in operational deployments [32]. The all-IP architecture and flat network design reduced protocol overhead compared to 3G hierarchical structures. NB-IoT and LTE-M variants addressed massive connectivity requirements for low-power sensors with 10-year battery life [33]. However, LTE does not offer network slicing and therefore cannot support all the traffic at the same quality of service level. Protection applications requiring sub-5 ms latency remained beyond LTE capabilities, necessitating parallel dedicated fiber infrastructure.

7.3. Paradigm Shift 3: 4G→5G (Best-Effort to Guaranteed QoS)

Fifth-generation technology introduced network slicing and URLLC service categories, transforming cellular networks from best-effort to guaranteed quality of service. Network slicing is the formation of several virtual networks from the same physical network tailored for certain applications [36]. Protection applications leverage dedicated URLLC slices, achieving 1–5 ms latency with 99.999% reliability, while AMI applications utilize massive connectivity slices for meter reading [36]. This capability addresses the fundamental 4G limitation that forced all traffic to share the same service tier. Multi Access Edge Computing deploys compute resources at cell sites, which enables local fault detection and autonomous control without cloud round-trip latency [42]. 5G URLLC targets protection system requirements, allowing wireless differential protection to replace dedicated fiber in some deployment scenarios [42]. Massive Machine Type Communication enables millions of connected devices per square kilometer addressing the limitations that were present in the previous generations [45]. The shift from a "best-effort" model to a "guaranteed Quality of Service" model represents a pivotal architectural advancement, enabling mobile networks to support mission-critical network protection applications that previously required dedicated infrastructure.

Each generation systematically addressed a fundamental shortcoming of its predecessor: 3G resolved the unidirectional communication limitation of 2G; the 4G overcame the latency issues that hindered real-time control in 3G; and the 5G addressed 4G's inability to guarantee Quality of Service for critical applications [8].

Table 4 Global Smart Grid Mobile Network Deployment Case Studies [13,14,15,16,17,18,19,20]

Country	Utility / Project	Technology	Application	Key Outcome
Italy	Enel Telegestore	2G/3G GSM	AMI — 30 million smart meters	First large-scale AMI deployment; remote connect/disconnect enabled
United Kingdom	Smart Metering Programme	3G/4G LTE	AMI — residential and commercial meters	53 million meters targeted; LTE adopted for NAN backhaul
USA	Duke Energy	4G LTE	AMI + distribution automation	Real-time outage detection; SAIDI reduced by 40%
China	State Grid Corporation	4G LTE + 5G	Distribution automation + AMI + protection	5G slicing deployed in 10 kV networks; sub-100 ms fault isolation
Sweden	Vattenfall / Ericsson	5G NR	Wireless grid protection (R-GOOSE)	R-GOOSE latency 3–8 ms over commercial 5G; protection feasibility validated
Pakistan	LESCO / FESCO	3G/4G	SCADA telemetry for distribution network	Cost-effective telemetry replacing leased lines; 60% cost reduction
EU (Multi-site)	Smart5Grid (Horizon 2020)	5G NR	Fault detection, DER monitoring, wide-area monitoring	Four live demonstrators across Italy, Spain, Bulgaria, Greece
EU (Italy/Greece)	NRG-5 Project	5G NR	Smart energy management	Validated 5G enabling solutions over real energy infrastructure
Switzerland	Research / DSO	4G LTE	PMU / synchrophasor in medium-voltage grid	LTE-based synchrophasor network validated; 30–80 ms latency achieved

8. Challenges and Future Directions

Despite 5G's advanced capabilities demonstrated in previous sections, persistent technical, economic, and regulatory challenges constrain widespread deployment in smart grid environments. This section examines six critical challenge domains and provides forward-looking perspectives on 6G research directions.

8.1. Spectrum Availability and Regulatory Complexity

Spectrum allocation remains a fundamental constraint for utility wireless deployments across licensed, shared and unlicensed bands. Licensed spectrum provides dedicated quality of service but requires substantial capital investment and regulatory approval processes. The Citizens Broadband Radio Service (CBRS) using 3.5 GHz frequency in the US allows for the development of private utility networks through spectrum sharing [34]. through spectrum-sharing mechanisms. European utilities utilize 3.7 GHz bands for private 5G deployments with similar shared-access frameworks [35].

The spectrum allocation in rural areas presents specific challenges, such as population density and large area covered by the spectrum. Regulatory barriers including lengthy licensing procedures and spectrum auction costs constrain rural utility deployments. Hybrid approaches combining 5G for urban/suburban areas with satellite or low-power wide-area networks for rural regions offer economic viability.

8.2. Cybersecurity

Wireless connectivity expands the attack surface through air interface vulnerabilities not present in wired infrastructure, as well as through vulnerabilities in the communication technologies used in smart grids [50]. The integration of electric vehicles via Vehicle to Grid systems introduces new Security vulnerabilities in SCADA systems [51]. Adversaries can poison state information through false state injection attacks, exhausting edge computing resources in 6G-enabled networks [48].

Mitigation strategies including Zero-Trust Architecture models, which require continuous authentication and authorization for every entity within the network is required [53]. End-to-end encryption at the application layer protects data confidentiality beyond the security mechanisms of the network layer. Threat detection mechanisms including artificial intelligence and machine learning technologies can help identify cyber intrusions [53]. However, traditional approaches of intrusion detection cannot cope with encryption of data transmission, which makes the necessity of future research [49].

8.3. Legacy System Integration

Millions of legacy SCADA remote terminal units and meters deployed on 2G/3G networks face forced migration as carriers decommission these networks [11]. Many SCADA networks have been deployed for several decades and were not initially designed taking into account any security factors [52]. Implementing cryptographic defense on old-generation devices is challenging due to computation constraints [52]. Migration challenges include high capital costs for equipment replacement, downtime risks during transition periods and protocol translation complexity between legacy and modern systems.

Solutions to protect legacy SCADA systems must be add-on rather than requiring complete replacement [52]. The smart grid is a combination of diverse legacy systems coupled with new technologies and architectural approaches [50]. Approaching security of future smart grid communication networks cannot be done with a complete new start, due to integration requirements [50].

8.4. Rural Coverage and Economics

Rural utilities face economic constraints from sparse population density and large geographic coverage areas requiring extensive infrastructure investment. Private 5G economics prove challenging with high capital expenditure for low device density in rural regions. Hybrid approaches combining 5G technology for urban and suburban areas with satellite or low-power wide-area networks for rural regions offer more economically viable models [26]. Wired solutions are not considered feasible in rural areas where population density is low because of exorbitant costs incurred during the implementation process [26].

8.5. Standardization Gaps

IEC 61850 power system communication standards and 3GPP mobile network standards evolve in parallel without unified integration frameworks. Smart grid communication systems require complex information and communication infrastructure with ongoing standardization efforts [26]. The true definition for cyber-physical smart grid has yet to be decided internationally, which makes it difficult for policymakers to develop synchronized roadmaps and cybersecurity regulations [54].

3GPP Releases 17 and 18 provide enhanced support for specialized industrial sectors and time-sensitive networking capabilities. However, gaps still exist between the standards of the power system and that of the cellular network, which calls for more standardization efforts.

8.6. 6G Outlook

6G research targets terahertz spectrum from 100 GHz to 10 THz with AI-native network architecture for autonomous network management [48]. Sub-millisecond latency enables ultra-fast protection and control applications beyond 5G capabilities. Integrated sensing and communications capabilities allow the network infrastructure to concurrently operate as a sensing network for monitoring purposes.

Digital twin synchronization enables real-time grid models updated continuously through 6G connectivity [48,53]. Deep reinforcement learning-based resource allocation schemes in 6G-enabled edge networks optimize energy demand management computation [48]. However, artificial intelligence algorithms for cyberattack detection remain limited in efficiency compared to model based approaches [54]. Commercial 6G deployment is expected in the 2030s, requiring continued research to address technical and security challenges.

List of Abbreviations

Abbreviation	Full Form	Abbreviation	Full Form
2G / 3G / 4G / 5G / 6G	Mobile network generations	IoT	Internet of Things
3GPP	Third Generation Partnership Project	IP	Internet Protocol
AI	Artificial Intelligence	LTE	Long-Term Evolution
AMI	Advanced Metering Infrastructure	LTE-M	Long-Term Evolution for Machines
AMR	Automatic Meter Reading	MEC	Multi-Access Edge Computing
CBRS	Citizen Broadband Radio Service	MIMO	Multiple-Input-Multiple-Output
CDMA	Code Division Multiple Access	mMTC	Massive Machine-Type Communication
DA	Distribution Automation	NAN	Neighborhood Area Network
DER	Distributed Energy Resource	NB-IoT	Narrowband Internet of Things
DSO	Distribution System Operator	NR	New Radio (5G standard)
EDGE	Enhanced Data rates for GSM Evolution	PMU	Phasor Measurement Unit
eMBB	Enhanced Mobile Broadband	QoS	Quality of Service
EV	Electric Vehicle	R-GOOSE	Routable Generic Object-Oriented Substation Event
FLISR	Fault Location, Isolation, and Service Restoration	SCADA	Supervisory Control and Data Acquisition
GOOSE	Generic Object-Oriented Substation Event	TCP	Transmission Control Protocol

GPRS / GSM	General Packet Radio Service / Global System for Mobile	UMTS	Universal Mobile Telecommunications System
HAN	Home Area Network	UDP	User Datagram Protocol
HSPA	High-Speed Packet Access	URLLC	Ultra-Reliable Low-Latency Communication
IEEE	Institute of Electrical and Electronics Engineers	V2G	Vehicle-to-Grid
IEC	International Electrotechnical Commission	WAN	Wide Area Network
DR	Demand Response		

9. Conclusion

This review traced the development of cellular communication technologies in smart grid applications across four generations. Second-generation GSM/GPRS enabled basic one-way automated meter reading but lacked bidirectional capability. Third-generation UMTS introduced two-way Advanced Metering Infrastructure with remote connect/disconnect, yet 50–100 ms latency prevented real-time control. Fourth-generation LTE reduced latency to 20–50 ms, enabling distribution automation and synchrophasor streaming, but best-effort service precluded mission-critical protection applications. Fifth-generation networks introduced network slicing and ultra-reliable low-latency communications, achieving 1–5 ms latency with 99.999% reliability for wireless differential protection.

Each generation systematically addressed a fundamental limitation of its predecessor. 3G resolved the unidirectional communication constraint of 2G, 4G overcame the latency limitations of 3G and 5G addressed 4G's inability to guarantee quality of service. Fifth-generation technology therefore represents the most complete wireless solution for smart grids to date, supporting applications from massive IoT sensor networks to mission-critical protection systems through tailored network slices.

Persistent challenges remain, including rural coverage economics, cybersecurity threats from expanded attack surfaces and legacy system migration as carriers decommission 2G/3G networks. Future research directions include 5G-Advanced ambient IoT for battery-free sensors, 6G AI-native networks with sub-millisecond latency, and integrated sensing and communication for simultaneous monitoring and connectivity. The shift from a best effort approach to a quality of service approach represents a major conceptual change, making cellular networks increasingly suitable for the most demanding smart grid applications.

Compliance with ethical standards

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The author declares no conflicts of interest in relation to this research to be disclosed

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