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Review Article

Communication Network Simulation for Smart Metering Applications: A Review

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Abstract

Many countries are witnessing the deployment of millions of smart meters, as they strive to upgrade their traditional grid to the smart grid already prominent in the developed parts of the world. Communication networks that can offer high-speed communication will be required for transmission of the copious amount of data resulting from the numerous smart meters and other intelligent electronic devices (IEDs) in the distribution network substation. Therefore, there is a need to critically assess the available communication infrastructure for eventual upgrade and deployment. In this paper, a survey of the communication network and networks simulation software used for this purpose was carried out, with specific emphasis on smart metering applications. Some critical requirements identified are security, quality of service (QoS) and optimal cost for system operation. Also discussed are methods employed in the works of literature to handle the critical issues raised. For data transmission between the meters and data concentrators; power line communication (PLC) was mostly cost-effective and hence, mostly deployed. In the wireless category, ZigBee (802.15.4), Wi-Fi (802.11), and WiMAX (802.16) among others are suitable and have been successfully deployed. OPNET, NS-3, NS-2, and OMNET++ have been successfully employed for communication network simulations in smart metering applications.

Keywords: Communication Network, Simulation, Smart Meter, Data Transmission, Advanced Metering Infrastructure.

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1. Introduction

Electrical energy usage is not optimized when consumers are not aware of their consumption patterns and financial implications. With smart meters, via a home display, consumers see exactly when and how much electrical energy they are using. With advanced metering infrastructure (AMI), smart meters have the capability of performing and reporting continuous measurement of customer's energy consumption rate in real-time. It captures the voltage, current, phase angle, and frequency of the supply. Besides, it can communicate with the consumers and the utility provider, in a mutual relationship for energy management and optimization. The installation of smart meters in buildings is the foundation and bridge to the construction of smart grids. A smart grid can be described as an electrical grid that is characterized by smart energy measurements, smart operations and control by including smart meters, smart appliances, smart devices, renewable energy and energy-efficient resources. Smart meters allow the interconnection and operation of all entities that make up the smart grid. Hence, the functionality of the smart grid relies heavily on the accuracy and effectiveness of its meters [1]; [2]. Smart grid concepts could be verified experimentally or through simulations [3].

Smart metering is regarded as a major component of the smart grid whose functionality drives its performance, and as new communication and information systems and technologies emerge, selection of the best communication technology for successful application of smart meter becomes an issue of interest. New technology can enhance the reliability and availability of information from such meters. However, effective simulation of the performance of the selected technology before deployment is very important. Performance analysis of an electric network will be enhanced by the selection of the appropriate simulator for the analysis, and this will eventually guide the selection of adequate infrastructure for metering applications.

[1] discussed smart grid architecture highlighting issues that are related to obtaining higher performance. Focusing on smart metering applications and the requirement for effective communications, the survey explores the flexibility of operation, reliability, and cost-effectiveness. In [4], common techniques for simulation of smart grid communication was surveyed, with emphasis on the framework for co-simulation and their enabling technologies.

In [5], three types of simulators in a smart grid environment were considered: power system, communication network, and co-simulators for simultaneous simulations of both communication and power networks. The research work focused on distinct simulators following the intended use cases, extent and detail of the simulation model, and architecture. The work by [6] focuses on smart grids and the required communication systems applicable for smart grid operations. The key areas are infrastructure for smart grid operation, which include smart measurement and metering, technologies for smart grid communication, and security concerns as related to successful smart grid operation. However, the survey does not consider simulators applicable for analysing the performance of the communication networks. [7] presented a review of simulation tools in communication networks. In their work, ten commonly used network simulators were reviewed, the strength and weaknesses of the said simulators were highlighted. A classification and comparison which consider the type, as well as the deployment mode including network defects and protocol supported, were also carried out, including the methods of simulation, techniques employed for evaluation and acceptability of simulation studies and outcomes. The review only considers general network simulators without any specific reference to smart metering applications. [3] carried out a survey of twenty-six smart grid co-simulators based on peculiarities such as simulators used, research themes, open-source availability and synchronisation mechanism for used simulators. In [8] a survey on basic principles of real-time as well as co-simulators for the improvement of electric power system protection, control and monitoring applications were presented. Several applications were also introduced for the same purpose. Besides, testing environments for smart grid predicated on real-time and co-simulators were presented.

Building on previous reviews, the interest of this work is in the review of the simulation of the communication networks for applications in smart metering. The aim is to survey and identify the communication networks for smart grids and the simulation tools that are employed in studying their performance with specific emphasis on smart metering applications.

1.1. Bibliometric Analysis

To provide an overview of the previous relevant work on communication network simulation for smart metering applications, a bibliometric analysis based on the IEEE Explore, Science Direct, Springer Link and ACM digital databases was carried out on 25th July 2020. The said analysis was carried out using the search syntax: ("Communication network simulation" OR "Communication network simulator" OR "Network simulation") AND ("Smart metering applications" OR "smart meters" OR "Smart grid"). An initial result of 2093 journal articles was returned after the search of all the digital databases. An inclusion/exclusion criterion was set for the selection of the most relevant articles, and articles considered were between 2010 – 2020 with a focus on communication network simulation for smart metering applications in a smart grid network. Only 45 articles made the final list of articles eventually considered for the review in this paper. Figure 1 shows the percentage of journal articles selected in each of the digital repositories. As can be seen from Figure 1, IEEE Explore is a traditional digital repository for smart meters and smart grid-related paper. Others are Science Direct and Springer Link.

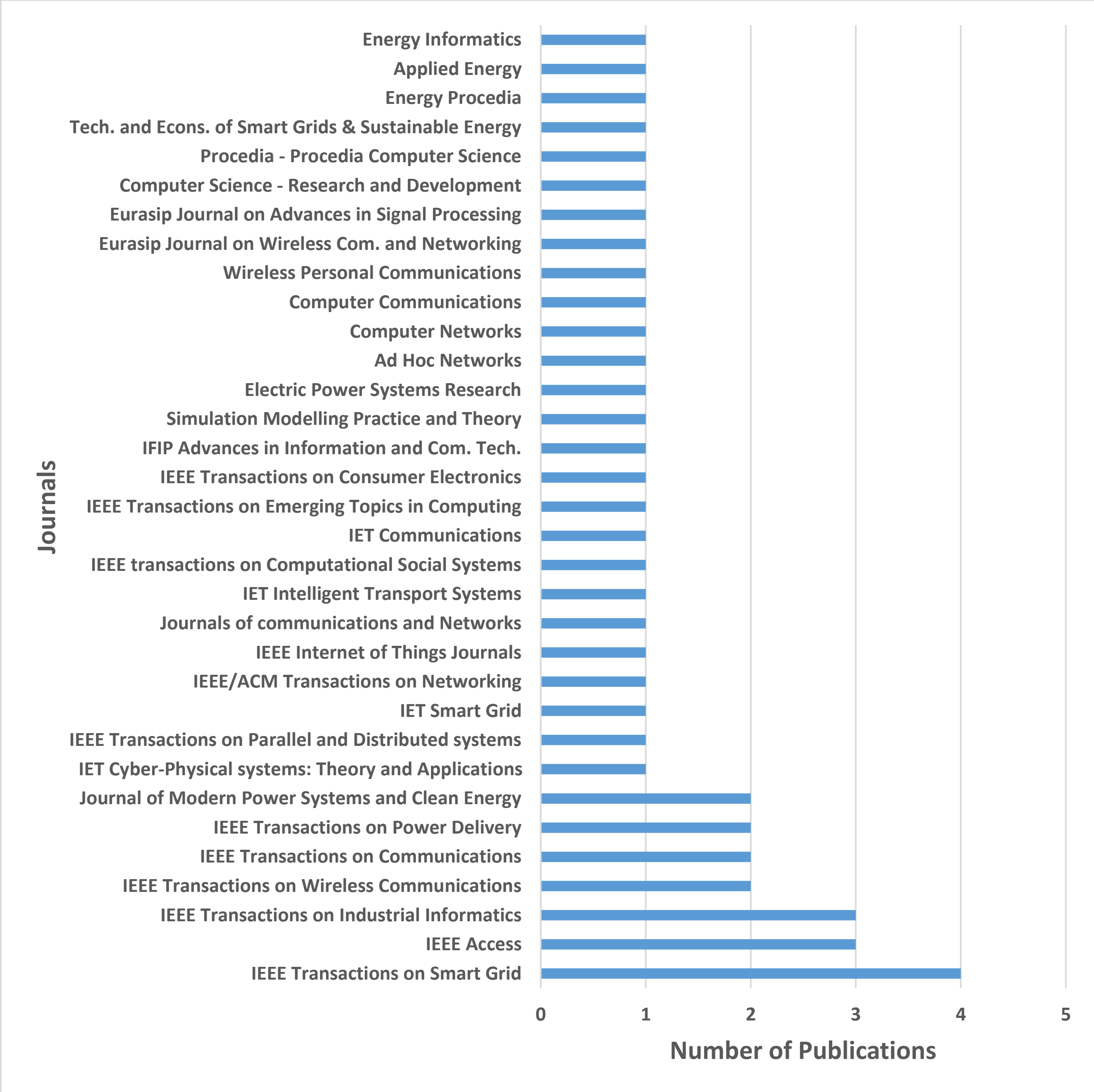

Figure 1. Percentage of journal articles selected per database.

1.2. Relevant Review Articles

Smart grid revolution is not possible without the advanced metering infrastructure (AMI). For AMI to be successfully implemented, a two-way communication scheme is a basic requirement. Several review works have been carried out to determine the veracity of the communication network. A comprehensive review of wireless communication technologies for smart grid applications was the focus of the review in [9]. The comparison of communication technologies for AMI applications including AMI network structures reviewed in [10] was based on privacy and security, cost of deployment, reliability and communication coverage, while the comparison of commonly deployed wired and wireless communication technologies in customer premises network was carried out in [11]. Adaptability to home area networks, protocol, coverage range and data rate were the elements of comparison. [12] reviewed energy policies for the implementation of smart metering infrastructures in Spain, Europe and the rest of the word. State of the art of communication technologies for smart grid applications was reviewed in [13]. A special focus was given to telecommunication technologies for smart metering applications and monitoring. Key elements of a smart metering system as well as a compilation of mostly deployed technologies together with their main features were the objectives of the review by [14].

Varying uses of metering data in a smart grid following privacy policies were reviewed in [15]. While [16] conducted a review on data analytics in retail markets, load forecasting applications, intrusion detection, demand response management and segmentation of consumers were also considered in the review work. Tools applicable in smart grid research, simulators for power system and communication systems simulations were reviewed by [5]. Besides, classification and comparison of communication network simulators were carried out in [7]. The work intends to aid researchers in selecting appropriate tools that will give reliable conclusions while using simulations to evaluate performances of designs before realistic implementation.

This review seeks to provide a comprehensive report on communication networks used for smart metering applications in the AMI network, and common simulators employed for their evaluation in the literature. Specific attention is given to the critical issues raised in different kinds of literature published in the immediate past decade. The paper is arranged as follows: Section II introduces the concept of smart grid, its basic components and also give an overview of the communications networks available for smart metering applications; section III discusses major network simulation software packages. Critical issues of simulation of a communication network for smart metering applications are raised and discussed in section IV. The findings of the research are analysed and discussed in section V while the conclusion of the review is given in section VI.

2. Smart Grid Concept and Smart Metering

The traditional electric power grid, an enormous interconnection of infrastructure for conveying electricity from generating plants to points of consumption, does not have the capabilities of the smart grid. The smart grid (SG) incorporates advanced two-way communications and computing capabilities [15] [17].

To monitor, analyse, control and communicate with the energy delivery chain, the smart meter is required. It helps enhance efficiency, optimization of energy consumption, lower cost and increase transparency and dependability of the energy supply chain [18]. The application of advancement in digital technology to systems and devices has enabled the smart grid to achieve its current status.

The grid will become smarter as new technology emerges for applications and devices closely related to the smart grid. New devices and systems allow for advanced sensing and control of grid elements, extensive information sharing and communication, more powerful computing, and better control. Declining costs of digital technology is another driver of the advancement being witnessed. The trend in digital networks will eventually result in greater levels of information exchange between utilities and their customers. The emergence of other infrastructures such as smart buildings and cities, transportation, and telecommunications can only be on the increase as the smart grid develops [19]. Figure 2 shows various units connected to and controlled by the smart grid. Data from each of the units are shared via the communication network with the aid of smart meters.

2.1. Major Components of a Smart Grid

The smart grid major components include the advanced metering infrastructure (AMI), the communication infrastructure and the control unit.

Automated meter reading (AMR) is equipped with one-way communication systems. However, the modern smart grid is well furnished with advanced metering infrastructure (AMI), making it capable of effective monitoring, measurement and control of consumer power consumption in real-time. Electricity monitoring and control is enabled by AMI. It also promotes applications that include management of outages in the network, energy billing, pricing, detection of faults, forecasting and demand response, thereby encouraging consumer participation in energy optimization [20].

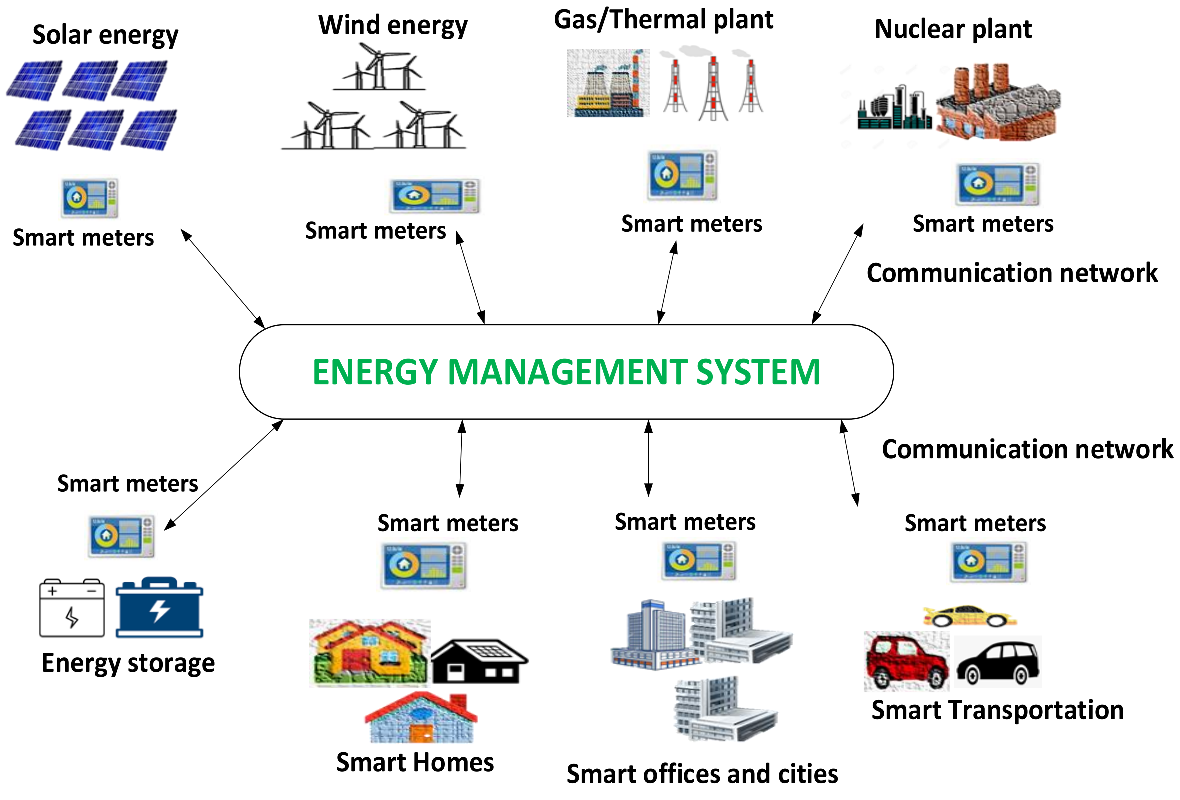

Figure 2. Concept of the Smart Grid applications

Smart grid communication infrastructure fundamentally has three networks frames: Home Area Network (HAN)/Building Area Network (BAN), Neighbourhood Area Network (NAN)/ Field Area Network (FAN), and Wide Area Network (WAN) [20, 25].

The performance of the three smart grid communication infrastructure is compared in Table 1 based on their data rate, coverage area, the technology used, and application domain. All smart grid components and communication infrastructure, including renewable energy sources, transmission, distribution, control, and monitoring it is built on WAN.

Table 1. Comparison of the smart grid communication infrastructure [20, 25, 1]

	Data Rate	Coverage Range	Implementation Technologies	Typical Applications
HAN	1 – 100kbps	1-100m	ZigBee, Wi-Fi, Bluetooth, PLC, Ethernet.	Home automation, building automation
NAN	100kbps – 10Mbps	100m – 10km	ZigBee mesh networks, Wi-Fi mesh networks, PLC, WiMAX, Cellular, Digital Subscriber Line, and Coaxial Cable	Smart metering, demand response and distribution automation
WAN	10Mbps – 1Gbps	10 – 100km	Optical Fibre, Cellular, WiMAX and Satellite communications	Wide-area control, monitoring and protection.

The harmonious interaction of the different components of the SG is made achievable by the control centre. The smart grid control centre or data management system (DMS) handles the collection and saving of the metering information data for the eventual purpose of processing and analysis. Besides, the control centre handles the consumer applications, system for weather forecasting, load management, control and geographic information systems applications. With the availability of information technology infrastructure and intelligent electronic devices (IEDs), smart grid control has evolved to a more sophisticated system capable of taking instructions, make decisions and managing the whole system while in operation [21].

Measurement data generated in the smart grid network while in operation is invaluable to energy companies. With such data, it is possible to make a myriad of predictions such as availability of energy, the likelihood of power failures, and forecasts of customers' behaviour or pattern of consumption with the aid of predictive analysis. This empowers energy companies to take dynamic actions instead of responding to events late and when only corrective actions can be taken after the damage has been done.

The smart meter is the core device of advanced metering infrastructure (AMI) [22, [22]. Its functions include observation of home appliances status and usage of power, collection of power usage information, and transmitting the same through the communication network to the management system, and in-home energy display [23]. It supports the tariff system based on time, this includes peak and off-peak pricing, operation-time, and pricing system in real-time [24, 9]. Besides, additional capabilities concerning the infrastructure such as anticipation and control of the load, and observation and monitoring of the quality of power can be provided.

2.2. Overview of Communication Technology for Smart Metering Applications

These are the wireless and wireline communication technologies for smart metering applications and they have varying coverage areas, bandwidth and energy consumption constraint. Table 2 summarises the available communication network commonly deployed for smart metering applications.

a. Cellular Technologies: GSM/GPRS/3G-4G/LTE

Taking the coverage area into consideration, the cellular network is among the most appropriate technologies for smart metering applications when the link for communication spans between the data aggregator and the energy company's server. Operating at 900 and 1800 MHz bands, the global system for mobile communications (GSM) and general packet radio service (GPRS) are good examples of a cellular network with existing network infrastructures, making them attractive to utilities for smart metering applications [23]. Network operators now provide SIM cards meant to be used with data modem devices of GSM, they came with provisions for data only services and offering tariff packages meant for such usage [24];[25].

Table 2. Summary of some common communication technology in smart metering applications.

Technology		Data Rate	Frequency Bands	Range
Wireless				
Cellular	3G-4G	60–240 kbps	824–894 MHz, 1900 MHz	about 50 km
	GSM	≥ 14.4 kbps.	900–1800 MHz	1–10 km
	GPRS	≥ 170 kbps.	900–1800 MHz	1–10 km
IEEE 802.15 Group	ZigBee 6LoWPAN	20-250 kbps	868 MHz/915 MHz/2.4 GHz	10-1000m
	Bluetooth	721 kbps	2.4–2.4835 GHz	1-100m
IEEE 802.11 Group	Wi-Fi	≥ 54 Mbps.	2.4 GHz/5.8GHz	1-100m
	Enhanced Wi-Fi	≥ 54 Mbps.	2.4 GHz	1-100m
	IEEE 802.11 n	≥ 600 Mbps.	2.4 GHz	1-100m
IEEE 802.16	WiMAX	70 Mbps	1.8–3.65 GHz	50 km
Satellite	Satellite Internet	1 Mbps	1-40 GHz	100–6000 km
Wired				
NB-PLC	PRIME G3-PLC	up to 500 kbps	3–500 kHz	Several km
BB-PLC	HD-PLC	Up to several hundred Mbps	1.8–250 MHz	Several km
DSL	ADSL	800 kbps Upstream and 8Mbps Downstream	25 kHz-1 MHz	5 km
	HDSL	2 Mbps		3.6 km
	VHDSL	15-100 Mbps		1.5 km

2.2.1. Wireless Technologies

b. IEEE 802.15 Group

i. ZigBee

The media access control (MAC) layer and the physical (PHY) layer of ZigBee a wireless technology is established on the IEEE 802.15.4 standard. Operating in the 2.4 GHz band and spanning between 10 and 100m is preferred in smart metering applications for information handling encompassing the smart meter and the data aggregator units, instead of handling information sharing in the link between the data aggregator and the utility server [22]. ZigBee is suitable for wireless control and monitoring. It performed excellently when the requirement of the application for optimum operations are low data rates and low power utilisation [26];[25].

In [27], a smart meter interfaced with ZigBee was designed and applied for Wireless Sensor Home Area Network. [28] analyses the effectiveness of ZigBee considering throughput, a ratio of packet delivery, delay average, and average energy used in different three-dimensional environments of a smart grid. The simulation results based on QualNet, reveals that IEEE 802.15.4 built on ZigBee is most appropriate for applications in a smart grid that require low reliability.

ii. 6LoWPAN

The IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) technology was designed to define mechanisms for header compression for sending packets of IPv6 to and from, networks based on IEEE 802.15. The basic concept of the internet of things (IoT) could be realised by 6LoWPAN since all devices, including sensors and actuators, can be assigned with an IP address. In [29], a NAN architecture built on 6LoWPAN for the operation of all the smart electric meters in the coverage area of NAN was designed. The system is to sustain the requirements for Quality of Service (QoS) of the various applications in the NANs coverage area.

An analysis of the effectiveness of a radio mesh network built on 6LoWPAN was carried out using the OPNET network modelling package for simulation. The potential of merging sensory devices of the modern smart meter with application logic using a technology built on 6LoWPAN over an event-driven Internet infrastructure was investigated in [30]. An experimental setup was used to monitor power quality, and initial results indicate that the smart metering infrastructure if combined with appropriate ICT tools, is capable of offering ingenious enhanced services. A cluster-tree based 6LoWPAN network for the NAN applications was investigated in [31]. To increase the throughput and reduce the latency of packet in the NAN, a simulation model built in OPNET was developed to analyse the effectiveness of demand management and data communications of a smart meter in a NAN. Results from the simulations carried out revealed that the performance of a NAN can be notably improved by using the staggered link design approach combined with a technique of aggregation of packet employed in the research.

iii. Bluetooth

Bluetooth is a wireless communication technology that was built on the IEEE 802.15.1 standard. It is an open wireless protocol designed to provide personal area networks (PANs). Bluetooth low energy (BLE) is an advancement in Bluetooth technology. The technology is capable of exchanging data within short distances from either fixed or mobile devices. Originally, the idea was to create an alternative wireless data link against the wireline data cables [32]. Even though Bluetooth technology has a low power consumption capability, its deployment in smart metering applications is very limited because of the short coverage area. [33].

c. IEEE 802.11 Group (Wi-Fi/Enhanced Wi-Fi/ IEEE.802.11n)

The wireless standards allow devices on the network to communicate with each other wirelessly. There are different standards of wireless technology, 802.11a which supports a bandwidth of up to 54 Mbps and signals in a regulated frequency spectrum of 2.4 GHz and 5 GHz. The 802.11b supports a maximum bandwidth of 11Mbps and signals in the unregulated frequency of 2.4 GHz. The 802.11g combines the good attributes of 802.11a and 802.11b, which supports the bandwidth up to 54 Mbps and a frequency of 2.4 GHz. The 802.11n is the newest of all and is designed to support multiple wireless signals and antennas. It supports a maximum of 100 Mbps of data rate.

d. IEEE 802.16 (WiMAX)

The Worldwide Inter-operability for Microwave Access (WiMAX) was built on IEEE 802.16 standard. It is broadband access wireless technology. It can support a speed of up to 70 Mbit/s bi-directional for transmission and capable of either a network topology that is point-to-point or point-to-multi-point [34]; [35]. WiMAX is suitable for joining the back-haul energy company system with data aggregators in a smart grid network. It is regarded many times as an alternative to cellular technologies such as GSM and CDMA. A possible drawback of this technology is that its bandwidth has to be shared among other users.

[34] presented a work that analyses the performance of a smart grid with the communication layer built on WiMAX technology. OPNET simulation software package was used to simulate the application traffic. The MAC and PHY layers of the WiMAX standard form the basis on which a wireless network architecture presented by [36] was built. The design

was meant to serve smart grid divers metering applications and the smart meters connected to the network. The analysis of the size of the cell, models of terrain, the capacity of the channel, packet delay and losses, and transmission power were carried out with the aid of OPNET simulation models. Simulation results of their research support the applicability of WiMAX for smart metering applications.

e. Long-range (LoRa)/Long Range Wide Area Network (LoRaWAN)

Long Range (LoRa) is the physical layer that generates the long-range communication link while Long Range Wide Area Network (LoRaWAN) is the communication protocol and system architecture for the network. LoRa operates on the unlicensed radio frequency bands, it enables long-range transmissions with low power consumption [37]. The application of LoRa and LoRaWAN is a wireless communication standard for smart devices is seeing consistent growth in the last few years. Attributes such as long-range, low power and low cost are the main reasons why this technology is becoming more important. LoRa has found applications in smart metering devices that require low data rates and long-range communication [38]. [39] successfully use LoRa technology for transmission of data from smart meters to utility servers. In Slabicki *et al*., (2018), OMNeT++ was used for LoRa simulation to study the adaptive configuration of LoRa when deployed in handling dense internet of things (IoT). To improve system security, an improved session key management was employed by [41] to secure the meter reading system based on LoRa technology. In similar research, [42] used a symmetric cryptography method for the protection of end-to-end communication established between the substation automation system and smart meters based on LoRa technology. The evaluation of the method used shows the possibility of practical implementation in real-world scenarios.

2.2.2. Wireline Technologies

a. NB-PLC

The transmission of data is done through a narrow band of frequency and at a low bit rate in Narrowband PLC (NB-PLC) technology. Technologies built on NB-PLC were designed for smart grid applications and automation in buildings and homes. For instance, in an earlier work conducted by [43], OMNET++ was used to implement a G3-PLC cross-platform simulator. In [44], PLC links were employed to evaluate the time of transmission between smart meters and local aggregators for different sizes of data. OPNET simulator was used in the assessment of infrastructure for smart metering applications built on PLC. The study engages several smart meters. By varying the size of smart meters and concentrators connected to the PLC medium, bandwidth limitations were investigated. To confirm data delivery by meters to the concentrators, a successful transmission rate within a specified time was also evaluated.

b. BB-PLC

Operating at a frequency band between 2 and 30 MHz and up to hundreds of Mbps data rates, Broadband PLC (BB-PLC) was introduced to be able to provide applications for internet access. The initial concept was to apply BB-PLC for the network applications around the home and also for last-mile communication. Like the NB-PLC, procurement of new infrastructure is not needed. BB-PLC has been deployed in smart homes, but, extensive use in the smart metering application is yet to be seen.

c. Digital Subscriber Line (DSL)

The DSL operates at a frequency range of 25 kHz– to 1 MHz and covers a range between 1.5 km - 5 km. It utilises the old phone lines for the transmission of data and has been used to offer smart metering applications. It is capable of providing a backhaul for the transmission of smart grid data from residential buildings to energy companies. DSL infrastructure already exists, making it a low-cost solution. A drawback of this technology lies in the fact that subscriber distance from utilities is proportional to its throughput.

2.3. Data Quality Challenges in Smart Meters

The energy data obtained from smart meters is used for analysis such as billing. Thus, for operational effectiveness, the quality of such data must be maintained. Data quality directly affects the operation and readiness of an electric power supply. The security, quality, and reliability of the electric power system lean heavily on the integrity of its data. As a result, data quality has been considered a prominent issue in the smart grid[45]. Data derivable from the smart grid are mainly categorized into three: measurement data, business data, and external data. Measurement data are data from smart meters whereas data from the consumers of electricity are business data. An example of external data is weather data [46].

Indices of low-quality data were reported in a study conducted by [47]: Data is regarded as missing data of low quality when data recording is missing for some time. The missing data could have serious effects on research outputs because relying on such incomplete data will eventually lead to a wrong conclusion. Another factor is the zero record periods; a situation where data is available but recorded as zeros [46]. To understand a record of this kind becomes very difficult, for one wonders whether the said records were altogether missing, sent, or were not recorded in the first place.

When values that are taken over a particular range of time are outrageously large or low as compared to the mean value of data recorded, they are termed out-of-range.

Error from measurement may be a result of a failure in communication, outages of equipment, data loss, and interruptions in power source among others. Other indices include unreliable data points which could come via premeditated cyber-attacks on the smart grid infrastructure. Attacks of this nature could involve false data injection via fake data-points. Unreliable data-points could result in the manipulation of the overall operations of the smart grid leading to operation failure. Also, when data that are time-stamped arrive out of the expected time, the quality of the data may be compromised. Delay experienced by the data could be a result of the communication network deployed for data transmission.

3. Simulation of the Communication Infrastructure

In the past and recent years, several simulation software was developed and utilised to assess the performance of the communication network infrastructures of smart metering systems. It is, therefore, necessary to take a deep look at some of the simulation tools in this regard. In communication network simulations, researchers seek to improve system performance (such as delays and throughput), reduce expenditures, and increase confidence that performance objectives are realised before the purchase or lease of equipment. Bottleneck recognition and pinpoint before the implementation of the system and reduction in development time for the system are further reasons why communication network simulation is embarked upon [48].

3.1. Simulation Software

An overview of the most common network simulators used for modelling the communication infrastructure for automated metering infrastructure is presented.

3.1.1. Network Simulator 2 (NS-2) and Network Simulator 3 (NS-3)

Network Simulator version 2 (NS-2) is an object-oriented discrete-event simulator. It has gained wide acceptance and uses among researchers today. It was developed in 1995 at Lawrence Berkeley Laboratory, University of California, Berkeley. It gives support for TCP simulation, routing, and multicast protocols over wireline and wireless networks. C++ is the programming language and for interface configuration and command OTcl was used. It is suitable for both distributed and parallel simulations. NS-2, though an open-source software, does not support the vivid graphical presentation of simulation output data.

Network Simulator version 3 (NS-3) is also an open-sourced discrete-event network simulator. Started in 2006 and written in C++, the simulator is fashioned as a library and capable of either statistical or dynamical link with a C++ programme. The commencement of simulation and its topology is defined by these libraries. Users of the simulation software package can setup simulations of communication networks. Analysis and simulations of traffic models, generators, TCP/IP protocols and the likes, channels such as Wi-Fi, and devices can be carried out with a simulator.

3.1.2. Optimized Network Engineering Tool (OPNET)

OPNET was developed at the Massachusetts Institute of Technology (MIT), as commercial software that gives a development environment that is comprehensive for aiding modelling of distributed systems and data communication networks. Simulation scenarios such as change of parameter after an elapsed time set, and update of topology, are often implemented by writing C or C++ code. With an easily understandable model library, a modular development, extensive modelling detail, an interactive GUI, and adaptable simulations results from the exhibition, OPNET stands out as advantageous over many other simulators. However, OPNET parameter categorization is not very transparent and the software package is very expensive. A simulation of 6LoWPAN based radio mesh network was designed to supply smart meters in a NAN network [29].

3.1.3. Objective Modular Network Testbed in C++ (OMNET++)

OMNET++ is a component-based, modular, and open-architecture discrete event simulator framework most commonly employed for the simulation of computer networks. More so, it has found applications in queuing network simulations among others [49]. Written in C++, the class library of OMNET++ has a simulation kernel, and for random generation of numbers, collection of statistics, and discovery of topology it uses the utility classes. There are two types of OMNET++ modules: the simple and compound modules. The algorithm definition is done through simple modules. They are active components of the simulator in which the occurrence of events takes place and the manners of the model, creation of events and response on events is defined. To form a compound module, a group of simple modules which are interacting together is required. The power of OMNET++ includes its GUI, object examiners that allow for zooming into the component level and the ability to display the state of each component during the simulation. Its modular architecture and abstraction, configurability, and comprehensive modules implementation and protocols are added advantages of the simulator under discussion. However, OMNET++ could be a bit slow due to its long simulation run and high memory consumption.

3.2. Comparative Analysis of Network Simulation Software Packages

Presented in Table 3 are the network simulators that are commonly used in designing AMIs. The comparison is based on their availability, the network protocol supported and the operating system supported among others.

Table 3. General comparison of simulation software packages for network simulation

Simulator	**Availability**	**Language**	**Network protocol supported**	**Current Version**	**Date of release**	**Operating System**
NS-2	Open-source	C++ and Python	TCP/IP, Multicast routing, TCP protocols over wired and wireless networks.	ns-2.35	Nov. 4 2011.	Linux, FreeBSD, macOS
NS-3	Open-source	C++	TCP/IP, Multicast routing, TCP protocols over wired and wireless networks.	Ns-3.30	Aug. 21 2019	Linux, FreeBSD, macOS
OPNET	Commercial	C and C++	ATM, TCP, Fibre distributed data interface (FDDI), IP, Ethernet, Frame Relay, 802.11, and support for wireless	Version 18.8.0	Feb. 4 2019	Linux and Windows
OMNeT++	Open-source	C++	Wireless networks	version 5.5.1	Jun. 13 2019	Linux, macOS, Windows

4. Critical Issues of Communication Network Simulation for Smart Metering Applications in Literature

In this section, a breakdown of major issues raised in the 45 journal articles from the IEEE Explore, Science Direct, Springer Link and ACM digital databases is presented. Three major issues were addressed by different authors using different methods. The major issues discussed in the reviewed papers are on: security of smart meters and the corresponding communication networks, quality of service obtainable from the operation of the smart grid and, optimal cost achievement in the smart grid operation.

4.1. Security of Smart Meters and Communication Network

Generally, attacks on AMI seek to compromise the confidentiality, integrity and availability of power and associated data [20]. If the right steps are not taken, the malicious attacks could result in power theft, loss of privacy and denial or disruption of power supply. Presented in Table 4 are some pieces of literature with a specific focus on the security of smart meters and the communication networks that provide metering applications. To effectively operate the smart grid, the issue of security of the entire network take a front stage in designers' considerations. A cyberattack could be mitigated with the careful design of the communication network supporting the grid. Methods highlighted in Table 4 have been successfully employed by the authors in the works referenced. The issues to tackle and the corresponding constraints are presented in the first and second column respectively, also presented are the communication networks employed as well as the simulation tools used.

4.1.1. Intrusion Detection System (IDS)

Unauthorised access to a network, data or information is regarded as an intrusion. Such attacks could render legitimate users stranded and make the system unresponsive to them. Therefore, an IDS seeks to identify and single out such an attack for stoppage and prevention of loss it could cause for the entire system for both the utility and consumers alike. For effective intrusion detection in the reviewed papers, [50] used two stages; an algorithm based on support vector machine (SVM) was used to detect intrusion in smart meters, while in the second stage, attack route generation was handled with temporal failure propagation graph (TFPG). The pattern recognition algorithm proposed, is employed to determine the similarity index between predefined cyber-attack and unexpected events. The high similarity index is an indication that a smart meter is being attacked. NS-3 simulation results reveal that the test scenarios were properly recognised by the intrusion detection unit. Meter data tampering algorithm was used for energy theft detection and mitigation in [51]. In [52] distributed Hash Trees (DHTs) was used to reduce the space requirement of a certificate revocation list (CRL) in smart meter operation while in [53] a scheme to ensure meter data privacy was employed considering smart meters, electricity utilities and trustful anchors. In [54] analysis of energy theft via cyber-attack is first carried out then, a detection method based on partially observable Markov decision process and Bollinger bands were used. To enhance the detection accuracy, a belief state reduction based adaptive dynamic programming, which is a probabilistic approach was employed. Simulations were carried out using the MATLAB software package.

4.1.2. Data and Information Protection

Protecting information and meter data during collection, while in transit or when stored is a significant step that is not taken lightly in the implementation of the smart grid. Smart meter data and the information they carried are used for control, monitoring and billing purposes. Attackers who are intent in deriving undue advantages from such resources seek to tamper with them. In pieces of literature, many authors have given methods to ensure the anonymity of consumers and protect information related to electric power systems. In [55] electric vehicle to grid (EV2G) communication was enabled using smart meters. The idea of distributed CRL management was introduced to achieve EV2G secure exchange of communication. Attack simulations have been conducted on a realistic electrical grid topology in [56]. The simulated network consisted of smart meters, a power plant and a utility server. In [57] differential privacy was applied to real smart metering consumption data. [58] presented a Protocol that decentralizes the certificate of authority (using split certification key and distribution key) and Hop-by-hop authentication was used to prevent a single point failure and minimise denial of service problem respectively. The method was able to transmit metering data safely and remotely using PLC. In [59] Laplace Distribution base time perturbation was employed in transmitting data from smart meters to utility servers and also to ensure protection while in storage. According to the work carried out by [60], a cluster of smart meters with a likelihood of sharing information within the AMI network is formed to impede delay, conserve bandwidth and storage. Therefore, the certificate revocation list will be local to the group. Two grouping algorithms: one based on routes between smart meters and the gateway using a bottom-up approach assuming the use of the shortest path and the other, considering the minimum spanning tree of the network uses a top-down approach for the grouping. The approach was implemented using NS-3 simulation software that runs a version of IEEE802.11s. The results established that the method achieves stability, comparing the size of the certificate revocation list and the size of signatures generated by certification authorities while ensuring the privacy of the communication network.

Table 4. Summary of the pieces of literature on the security of smart meters and Communication network

Critical Issues Considered	Constraint	Communication Technology	Simulation Tool/Method	References
Intrusion Detection for Cybersecurity of Smart Meters	Reduced vulnerability under malicious attack	IEEE 802.15.4	NS-3	[50]
Detection of energy theft cyber-attack	Reduced vulnerability under malicious attack	ZigBee, Bluetooth, WiMAX and LTE.	MATLAB	[54]
Remote meter reading security requirements	Preventing certification key exposure	PLC	-	[58]
Security of communications between smart meters	Reduction in delay, bandwidth and storage conservation	IEEE 802.11s	NS-3	[60]
Maintaining the privacy of the user	Allowing state estimation access	IEEE 802.11s wireless mesh standard	NS-3	[61]
Simultaneous detection of meter manipulation and bypassing	Time-efficient and detection accuracy	PLC and Wi-Fi are applicable		[62]
Security of smart meter data for Electric Vehicle (EV) Charging	Secure and efficient EV communications	IEEE 802.11s, IEEE 802.11p and LTE	NS-3	[55]
Security against distributed denial of service (DDoS)	Large-scale DDoS	wireless network	$NeSSi^2$	[56]
Differential privacy on real smart metering data	Large dataset required		MATLAB	[57]
Meter data security	CRL distribution and storage cost effectiveness	IEEE 802.11s	NS-3	[52]
Meter data privacy	Consumer data protection	IEEE802.11ah	NS-3	[53]

[61] employed vectors for obscurity which are separated among multiple gateways to reduce vulnerability. A partial vector for obfuscation is sent from each gateway handling sets of smart meters to other gateways. If the obfuscation vector for a gateway is compromised, the attacker can only have access to that section of the grid and the damage will be limited. Advanced encryption standard (AES) was employed for hiding while elliptic curve cryptography (ECC) gave authentication to the obfuscation values dispatched within the AMI network. The implementation of the proposed approach was carried out in NS-3. Simulation results revealed overheads on both meters and communication network is insignificant. Intermediate monitor meter (IMM)-based power distribution was analysed in [62]. The NAN was broken into the smallest unit networks forming segments, to detect non-technical loss (NTL). The intermediate monitor meter power distribution network model was used. A timely and 95% detection accuracy was achieved via simulations.

4.2. Operational Cost and Energy Usage Optimization

Huge data transmission is involved in an effective smart grid. Efficient collection and communication of data in a smart grid for monitoring, control and billing purposes could place the financial burden on both the utilities and the consumers. However, careful design of the network can reduce this challenge. Table 5 illustrates critical issues to address, communication networks that have been deployed and methods that have been simulated to achieve cost-effective operation of the smart grid.

A routing mechanism that embraces minimization of energy consumption and elongation of the lifetime of the network is appropriate to cut both the deployment and operational cost of smart meters in the AMI network. Reviewed research papers with a specific interest in the said area are presented in this section. A routing mechanism that is both energy and congestion aware for smart meters network was proposed by [63]. The technique, an adaptive selection of parent nodes that take into considerations the remaining energy of surrounding nodes and queue utilization was utilized. Cooja simulation software 3.0 was used to evaluate the scheme proposed and the results indicate reduced average power consumption and an improved packet delivery ratio. Cost minimization for meter data collection (CMM) problem was formulated by [64] to resolve the issues of channel selection and scheduling. Two power pricing model were employed: linear pricing (a mixed-integer linear programming problem) and nonlinear pricing (a nonconvex mixed-integer nonlinear programming problem) models and three-layer network model: home area network, neighbourhood area network and wide area network were also employed. In [65] an optimization framework to determine the extent needed for data aggregation was designed for a multi-level data concentrator unit topology. Then, an algorithm for managing the volume of AMI data traffic was proposed which doubles in ensuring QoS in a situation of congestion. NS-3 simulator was used for evaluating different network congestion for different scenarios of data traffic. The results showed that the approach can handle latencies during congestion in AMI networks.

In [19] data traffic in the AMI are grouped as either random or scheduled, a soft MAC protocol (SMAC) has an alternate operational mode given the type of data to be collected. SDMAC is used to collect scheduled data while OTRA-THS is employed for random data collection. The changes in mode translate to a reduction in latency due to data collection and control overheads. As a result of the said reduction, more meters can be served by a base station. This reduces the number of base stations required for data transmission and hence the required bandwidth. The overall capital and operational cost will be reduced. The proposed approach was simulated and analysed using a Markov chain. The result demonstrated the capability to reduce both capital and operational expenditure.

The communication connection that can experience failure in a broken network, communication topologies and questions related to access networks were first examined in [66]. Then, the proposed solution was evaluated and optimised to maintain a robust and reliable communication architecture while still minimising the deployment cost of the communication network. Simulation results show that the reliability of a single communication falls with the number of redundancies. [67] and [68] treated household separately and a forecast for 24 hours was done using SVM and neural network-based methods. The reasonable forecast was achieved through the technique applied. Also, the demands of consumers with and without smart meters were handled using a hybrid demand modelling technique in [69].

4.3. Quality of Service (QoS)

The efficiency and continued reliability of the smart grid rest so much with the quality of service integrated into its communication infrastructures, automated control, metering technologies and energy management techniques. Various issues critical to achieving QoS of the grid are highlighted in Tables 6 and 7. Issues ranging from mitigating impulsive noise, handling congestion and traffic in the network data collection and improving packet delivery ratio.

Table 5. Summary of works of literature on specific cost-driven constraint

Critical Issues Considered	Constraint	Communication Technology	Simulation Tool/Method	References
Energy usage minimization and prolong a network lifetime	Low energy usage and low processing power	IEEE 802.15.4g, IEEE 802.15.4e, and IEEE 802.11 standards	Cooja simulation software 3.0	[63]
Meter data collection	The optimal overall cost for both power and communication	Secondary spectrum in cellular networks	-	[64]
Data congestion and traffic.	Zero investment in infrastructures	PLC and low power wireless network are applicable	NS-3 simulator	[65]
Latency reduction and control overhead in smart meter data collection	Reduction in the capital and operational expenditure.	3G Cellular	Markov chain	[19]
Reliability and resilience of the access network in AMI	Minimization of communication deployment cost	A mesh-based NAN	-	[66]

4.3.1. Network Reliability

For AMI, low bandwidth and high latency is a requirement for smooth operation. The- different aspect reliability encompasses to meet the need of unfettered AMI operations includes the provision of redundant communication paths, approximated latency of the network, message loss probability and jitters. In the reviewed papers, several methods have been employed to ensure network reliability which includes:

Reinforcement learning algorithms were applied in [70] to mitigate the latency of AMI communications in Low power wide area networks (LPWANs). The analysis of the effects of a collision on different frequency access schemes was carried out. A new communication framework called Adaptive Forwarding Area Routing (AFAR) was proposed by [71] for smart grid communication. The said communication framework mitigate delay in smart meter communication in the smart grid. To minimise the network traffic associated with proactive and reactive, on-demand protocols was used in [72], the proposed application layer approach was employed. Two smart polling algorithms proposed are the routing protocol for low-power and lossy networks (RPLL) and the lightweight on-demand Ad hoc distance-vector routing (LOADng). Upon a polling request from the data concentrator, a query for search path is broadcasted to the whole network to identify a feasible route which is delivered using relay nodes to the specific smart meter via the MAC. Smart meter response is similarly transmitted to the data concentration unit in the uplink direction. Simulations were carried out using OMNET++. To enable AMI communications, a two-level frequency hop (FH) sequence set was proposed in the network design by [73]. For data traffic, the proposed two-level sequence set used a general Poisson model, in terms of error probability of FH based AMI communication network, average bit rate was used to determine the QoS metrics. Results show the method can give QoS to power consumers [74]. Based on the interference limitations, smart meters' best configuration was calculated for each smart meter in the network by spectrum engineering advanced Monte Carlo analysis tool (SEAMCAT), a software tool formed on the Monte-Carlos simulation method. The proposed scheme uses the TV band spectrum. The simulation results indicate that smart meters and digital television can simultaneously operate without negative effects on other wireless networks.

Attenuation, delay spread, and coherence bandwidth were taken into consideration while analysing the channel response [75]. To achieve monitoring, a support vector machine was used in research conducted by [76] to segregate power disturbance from regular values. In a pilot project carried out in Spain, current communication technology suitability for

AMI applications was evaluated by [77]. [78] used smart meter information and outage area identification technique to determine the impact of communication performance of AMI on outage management. Application of smart meters data was used by [79] for distribution network observation and monitoring. A new simulation framework was proposed for achieving a detailed large-scale RF-mesh AMI system in [80].

4.3.2. Impulsive Noise Mitigation

Voltage variation and spike, short-duration irregular pulses and intermittent occurrence of energy spikes all describe impulsive noise which greatly degrades signal quality and could reduce significantly the QoS of a system. Mitigating impulsive noise has seen much attention from several authors, and the methods used in the papers reviewed are presented here.

[81] proposed a Polling procedure for AMR and used neighbour relay polling and clustered polling in their research. Simulation results reveal that using smaller packets before the transmission will reduce significantly the effects of impulsive noise in the AMR system. The technique of blanking/clipping for impulsive noise mitigation in a narrowband OFDM PLC system was used in [82]. The impulsive noise was simulated using Middleton’s class A model. The PLC bit error rate (BER) performance was simulated in MATLAB. The results show that the BER of the communication network was slightly improved with the method used. Noises and signal attenuations were modelled using MATLAB software package while Network topology and related processes were modelled using OMNET++ by [83]. The output of the MATLAB simulations was applied as the input for the network model. The communication layer stack was completed using the device language message specification (DLMS). Simulation results show that the required time to reading the meters increase notably in the presence of impulsive noise.

Table 6. Summary of literature on QoS of network reliability and Impulsive noise mitigation

Critical Issues Considered	Constraint	Communication Technology	Simulation Tool/Method	References
Acquisition of data and automatic meter reading	Minimization of Network traffic	PLC	OMNET++	[72]
Network security and Quality of services (QoS)	Malicious attacks on the network	ZigBee, Bluetooth, WiMAX and LTE.	-	[73]
Optimization of data transmission	Minimization of interference to the digital television system and SMs	TV white space	Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT)	[74]
Data collection delay and throughput	Impulsive noise interference mitigation	PLC	-	[81]
Feasibility of using PLC infrastructure for data communication	Impulsive noise interference mitigation	PLC	Middleton’s class A model and MATLAB	[82]
Data communication	Impulsive noise, channel attenuation and multi-path effects	PLC_PRIME	OMNET++ and MATLAB	[83]
Reduction of latency in AMI communication	LoRaWAN AMI backhaul	LoRaWAN	MATLAB	[70]
Performance of NB-PLC for metering communications	Consideration for channel noise	NB-PLC		[75]

In [84] time taken to read the meters; the number of registered nodes were defined as performance key indicators for the performance of the communication network. MATLAB was used to implement the physical layer and the mode of communication while OMNET++ event simulation software was employed for the simulation of the upper layer with its logical effects. The results show that the process of registration impact performance.

4.3.3. Data Collection Technique

Smart meters in AMI can achieve two-way communication of data and power system sensitive information for system control and billing processes. A few methods employed for data collection between the consumers who usually houses the smart meters and the utilities which provide the electric energy are explored in this review paper. Table 7 gives a summary of some of the methods used. [85] proposed a data collection mechanism for wireless automatic meters reading (WAMR) based on IEEE 802.11p and using public transportation buses enabled with wireless communication capability. The smart meters transmit data to the bus stop while the data were transmitted to the passing bus for onward transmission to the server of the utility. Ad-hoc on-demand distance vector (AODV) and Dynamic Source Routing (DSR) protocols were simulated using an NS-2 simulator to obtain an end-to-end delay and the ratio of delivery. Results of simulations indicate a better delivery ratio and an end-to-end delay while using DSR. In the model presented by [86] concentrators were allowed to determine communication links. A stochastic reinforcement learning algorithm was designed for the alternative probabilistic route. This is to avoid possible information interchange among meters. The approach maintains QoS under internal faults and external attack as shown by simulation results. A genetic algorithm is used to perform the optimization process when transmitting data between smart meters and data concentrator units.

Table 7. Summary of literature on QoS of data collection methods

Critical Issues Considered	Constraint	Communication Technology	Simulation Tool/Method	References
Data collection from smart meters using vehicular ad hoc networks	End to end delay reduction and high delivery ratio.	IEEE 802.11p	NS-2 Simulator	[85]
Resilient and Reliable meter data collection	Strict data transmission latency	ZigBee, Bluetooth, WiMAX and LTE.	-	[86]
Scalability and Replicability performance of PLC-PRIME	Integration of both physical and upper layer	PLC	OMNET++ and MATLAB	[84]
Outage Management system	Smart meter information-dependent	NB-PLC and BB-PLC	-	[78]

4.3.4. Latency and Throughput

Latency is a function of the time required for a packet to be transferred across a network, and it could be taken as a one-way or two-way (round) trip. Throughput describes the quality of the data being transmitted and received over the communication network within a time unit. Applications in smart grid require varying latencies and throughput to ensure QoS. Presented in Table 8 are various methods employed in the review paper for the reduction of end-to-end latency and throughput enhancement techniques.

A scheduling algorithm where all the meter nodes follow distinct paths to each gateway in a mesh network architecture that is multi-gate in nature was developed by [87]. The stability region of the network was quantified for the application of the scheduling algorithm. The simulation results show that the approach was able to achieve reduced latency upon implementation. A communication network for high-rise building was developed by [88]. The network has two parts: the backbone network and a floor network, each of which represents frequency channels used. A multi-interface management framework was both clarified and designed for the coordination of multiple interfaces operations. The network is applicable in divers smart meter management functions as the demand side management for smart grid utilization. Both experimental results and simulations carried out using OPNET software revealed a significant improvement in latency at the application layer of the backbone and floor networks.

In the work by [89], measurement was performed to get initial data to formulate objectives functions for large scale optimal solution. Then, a model to mitigate interference was developed before Non-Dominated Genetic Algorithm-II customization for design development. Evaluation of large-scale analysis was implemented using the OPNET simulation software package. According to [90], IEC 61850 standard was used to model smart home system and smart meters to bring about its integration to a power grid while striving to ensure interoperability of the different devices. Riverbed Modeler simulation evaluations were carried out using various wired and wireless communication technologies. End to end delay performance and packet delivery rate were improved by the proposed approach.

Table 8. Summary of works of literature on Quality of service under various constraints

Critical Issues Considered	Constraint	Communication Technology	Simulation Tool/Method	References
Network reliability Delay reduction	Varying outage conditions	IEEE 802.11	-	[87]
High traffic communications	Intra and inter-floor communications.	Multi-interface ZigBee building area network	OPNET	[88]
High traffic smart metering	Interference mitigation capability	ZigBee-based	OPNET	[89]
Interoperability among smart home systems and smart meters	Interaction between the microgrid and the main grid	LAN, Wi-Fi (IEEE 802.11n/g) and WiMAX.	Riverbed Modeler Simulator	[90]
Evaluation of radiofrequency mesh network performance	Large scale network	RF-Mesh	-	[91]
Timely and reliable smart meter communications	Preamble congestion	long term evolution (LTE) network	OPNET	[92]
Establishing paths with minimum end to end delay and packet loss ratio	Using the shortest distance between SM and DCU	IEEE 802.11s	OPNET	[93]
Network performance evaluation	Operate in a large geographical area	RF-mesh		[80]
Delay mitigation	Smart grid application	AFAR	OPNET	[71]

Based on computational delay the performance evaluation of a large-scale radio frequency mesh was established by [91]. Frequency hopping spread spectrum-based time-slotted ALOHA was used. Based on Markov modulated modelling, an analytic formulation for the delay was derived. Simulation results established the feasibility of the approach. [92] used an approach that employs a combination of contention and non-contention random access procedure in smart grid data communication. Access mechanism uses periodic time communication that is fixed. Although LTE was designed for human-to-human communication, the proposed model which combined several preamble signatures shows effectiveness when tested for machine-to-machine communication. The simulation results carried out using OPNET software shows improvement in latency, a smart meter packet scenario was used for the simulations. However, packet loss was not estimated in the work. Using the enhanced hybrid wireless mesh routing protocol (HWMP) routing technique, each node is chosen to ensure a minimum end to end delay and packet loss ratio. The proposed method chooses the shortest path between the smart meters and data concentrators leveraging on the relative position of the node selected and signal strength. To have more ranges for hop selection, the sector is divided into ranges. OPNET modeller simulations reveal shorter routing paths were selected by the proposed methods compared with existing methods [93].

5. Findings and Discussions

In the previous sections, some research papers were reviewed with an emphasis on smart metering applications. Considering Tables 4-7, which gives a summary of the literature on security, quality of service and optimum operating cost of the smart grid in the core domain of the review, the following points were observed:

The critical issues that attract the attention of most of the authors in the kinds of literature are the quality of service, smart meters and communication network security and optimum cost operation of the smart metering applications in the AMI network. QoS requirement has some constraints to take into account while designing the system such as interference mitigation, varying outage conditions, congestion, impulsive noise mitigation end to end delay mitigation, and outage probability determination. Various types of information exchange demand varying QoS. An enhanced routing protocol such as the routing protocol for low-power and lossy networks (RPLL), the lightweight on-demand Ad hoc distance-vector routing (LOADng), Ad-hoc on-demand distance vector (AODV) and Dynamic Source Routing (DSR) protocols were successfully used in the articles reviewed. Polling algorithm like neighbour relay polling and clustered polling were also successfully deployed.

The designs in several of the literature use methods such as Advanced Encryption Standard (AES) and elliptic curve cryptography (ECC) to protect the privacy of users. Intrusion detection and prevention were also successfully done. To fend off a cyber-attack that was carried out with the intent to manipulate data for economic gain, an algorithm based on a support vector machine (SVM) was used to detect intrusion in smart meters. The objectives of the methods and designs employed in the reviewed literature seek to improve the financial implications of operating the smart grid.

5.1. Communication Network Simulators

Considering Figure 3 and Table 4-7, it was evident that NS-2, NS-3, OPNET and OMNET++ are popular among researchers for the simulation of communication networks. NS-2, NS-3 and OMNET++, which is an open source software, have been widely used. The simulators could be used to study the performance of smart meters over various communications networks. Metering applications generally is a current area undergoing steady development over the years.

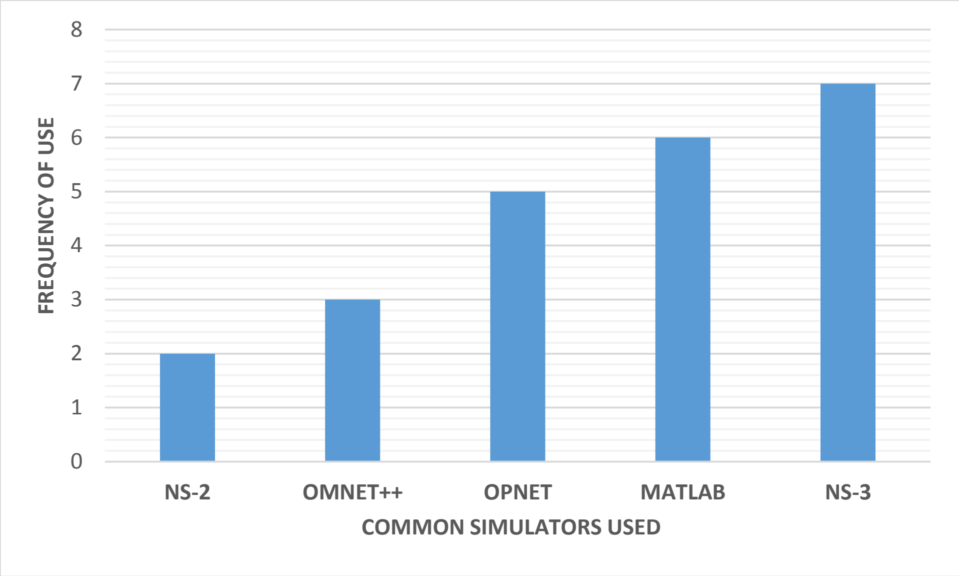

Figure 3. Common simulator deployed in the reviewed journal articles

5.2. Communication Network

Power line communication (PLC) is suitable for smart metering deployment. Power line Communications use the existing AC wired infrastructure. Therefore, no extra cost is needed for cabling purposes before the deployment of the technology. While it is not as fast as actual Ethernet cables, PLC speeds are often fast enough to deliver most consumer-based content. In the wireless category, ZigBee, Wi-Fi, Bluetooth, and WiMAX among others are suitable for deployment, and they have been successfully deployed. LTE network originally configured for human-to-human communication has been tested for adaptability for machine-to-machine communication in applications such as smart metering. The simulation results show a great deal of applicability.

ZigBee is more suitable when accuracy is not a major concern. It is suitable for smart electric grid applications with fewer reliability demands, which requires low energy. Wi-Fi networks could also fit into use for data communication between the data concentration unit and the meter. The Wi-Fi network can operate adequately in a Local Area Network (LAN). WiMAX and cellular network are deployable for metering activities between the data aggregation unit and the utility server. WiMAX was designed particularly for metropolitan area networks (MAN) communications as it provides very high transmission rates at a range unequalled by other wireless protocols.

6. Conclusion

In this paper, a comprehensive review of communication networks and simulators for smart metering applications has been provided. This includes communication networks applicable for smart metering applications details of common simulation software for communication networks, and the critical issues of considerations while installing smart meters in an AMI network. The current issues raised have been discussed. The issue of security, quality of service and optimum operational cost remains paramount in smart grid implementation. A review of this kind in the future could look closely into the simulators and networks employed at each category of the smart grid communication infrastructure; the HAN, NAN and WAN. Also, analysis and methods of improving energy data quality from smart meters based on the packet lost during transmission in the communication channel should be focused upon in similar review in the future.

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