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10.1016/j.egyr.2023.01.085
Qays, M. O., Ahmad, I., Abu-Siada, A., Hossain, M. L., & Yasmin, F. (2023). Key communication technologies, applications, protocols and future guides for IoT-assisted smart grid systems: A review. Energy Reports, 9, 2440-2452. https://doi.org/10.1016/j.egyr.2023.01.085
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Energy Reports 9 (2023) 2440–2452

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Key communication technologies, applications, protocols and future guides for IoT-assisted smart grid systems: A review

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ARTICLE INFO

Article history:
Received 18 August 2022
Received in revised form 10 January 2023
Accepted 19 January 2023
Available online xxxx

Keywords:
Internet of things
Interoperability
IoT protocols
Layered models
Smart grids

ABSTRACT

Towards addressing the concerns of conventional power systems including reliability and security, establishing modern Smart Grids (SGs) has been given much attention by the global electric utility applications during the last few years. One of the key advantageous of SGs is its ability for two-way communication and bi-directional power flow that facilitates the inclusion of distributed energy resources, real time monitoring and self-healing systems. As such, the SG employs a large number of digital devices that are installed at various locations to enrich the observability and controllability of the system. This calls for the necessity of employing Internet of Things (IoT) to achieve reliable integration of all digital devices and proper tracing of various apparatuses in the grid. In this paper, the communication technology, architectural design, cutting-edge applications, and protocols of IoT-assisted SG systems are comprehensively reviewed. The main concerns, future challenges, and research gaps of IoT-assisted smart grid systems are highlighted in detail. Based on this review, key findings are concluded to pave the path for further research directions on IoT-assisted SG systems.

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https://doi.org/10.1016/j.egyr.2023.01.085
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1. Introduction

Traditional power grids are centrally controlled to warrant a balance between supply and demand while maintaining system stability. A substantial energy waste is endured in the current power grids (Deng et al., 2015) that exhibit few challenges such as continuous increase in load demand (Tonyali et al., 2016; Buswig et al., 2019), interoperability of devices made by different manufacturers, increased penetration level of renewable energy sources (RESs) and aging of critical assets. With the aim of addressing these challenges, converting conventional grids into smart grids (SGs) has been given much attention by worldwide electricity grids operators (Yaacoub and Abu-Dayya, 2014; Yigit et al., 2014).

Nevertheless the main challenge of SGs is the necessity for real-time tracing of all installed components within the grid via high speed, encyclopaedic and co-operative modern communication systems to facilitate full observability and controllability of various grid components (Yang, 2019). In contrast, Internet of things (IoT) is a network of physical devices that are coupled by the internet. This configuration helps sensing, analyzing, and controlling, all components within the grid. IoT technique is able to assist smart grids by associating multiple system purposes for the energy production, transmission, storage, distribution, and usages by integrating advanced devices to facilitate connectivity, automation, and real-time tracking (Saleem et al., 2019; Affam et al., 2021). Few surveys on IoT-assisted SG systems can be found in the literatures. As an example, Collier (2015) presented the main challenges for the inclusion of IoT technology into existing grids. Advanced Metering Infrastructure (AMI) and smart metering are presented in Al-Turjman and Abujubbeh (2019) without covering other vital features of IoT-aided SG systems, such as architecture, utilization, and prototypes. Gupta et al. (2019) investigated the security and complexity of IoT-assisted smart grid systems. As displayed in Fig. 1, several kinds of economical areas have partaken with the global application of IoT projects, however industrial sector is mostly rated for the last few years (Anon, 2022b). The bidirectional data flow of IoT-assisted SG systems was discussed in Akkad et al. (2022). The research focused on the internet-based cybersecurity threats by modeling 45 security controls. Reported results recommended the necessity of developing a formal template for maintaining and verifying the information flow. IoT platform was implemented in Hildén et al. (2022) to collect data of building appliances integrated with SG systems. A data collector installed with a photovoltaic (PV)-battery integrated system was employed to analyze and control the system. The paper concluded the economy of energy market consideration for the industrial applications.

The application of IoT for economic and sociological operation of power systems is presented in Bedi et al. (2018a). Reka and Dragicevic (2018) presented the technical operational merits of the IoT-assisted smart grid systems. Another review published in Sohraby et al. (2017), focuses on the satellite services for the SG systems. A brief survey on individual SG technologies, IoT and energy management is presented in Jain et al. (2014). Although a conceptual model of SG combined with IoT setting was presented in Motlagh et al. (2020), the main concern was given to the communication layer of the SG system.

A number of review papers on IoT outlines, implementations, challenges and structures can be found in the literatures (Al-Fuqaha et al., 2015; Nitti et al., 2016; Granjal et al., 2015; Sicari et al., 2015). However, most of these papers are focused on IoT safety and security cloud computation and social issues. IoT based software defined networking (SDN) including data mining (Sood et al., 2016; Tsai et al., 2014), and Long Term Evolution (LTE) scheduling (Mehaseb et al., 2016) have been also presented in the literature. The standard form of IoT is presented in Palattella others (2013) and Sheng et al. (2013) while Gluhak et al. (2011) focuses on conducting various tests of IoT. In addition, some books such as Sinclair (2015), Rossman (2016) and Kranz (2016) presented the IoT in depth. Applications of IoT platforms were investigated in Panduman et al. (2022a) to integrate data synchronization and communication. It studied five real-time projects using Message Queuing Telemetry Transport (MQTT) device and machine learning. There were, however, some problems associated such as parallelism, distributed network, and multi-rule optimization.

Ma et al. (2013) presented the general outline of challenges and standardization accomplishments for SGs while the implementations and structures are elaborated in Al-Anbagi et al. (2016) and Erol-Kantarci and Mouftah (2015). Information handling technologies for SG systems are reviewed in Liang et al. (2014) while SGs security issues are reviewed in Komninos et al. (2014) and Yan et al. (2012), and the confidentiality metering is presented in Finster and Baumgart (2015). Energy efficiency of SGs is discussed in Sun et al. (2016) and Hernandez others (2014), load-balancing is discussed in Hossain et al. (2016) and Rahman et al. (2014), pricing and optimization approaches are proposed in Vardakas et al. (2015), and the impact of RESs is investigated in Reddy et al. (2014). Recently, cloud-aided security for IoT-based SCADA systems has been surveyed in Sajid et al. (2016).

Based on the above discussion and to the authors' best knowledge, a comprehensive state-of-the-art review on IoT-assisted

Nomenclature

AC	Alternating current
AMI	Advanced Metering Infrastructure
AMQP	Advanced Message Queuing Protocol
CoAP	Constrained Application Protocol
CORBA	Common Object Request Broker Architecture
DCPS	Data Centric Publisher Subscriber
DDS	Data Distribution Service
DTLS	Datagram Transport Layer Security
EMS	Energy Management System
EV	Electric Vehicle
GPS	Global Positioning System
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
NB-IoT	Narrow Band-Internet of Things
LTE	Long Term Evolution
LwIP	Lightweight Internet Protocol
M2M	Machine-to-Machine
MBWA	Mobile Broadband Wireless Access
MQTT	Message Queuing Telemetry Transport
NMEA	National Marine Electronics Association
OASIS	Organization for the Advancement of Structured Information Standards
OPC UA	Open Platform Communications United Architecture
ORB	Object Request Broker
PLC	Power Line Communications
PMU	Phasor Measurement Unit
QoS	Quality of Service
RES	Renewable energy sources
RFID	Radio-frequency identification
SAS	Substation Automation Systems
SCADA	Supervisory control and data acquisition
SHS	Smart Home System
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless sensor network
WWW	World Wide Web
XML	Extensible Markup Language
XMPP	Extensible Messaging and Presence Protocol
ZeroMQ	Zero Message Queuing

smart grid systems covering aspects such as application, communication techniques, and architecture has not been published yet. This claim can be noticed from Table 1 that summarizes the recent published research papers in this field in a comparable way.

An outline of this article is shown in Fig. 2. The overview of IoT technique, smart grid systems as well as their integrations and standardization are presented in Section 1. The current implementations and architectures of IoT-assisted smart grid systems are covered in Sections 2 and 3; respectively. Afterwards, different kinds of IoT protocols utilized in SGs are discussed in Section 4. Section 5 presents the analysis of available prototypes, large data management and communication technologies for IoT-assisted smart grid systems. Section 6 highlights the future challenges and guidelines for IoT-assisted smart grid systems. Finally, a brief conclusion of this paper is drawn in Section 7.

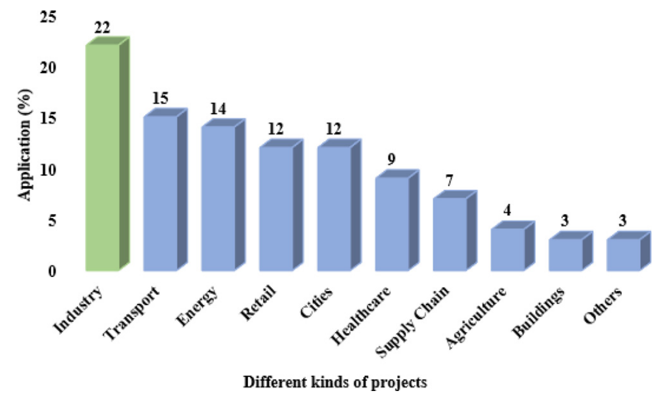

Fig. 1. IoT applications for different global projects (Anon, 2022b).

2. Overview of IoT and SG systems

2.1. Internet of things

Internet of Things is a concept based on a protocol that enables entities to be connected through the internet. It exchanges information amongst numerous smart devices in order to monitor, track and control system's operation (Zanella et al., 2014). In the last decade, IoT-aided technology has mechanized the maneuvers of several systems, relevant to medical technology, transport, military, smart home appliances, and power grids. This technology employs smart devices and systems such as sensors, actuators, Global Positioning System (GPS) as well as various communication techniques, including WiFi, Bluetooth, and ZigBee (Al-kahtani et al., 2022).

2.2. Smart grids

The term "Smart Grid" refers to a new era of electricity that utilizes information technology to generate, deliver, and consume electricity. Smart grid has been identified as a possible solution to reduce electrical energy waste by addressing the challenges that traditional power grids face in terms of effectiveness, stability, security, power quality and the day-to-day increase of the electrical energy demand (Tonyali et al., 2016; Buswig et al., 2019). A typical smart grid topology is shown in Fig. 3 that comprises power flow and power system sectors. The two sectors are further bonded by power production, transmission, distribution and prosumption which can consume or generate electrical power independently.

2.3. Iot integration in SG systems

In case of conventional grid systems and due to the lack of real-time monitoring systems, some abnormal events and service interruption need to be reported by the end user. In contrast, SG employs IoT technology with unique IP addresses to monitor all components of the grid in real time. Moreover IoT technology plays a critical role for identifying SG data, supportive-network's structure, procedure, data storage security, and measurement (Atasoy et al., 2015). Additionally, IoT can be employed for all components of the SG including power production, transmission, distribution and consumption (Hu and Li, 2013; Viani et al., 2013). IoT technology has been utilized for supervising and maintaining the energy production and consumption, energy storage, handling the distributed power plants, and RESs (Wu, 2011; Wang et al., 2012; Basit et al., 2017). It can also be used to monitor

Table 1
A brief summary of published papers on IoT and Smart Grid technology.

Main topic	Reference	Publication year	Focus
IoT-assisted Smart Grid	Sohraby et al. (2017)	2017	Machine-to-Machine facilities utilized in SG.
	Reka and Dragicevic (2018)	2018	Application of IoT in smart grids.
	De La Torre Parra et al. (2019)	2019	Deep packet inspection for security issues of IoT-assisted smart grid systems.
	Gupta et al. (2019)	2019	Vulnerabilities, security threats and countermeasures for IoT-assisted smart grid systems.
	Al-Turjman and Abujubbeh (2019)	2019	IoT-assisted smart grid systems to regulate power quality.
	Tightiz and Yang (2020)	2020	IoT communication protocols for SGs.
	Muleta and Badar (2021)	2021	Energy Management System (ESM) for IoT-integrated SGs
	Akkad et al. (2022)	2022	Bidirectional data flow of IoT-assisted SG systems
	Hildén et al. (2022)	2022	Data collection from PV-battery integrated system with IoT-assisted SG.
	This paper	2023	This paper is aimed at providing an overview of current integration efforts, with an emphasis on IoT-assisted smart grid systems.
IoT	Sood et al. (2016)	2016	IoT application for software defined networking (SDN)
	Androcec and Vrcek (2016)	2016	Service interoperability in IoT
	Minoli et al. (2017)	2017	Systems of building management for the Future Energy optimization
	Bedi et al. (2018b)	2018	Electric Power along with energy systems
	Noura et al. (2019)	2019	Interoperability for IoT Taxonomies
	Pereira et al. (2020)	2020	Resource-constrains in IoT Devices
	Zahoor and Mir (2021)	2021	Resource management in healthcare by IoT
	Amjad et al. (2021)	2021	Application of Layer Protocols for Data Interoperability
	Panduman et al. (2022b)	2022	IoT application with big data analysis
Smart Grid	Sun et al. (2016)	2016	Energy competence in smart grid systems
	Al-Anbagi et al. (2016)	2016	Architectures and utilizations of SGs
	Tripathi et al. (2020)	2020	Power System Network in SGs
	Feng et al. (2021)	2020	Encountering the edge computing in SGs
	Zainab et al. (2021)	2021	Technologies of Big Data Management in SGs
	Khan et al. (2021)	2021	Management of Big Data Resources in SG Systems

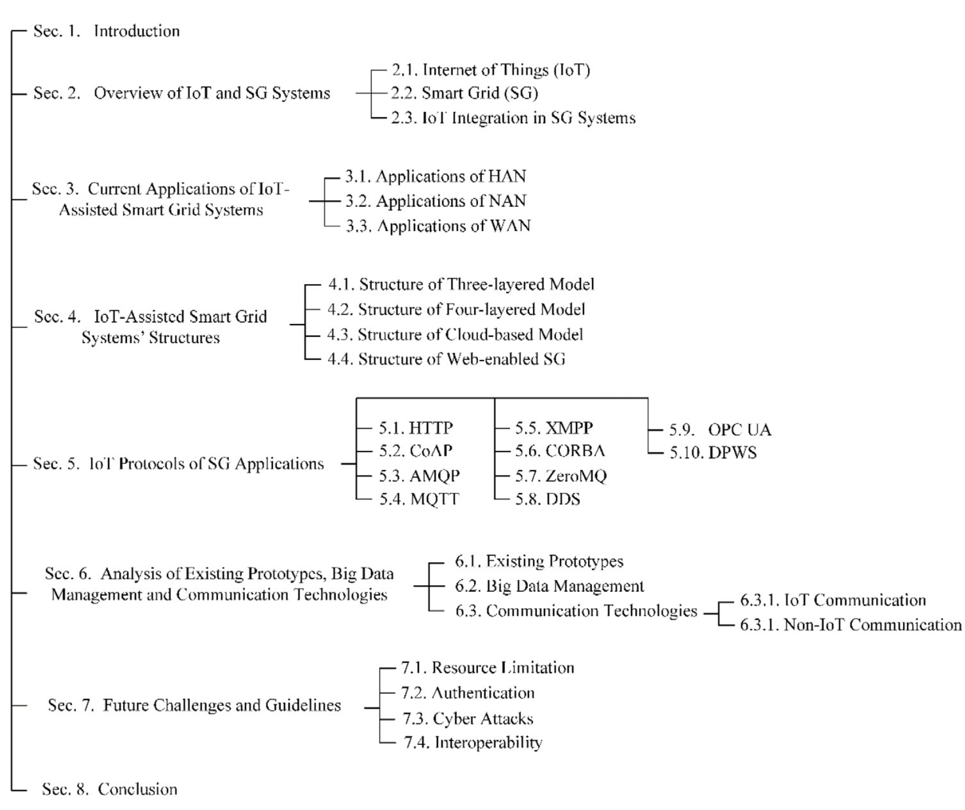

Fig. 2. Outline of the article.

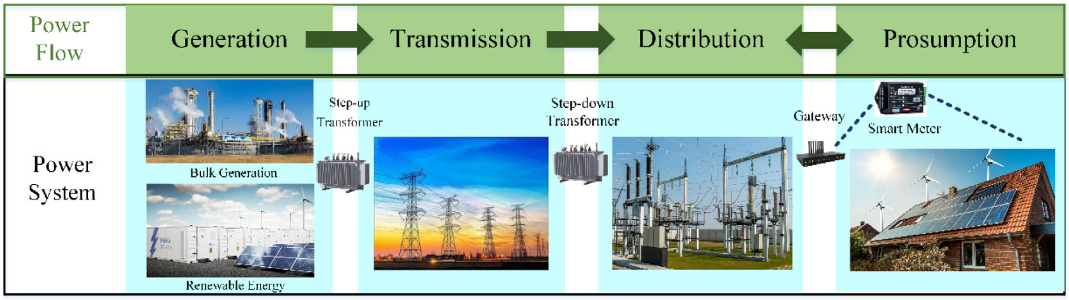

Fig. 3. Representing SG architecture for power flow and power systems.

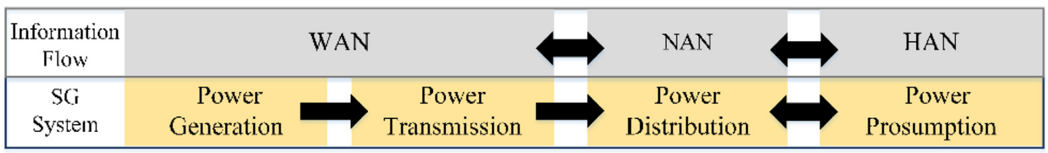

Fig. 4. Typical SG architecture.

transmission lines and substations (Wu, 2011; Wang et al., 2012). As an end user application, IoT is applied for smart homes, charging/discharging batteries of electrical vehicles (EVs), load control, and energy management.

3. Current applications of IoT-assisted smart grid systems

A typical IoT-assisted smart grid topology is shown in Fig. 4 that comprises power production, transmission, distribution and prosumption as well (Saleem et al., 2019). Additionally, it has three networks for proper energy management and control. These are: Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN); those are briefly described below (Hu and Li, 2013; Viani et al., 2013).

3.1. Applications of HAN

The first layer in Fig. 4 is to manage the users' energy through the HAN which is directly involved with various household smart appliances (Khan et al., 2016; Ahmed et al., 2021; Mukhopadhyay and Mukhopadhyay, 2016), electrical vehicles (EVs) (Qays et al., 2020c,a, 2019), and residential RESs (Jaradat et al., 2014) such as rooftop photovoltaic and micro turbine systems (Qays and Yasmin, 2020; Yonis Buswig et al., 2020; Qays et al., 2020d; Ohirul Qays et al., 2020; Qays et al., 2020b). Such network is attached with the IoT technology, which employs sensors to gather real-time meteorological data that aids for projecting the energy accessibility in the near future.

3.2. Applications of NAN

The second layer of SG network is known as NAN which consists of smart meters pertaining with multiple HANs. It assembles the service information from the installed HANs and transfers the data to WAN, the third layer. The NAN application is mainly implemented in smart distribution (Ma et al., 2016) and smart patrolling sectors (Anon, 2021b). By the support of IoT technique, it detects the climate conditions and resolve the influences.

3.3. Applications of WAN

WAN acts as the backbone for communication activity between power generation and transmission systems. The power transmission employs a WAN network along with IoT-assisted smart grid to safeguard the transmission system from infrastructural destruction caused by looting the apparatuses, unusual calamities, and improper development (Chen et al., 2012; Zhen et al., 2012). Several kinds of sensors such as leaning/vibration sensor, and video cameras in an IoT-assisted transmission tower produce early alerts for any abnormal event, allowing for swift remedial action. Any type of signal from the sensors is accepted by the sink node which is further converted to data, and shipped off the observation unit via internet or some other correspondence arrangement.

4. IoT-assisted smart grid systems' structures

The SG architectures show how domains interact with one another at different levels of information controlling. The IoT clients comprise end users and electricity producers in hierarchical regions for administrating the electrical progressions (Trefke et al., 2013). This is an architectural reference with the goal of illustrating SG usages from a structural perspective (Gottschalk et al., 2017). Different kinds of interoperable layers are included in the architectures to handle the business-related aspects, information functionalities, and installed devices as explained below.

4.1. Structure of Three-layered model

As shown in Fig. 5, three individual layers are included in three-layered structure (Khattak et al., 2019; Song et al., 2015). Firstly, the perception layer aims to sense and collect the data through several sorts of devices such as cameras, RFID tags, WSN, GPS, and M2M. Secondly in the network layer internet is accountable as the core network for routing and transmitting the information by accessing other telecommunication networks. Public and industry-specific communication networks are also relied on this network. It maps the information collected from perception layer by IoT components (Song et al., 2015)

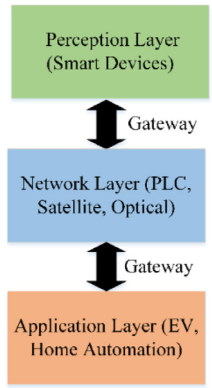

Fig. 5. IoT-assisted Three-layered Structure for Smart Grid systems (Khattak et al., 2019).

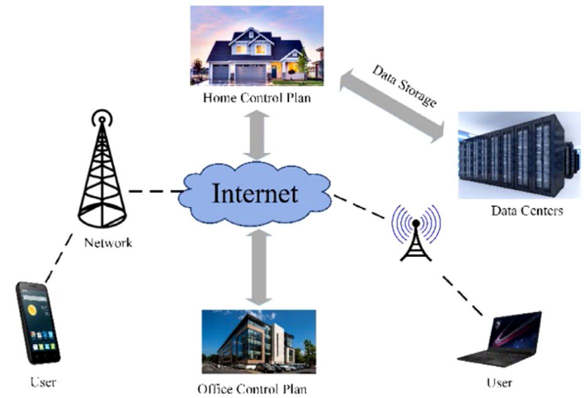

Fig. 6. IoT involvement for advanced position-based automatic energy control (Pan et al., 2015).

Table 2
IoT-assisted four-layered Structure for Smart Grid systems.

Layers	Application
Terminal layer	• Monitor RTUs • Control smart devices
Field layer	• Data collection • Setup field networks
Communication layer	• Wired communication network • Wireless communication network
Master station layer	• Smart grid functionalities • Information passing

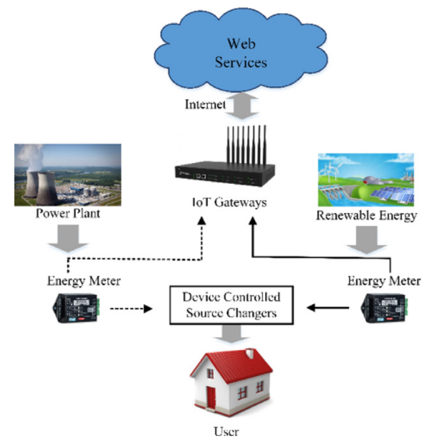

Fig. 7. Web-enabled smart grid architecture (Mohanty et al., 2014).

and transmits it to the third layer namely; application layer. The next layer's role is to process the data continuously and troubleshoots IoT components for SG problems. It is utilized in numerous types of web-servers relevant with home automation, EVs, and power transmission to achieve information exchange at the highest security level.

4.2. Structure of Four-layered model

As shown in Table 2, this architecture consists of four different layers (Banga et al., 2021; Wang et al., 2012). The first terminal layer deals with the IoT components installed in remote terminal units (RTUs), and controls the advanced devices. Afterwards, data are collected from IoT devices in the field layer and are processed based on the type of IoT device. The communication layer can be either wired or wireless and is consisting of a number of communication systems. It offers internet access conductivity, e.g. optical networks for wired network as well as LTE for wireless networks. This structure is further served as a middleware among IoT components and the next master station layer. The last layer controls and copes with all of the SG functionalities and therefore it is measured as an interfacing model to the IoT-assisted smart grid systems.

4.3. Structure of Cloud-based model

DHTG The fundamental energy consumption data saving, and rescue facilities are provided in this cloud architecture along with the maximum computation-intensive modeling. The cloud also contains an application layer to manage the user-friendly web interfacing systems. As shown in Fig. 6, the cloud-based architecture contains a tree-like assembly control plane that includes a few layers of energy saving policies at a number of levels such as rooms of building, departments, and so on (Pan et al., 2015). In here, smartphones or PCs are well-appointed with various networking interfaces, like Wi-Fi, 3G, LTE, Bluetooth, and GPS which aids to attain exact location positioning. The energy saving policies can be dynamically modified by the consumers through their smartphones after a preliminary verification and approval. The location data from cell phones is used to create automatic control rules that may turn on or off energy-consuming items in homes and offices.

4.4. Structure of Web-based model

The web of things includes a number of web services as illustrated in Fig. 7. The web browser performs the likewise interfacing way for these web services (Mohanty et al., 2014). In this architecture, the energy resources are linked to modern energy meters that are in charge of collecting data on residential energy uses. IoT gateways that routinely interface with these meters receive meter readings from energy supplies. Data from IoT gateways are collected and updated on a regular basis, and the server delivers web services on top of specific IoT devices. The household appliances are linked via the SG, to enable the management of power sources by altering source controllers distantly via IoT devices.

5. Iot protocols of SG applications

The foremost challenge of SG application can be found in the communication protocols of heterogeneous and distributed elements. Middleware works assist the interfacing of heterogeneous substances, data collection security trade, and circumstance assessments. Though IEC 61850 data model is applied in SG systems

Table 3
Characteristics of IoT protocols.

Protocols	HTTP	CoAP	AMQP	MQTT	XMPP	CORBA	ZeroMQ	DDS	OPC UA	DPWS
Transport	TCP	UDP	TCP	TCP	TCP	UDP	TCP	UDP, TCP	TCP	UDP, TCP
QoS	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes
Complexity	Low	Low	Low	Low	High	Medium	Medium	High	High	Medium
Low power and lossy network	Fair	Exc.	Fair	Fair	Fair	Poor	Fair	Poor	Fair	Fair
Security	SSL, TLS	DTLS	SSL, TLS	SSL, TLS	TLS	SSL	TLS	DTLS, SSL	SSL	SSL
Message pattern	Req/Res	Req/Res, Pub/Sub	Req/Res, Pub/Sub	Pub/Sub	Req/Res, Pub/Sub, Push/Pull	Req/Res, Push/Pull	Req/Res, Pub/Sub, Push/Pull	Pub/Sub	Req/Res, Pub/Sub, Push/Pull	Pub/Sub
Extensibility	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Message priority	Yes	Yes	Yes	No	No	No	No	Yes	No	Yes
Real-time	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No
Application	Smart Energy	SHS	AMI	Smart Meter	SG	SAS	SHS	EMS	SAS	Electricity Market

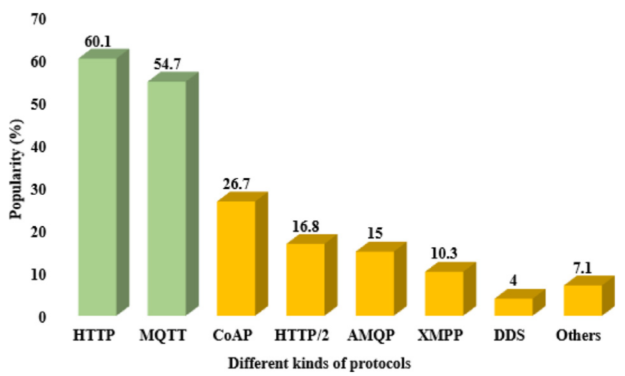

Fig. 8. Popularity of different kinds of protocols (Aloufi and Alhazmi, 2020).

for the last few years (Kumar et al., 2022), the main challenging issue can be found in communication duration. To overcome this factor, different kinds of IoT protocols approached in SG usages are described in Tightiz and Yang (2020) and Wytrębowicz et al. (2021). Herewith, Fig. 8 displays the popularity of several IoT protocols in percentage while Table 3 compares the IoT protocols by considering several categories such as data security, complexity, and message structure.

5.1. HTTP

It is the most popular IoT protocol that is used in the application layer. HTTP establishes www and hypertexts that facilitate easy access to users. HTTP/2 is another resourceful web server of HTTP which was published in 2015 to support maximum web browsers. Utilization of lower memory is the principal merit of HTTP due to fewer simultaneous networks. However, optimization is not possible for mobile devices.

5.2. CoAP

CoAP demonstrates reliability by continuously issuing an acknowledgment message until the approval message is received from the other communication partner. It is a slow network and does not include encrypted features. However, it can support numerous asynchronous messages/languages.

5.3. AMQP

The architecture of AMQP was standardized in 2011 by OASIS and it includes three individual elements: data exchange, queue and binding. The messages are sent from exchange as a broker to a queue by prioritizing them. Several sorts of schemes such as direct, and fanout are defined in binding. Albeit this protocol facilitates wide message structures/broadcasts, it is not appropriate for resource constrained usages.

5.4. MQTT

This protocol was firstly introduced in 1999 as an appropriate candidate for distributed sensors. Usually, three levels of QoS are found among which level zero is the fastest and lowest part as the message confirmation is not involved. Level one and level two confirm a minimum of one or more messages delivery to the controlling sector; respectively. It is a lightweight protocol and easy to implement, but it contains limited scalability due to the broker.

5.5. XMPP

This is an open standard protocol that supports not only the synchronous model but also the asynchronous model as well. In here, XML streaming model converts the XML stanza messages to data. Although this is a stable protocol and highly customizable for SG applications, it is not suitable for constrained devices.

5.6. CORBA

In this protocol, both client and server can be acted as object by the contact of ORB and facilitating the platform-free interconnection. While a request is sent from a client, it is received by the server via DSI that can map the object references in ORB. Since it supports a vast number of languages, it cannot work in a speedy mode.

5.7. ZeroMQ

It is an asynchronous protocol where a queue is provided to share the messages. In a high volume of data throughputs and duration, ZeroMQ is a proper application. This is a broker-less protocol, but it outfits for the constrained devices.

5.8. DDS

DDS is a non-intermediate information exchanging protocol with no risk of bottleneck disappointment. All applications such as data readers/writers/publishers/subscribers can communicate and interact through a domain. DDS has the advantages of eliminating the need for participants' information by using discovery methods along with the DCPS procedure. It is also suitable for extended QoS and large systems.

5.9. OPC UA

OPC is resulted from the combinational works of automation industries without sharing the device's information to the participants. It contains two models in its architecture namely transport and data. When clients are contacted with the transport model, the data model guides the servers for depicting the objects. Resource constrained practices are generally applicable in this protocol. Nevertheless, it requires firewall configurations.

5.10. DPWS

DPWS characterizes two individual sorts of services namely hosting and hosted services. The hosting services help the devices to discover any process and control the functionality of hosted services. The main advantage of DPWS is resource constrained implementations whereas some security concerns can be found in services.

6. Analysis of existing prototypes, Big data management and communication technologies

6.1. Existing prototypes

Prototypes are vital in the creation of large systems since they allow the producers to examine different system's features and validate its performance under different operating conditions before going live with the final product. Amongst the obtainable prototypes for IoT-assisted smart grid systems, energy conditional prototype is a smart gadget attached with a position sensor that broadcasts its location to two servers into two different locations at specified intervals. The distance is calculated between the smart devices by the servers (Pan et al., 2015). Two sorts of software packages are required in this prototype. As shown in Fig. 9, one of them is in charge of GPS data capturing and sending it to the server in NMEA 0183 format. Another one is the Wi-Fi router configuration and administration software that includes a mapping of ports facility to communicate the server from outside of the network address translation. Another available prototype is the renewable and non-renewable energy resources which is offered for IoT-aided home application via HAN architecture (Mohanty et al., 2014). The application comes with a Graphical User Interface (GUI) for managing user accounts and accessing web services. After the verification of user's registration, the consumers will be able to monitor their home power consumption, and arrange the timetable of power resources (Iannaccone and Iannaccone, 2006). The LPC1768 CPU is connected to an Ethernet connection RJ45 in order to include the internet in this prototype. The LwIP protocol is used to create an internet connection by mapping MAC along with the IP address (Spanò et al., 2015, 2013). Additionally in Switzerland, an online prototype of a medium-grid voltage monitoring system (Pignati et al., 2015) was introduced to estimate network state using a Phasor Measurement Unit (PMU). This prototype can provide information about load demand, integrated power, heat producing units, as well as injections of active power. Three main components were used for this system including a devoted PMU that is coupled to the medium-grid voltage substation, a communication network to support duration constraints, and state estimation processes for actual nursing conditions that take phasor-data concentration into account.

6.2. Big data management

Owing to the necessity of instantaneous information as well as the large volume of analyzed data, management of big data is ideal for IoT-assisted smart grid systems. For the inclusion of IoT skills along with smart grids, managing large amounts of data comes at a cost, including storage and processing on a regular basis. This issue includes energy consumption, sophisticated metering records, power line failures, and so on (Shobol et al., 2019). In this regard, cloud computing and fog computing as shown in Fig. 10 provides a service-oriented approach to deliver end-customers a ready-to-use implementation (Atlam et al., 2018). It is a sharing service that allows to access the data instantly via internet and facilitates the reduction of the operational cost and distance which is essential to travel in the network-systems. Utility businesses gain a variety of benefits as a result of this, including lower maintenance costs, improved collaboration, and lower energy costs (Markovic et al., 2013). MapReduce (Lu et al., 2018) and Stream processing (Carvalho et al., 2017) techniques divide large data sets into smaller ones and runs them on numerous machines at the same time implementing identical codes for maintaining great fault scalability and reliability.

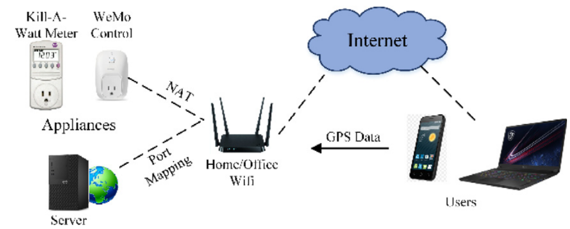

Fig. 9. Automated energy regulation based on smart location framework (Pan et al., 2015).

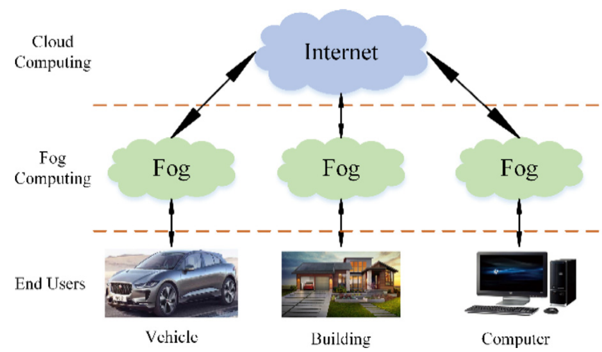

Fig. 10. Structure of cloud computing and fog computing (Atlam et al., 2018).

6.3. Communication technologies

For smart grids, a variety of IoT and non-IoT communication methods comprising unique features, advantages and disadvantages are briefly discussed in this sub-section. Fig. 11 denotes the condition of IoT and non-IoT techniques in terms of their data rates, covering distance as well as power consumption factors (Reda et al., 2018; Anon, 2022a). A summary is further provided in Table 4 for each communication technology in details.

6.3.1. IoT communication

Several types of wireless IoT techniques are available, for instance 5G, Z-Wave, 6LowPAN, and ZigBee. Amongst them from Fig. 11, 5G (Karipidis et al., 2021) provides the highest data range whilst LoRaWAN (Schroder Filho et al., 2016) is the lowest. On the other hand, NB-IoT (Li et al., 2018) covers maximum distance than others. A wireless IoT-assisted SCADA system was proposed in Qays et al. (2022) to monitor the operation of RESs. A Wind–Photovoltaic-Battery hybrid model was simulated using

Table 4
Smart grid communication technologies.

Focus	Protocol	Ref.	Merits	Demerits	Application areas
	5G	Karipidis et al. (2021)	• High bandwidth, • Low latency, and the	• Low range; • Expensive • Privacy concerns	• Monitoring and control on the distributed sector (NAN and WAN)
	Z-Wave	Anon (2021d,e)	• Reliable and scalable; • Low Latency	• WAN and NAN are not compatible.	• Home automation (HAN)
	6LoWPAN	Kuzlu et al. (2016), Anon (2021c)	• Low-powered; • Robust;	• Short range; • Poor data rate;	• Smart metering • Home automation (HAN)
IoT communication	LoRaWAN	Schroder Filho et al. (2016), Anon (2021f)	• Increase gateway capacity • Low-powered interference • Various data speeds	• Not applicable for real-time monitoring systems; • Low transmission rate	• Online monitoring of electricity transmission (NAN and WAN)
	ZigBee	Yi et al. (2011), Güngör others (2011)	• Low cost and • Low power usage	• Low data rates • Short range	• Home automation • Energy monitoring (HAN)
	WirelessHART	Chhaya et al. (2017), Anon (2021g)	• Reliability; • Robustness; • Backward compatibility	• Lack of security standards; • Low data rate;	• Energy production and smart meters (HAN and WAN)
	Bluetooth	Anon (2021a)	• Low power consumption	• Lack of security standards • Low data rate	• Home automation (HAN)
	NB-IoT	Li et al. (2018), Wang et al. (2017)	• Low cost, • Low complexity	• High Latency	• Home automation • AMI (HAN and NAN)
	Cellular Communications	Hossain et al. (2012)	• Wide area coverage; • Enhanced quality of service	• Network congestion occurs; • Service is not assured in adverse situations.	• DER monitoring and management (HAN, NAN and WAN)
	WiMAX	Guainella et al. (2007)	• High data rate • Long range and	• Low frequencies require leasing; • High frequencies do not penetrate obstacles.	• Automatic meter reading • Real-time pricing (HAN)
	MBWA	Ahmadi (2011)	• Low latency; • high mobility and bandwidth	• Poor Infrastructure is scarce; • costs are high;	• Wireless SG monitoring; • EVs (NAN and WAN)
Non-IoT communication	Digital Microwave	Kizer (2013)	• Long distance coverage; • High bandwidth and data rate	• Multipath interference cause problems.	• Distributed substation and DER (HAN and NAN)
	PLC	Güngör others (2011), Lewis et al. (2009)	• Low installation cost • Long distance coverage	• Noisy and harsh medium that is susceptible to perturbations. • Management difficulty	• Automatic meter reading; • Low voltage distribution (HAN and NAN)
	Lines of Digital Subscribers	Frenzel (2018), Guenach et al. (2009)	• Long distance coverage; • High bandwidth and data rate	• Distance affects quality; • installation costs are expensive	• Smart metering (HAN, NAN and WAN)
	Optical Communications	Jianming et al. (2011), Ancillotti et al. (2013)	• Long distance coverage • Reliable	• High fiber deployment costs • Difficult to modify	• Infrastructure for physical networks (NAN and WAN)

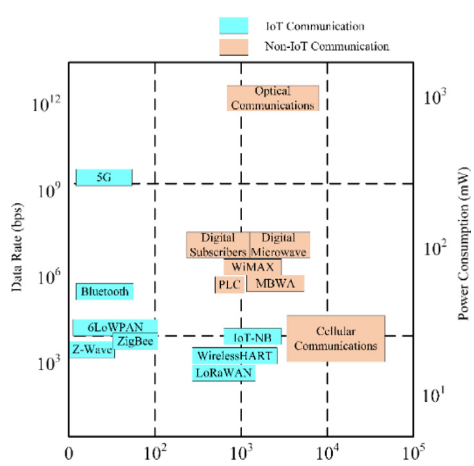

Fig. 11. Situation of IoT and Non-IoT Communication Technologies.

Simulink software and experimented in the laboratory environment through Wonderware Intouch software. The real-time data was further monitored by the ThingSpeak website. However, the discrimination between sending and receiving data was seen to be mainly caused by the wifi speed which is another principal factor in IoT communication technique.

6.3.2. Non-IoT communication

The Non-IoT communication techniques make sure the utmost data rate and coverage distance e.g. optical communication (Jianming et al., 2011; Ancillotti et al., 2013) and cellular communication (Hossain et al., 2012). In the remote and challenging areas, this technique outperforms over other ones. Nevertheless, the complexity of physical infrastructures diminishes its proper efficiency.

7. Future challenges and guidelines

Despite the fact that IoT techniques are commonly used in smart grids, they may present a plethora of security flaws for further challenges and research guidelines. Because IoT-assisted SG systems are monitored and regulated through the open internet, less protection against cyber-attacks than more established mobile and permanent networks is provided. After manipulating data, generated by smart devices or transferred from the utility, an attacker can disrupt the real-time balance of energy output and consumption by inflicting significant financial losses to the utility and power assets (Bekara, 2014; Ciavarella et al., 2016). Hence, employment of practical elements as a roadmap of future trends for IoT-assisted SGs are demonstrated in Fig. 12 whereas the security contemplation for IoT-assisted smart grid systems is discussed below.

7.1. Resource limitation

Numerous devices and things are resource restricted in an IoT-aided SG system, particularly those are arranged for excessive quantities. Such type of stuffs are not able to offer complex security algorithms due to the limited measurement and storage sizes. This restriction creates more difficulties in terms of implementing the classical security measures (Bekara, 2014). When developing security solutions for IoT-assisted smart grid systems, more caution is required to ensure that IoT devices with limited resources can manage the anticipated security solution.

7.2. Authentication

The smart meters must be authorized by the energy suppliers for billing issues (Dalipi and Yayilgan, 2016). Since establishing a trustworthy relationship between smart devices is easy to make, it is more difficult when they are maintained by different entities. In contrast, the uniqueness of IoT components in smart grid system is confirmed once again so as to escape any misapplication of the system. Only the certified employer or scheme should be accredited towards accomplishing the deeds to admit the resources (Bekara, 2014).

7.3. Cyber attacks

The SG system involves a range of physical assets, such as AMI, and transformers, which are operated by IoT. As a result, cyber-attacks on the smart grid are posing a threat to the regulation and causing indirect damage to these assets (Gunduz and Das, 2020; Mesbah, 2018). The higher the number of IoT-assisted smart grid applications are produced, the greater the need to guard against cyber-attacks. In this regard, code of practice such as IEEE 802.15 (Chhaya et al., 2017), Security for IoT consumers (Anon, 2020), and Electrical Equipment Safety System (Harkin et al., 2022) should be followed strictly under the federal-law.

7.4. Interoperability

In order to meet the diverse requirements of IoT-assisted SG systems, heterogeneous communication methods are required. In contrast to conventional telecommunication standards, the modern communication standards of IoT-assisted smart grid systems need interoperability among interfaces, message and workflows. Interoperability is also necessary for effective business rules, which poses a significant challenge due to the problems associated with multiple vendors and legacy systems (Noura et al., 2019; Reddy et al., 2022). As such, instead of focusing on one specific communication technology for IoT-assisted SG systems, a consensus must be reached on the use and interpretation between different technologies (even non-IoT) and standards.

8. Conclusion

Future smart grids are capable of resolving the issues of traditional one-directional information and power flow networks including the continuous increase of the energy consumption, and interoperability of various devices within the network. The IoT technology aids smart grid by supplying advanced IoT-devices towards monitoring, analyzing and controlling the entire system. This refers to the Internet of Things-assisted smart grid system, which supports and develops several network utilities in the power sector. A comprehensive state-of-the-art review of IoT-assisted SG systems, along with a number of issues that must be solved through extensive research and prototyping has been presented in this paper. Main challenging and research gap points can be drawn as below:

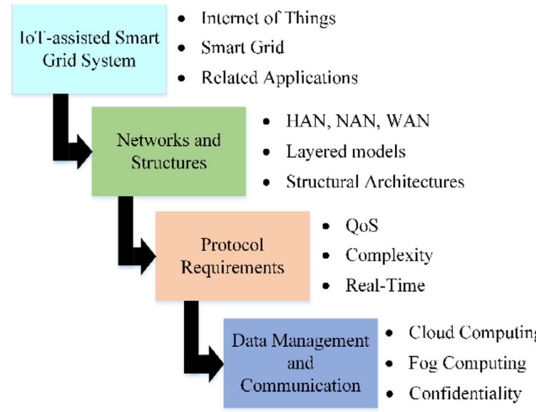

Fig. 12. Relationship of effective elements with IoT-assisted SG systems.

- Regarding the communication techniques, lack of data consistency creates the complexity of IoT-assisted SG systems. Hence, it is necessary to measure the device-configuration utilized for IoT-assisted SG systems.
- From the viewpoint of applications, a little attention was given to the applications of IoT-assisted smart grid systems. Subsequently, development of remaining applications is essential.
- After the analysis of architectures, the present designs place a strong focus on generic layered structure, which are primarily modeled for remote household appliances and do not cover all components of power system networks. Thus, the designing of a new reference architecture is needed for IoT-assisted smart grid systems.
- A few quantity of published prototypes are available for IoT-assisted smart grid systems, which are not easily accessible for open-source test-beds and simulation tools towards enabling the performance assessment. This calls for more effort in developing various prototypes to assess the performance of the system under different operating conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

This research work is supported by Edith Cowan University Higher Degree by Research Scholarship (ECUHDRS), Joondalup 6027, Western Australia, Australia.

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