

Review

Smart Plugs: Paradigms and Applications in the Smart City-and-Smart Grid

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Abstract: In the current energy ecosystem, the need for a Hybrid Appliance Load Monitoring System (HALMS) to establish a smarter grid and energy infrastructure is undeniable. The increasing popularity of the Internet of Things (IoT) has suddenly pushed the demand for smart and connected devices. This review introduces the term smart plug as a device that uses IoT for establishing HALMS. These smart plugs are a handy solution to make the so-called ‘dumb’ devices smart. The strategy of smart plugs to enhance the energy management experience in connected spaces is presented. This study extensively highlights the current smart plug technologies and the relevant activities and limitations that need to overcome the requirements of HALMS.

Keywords: energy management; internet of things; smart plugs; appliance load monitoring; smart metering; smart grid; smart city

1. Introduction

Electricity forms the backbone of the modern world but the rises in energy demand with the increasing urbanization over the past decade have overloaded the current energy ecosystem and electricity grids all over the world. Hence, there is an urgent need to shift towards a smarter energy infrastructure which is more efficient and interconnected. The use of smaller localized and distributed energy generation, incorporating renewable sources of energy, help in creating a dynamic energy ecosystem wherein the consumers of electricity can also play a vital role in a distributed generation of power.

The consumers are now not only limited to the end user of energy but also contribute to energy generation through local grids as well and thus can be recognized as prosumers. The electrical nodes in the existence of prosumers are recognized as smart homes/society. Therefore, it is necessary to have smart distribution systems that enable the bi-directional flow of power and interaction between the components of the microgrid. At this stage, the use of smart plug (a device that can be used for efficient energy management and load monitoring in the home environment with the help of the Internet of Things (IoT) theme) is a possible solution to make smart-meters more intelligent and establish the compatibility between smart-meters and Phasor Measurement Units (PMUs).

The utility can use the IoT theme as a viable solution to acquire the data from both smart-meters and PMUs that will not only help the utility for load forecasting but also offer optimal pricing to prosumers/consumers. However, a major limitation with IoT for smart city applications is the lack of interoperability, especially at the device level operation. To realize a secure Cyber-Physical System (CPS), it is very essential to develop for all the solutions of a smart city using a common standard. The smart plug can be used as a Plug-and-Play device, which is a very important aspect to popularize the concept of a smart home/smart society. This will not only reduce the latency and the cost of operation

while using the smart plug for control and the monitoring of electrical loads but also encourages development of low-bandwidth solutions for internet independent data communication networks [1]. At this stage, the available/developed IoT solutions can encourage the use of load monitoring at the smart city level. It requires the bulk of data handling to be coordinated by centralized supervisory control and monitoring system, namely, the Supervisory Control and Data Acquisition (SCADA) or control center. Highly dense city populations increase strains on power distribution networks. Thus, solutions need to be ‘Smart,’ that is, highly efficient, economically viable and sustainable as well. Information and Communication Technology (ICT) is the key factor for such cities to address the challenges in a smart manner. Here, the smart plug technology has recognized its presence to deal with such issues.

One of the objectives related to the design of a smart grid system is to combine the traditional grid with the latest ICT, resulting in an optimized energy management system [2]. The management of generation and distribution resources can only be performed by the concerned authorities and personnel in the on/off-grid called the Utility. Optimization of the energy consumption in the off-grid environment is something where every individual (prosumer) in the grid ecosystem can contribute while the same is managed by the Utility in a grid-connected integrated ecosystem [1–7].

Optimized energy consumption not only means efficient utilization but also a reduced loss of energy. For this to take place, we must first be able to make accurate and precise data measurements to analyze the cause of energy wastage. The energy consumption data from the present generation of Electronic Meters gives us only data of the energy consumed by any building or space in (kilo-Watt-hour) kWh but not the energy loss during the stipulated time durations. In the present-day technology, there are gaps in the existing device architectures (electronic meters), as well as in human behaviors, which cause energy wastage and are left undetected by the energy data supplied by the electronic meters. Hence, there is a strong need to measure, analyze and detect the exact sources of wastage in any energy consuming space at an appliance level. Hybrid Appliance Load Monitoring System (HALMS) is one such research area that deals the same. The need for HALMS arises from the need for a more connected and efficient electrical grid and eventually a smarter energy infrastructure that can meet future energy demands. The recent developments in DC microgrids, off-grid energy generation and Distributed Energy Resources (DERs) have indicated the requirement of HALMS that will be inevitable for efficient energy management.

Appliance Load Monitoring (ALM) has been an area of research for a long time; however, the recent appearances of HALMS add a new frontier to the research directions. It was formally introduced for the first time by GW Hart [8], who proposed a Non-Intrusive Load Monitoring (NILM) based approach for the identification of connected loads. Since then there has been considerable advancement in the research and implementation on the NILM side. While the NILM based devices and techniques have come a long way since the time of their formal introduction, they have not been able to reach a mature implementation stage due to various reasons. NILM based systems insist on single point sensing from where all the aggregated load data is collected and then again disaggregated to analyze the power consumption of each load [9]. Despite the advancements, this method has not been able to provide the level of accuracy required for a successful commercial and wide-scale implementation. Apart from that, these systems are passive in the sense that very few of them provide any real-time insights regarding the appliance level consumption.

The utilities can provide suggestions regarding the optimum usage only after the analysis of the aggregated data. The algorithms used are usually not applicable to all scenarios and usually computation intensive. Despite all these limitations, NILM based ALM has given us some valuable insights as to how to approach the load monitoring problem in a better way. Further, we discuss the different works in NILM in recent years, which have been decisive in driving the research towards an improved load monitoring system. These works include hardware approaches, software and middleware design as well as algorithm analysis for load identification [10–12].

The second approach for ALM is gaining popularity in terms of Intrusive Load Monitoring (ILM). This approach makes use of individual device sensing using smart devices and sensors (smart outlets). Researchers and Industry, after a long time, have turned to this approach after NILM accuracy hit a plateau [11]. Although, ILM has been largely ignored since a longtime due to the installation complexity and cost the recent developments in IoT and smart/intelligent sensing systems have led to the development of cheaper and convenient solutions, which can match NILM based devices in terms of cost and ease of use [13–19]. ILM also has the obvious advantage of accurate load monitoring, remote control of devices, more accurate load identification and real-time insights of energy consumption due to the distributed sensing approach.

There are a lot of commercial products when it comes to NILM and ILM. However, the bitter part of the fact is that both techniques lack the efficacy as standalone techniques for large scale and long-term implementation [11]. The major difference between both techniques is that while the NILM techniques are more suitable for the utility side but not the useful insights to consumers/prosumers; the ILM products cater more to the individual. A certain level of synchronization is still missing between both the approaches which are needed to bridge the gap leading to an efficient hybrid load monitoring technique. On the ILM side, smart plugs present a viable solution to complement NILM devices appropriately for developing a better approach to load monitoring. In the present work, we discuss how smart plugs have become a major subject of research under ILM techniques. A detailed discussion on the various features of the available smart plugs in the market and the scope of research are done in the further sections. The possibility of new features, advantages, disadvantages, ease of implementation and various use cases have also been elaborated in detail. This paper presents a comprehensive review of the smart plug technology as a potential contributor to Green Energy and the smart grid/micro-grids and smart cities.

2. Latest Technologies

Of all the NILM and ILM solutions being used for load monitoring, smart meters and smart plugs have seen a great rate of acceptance among users. Although Smart meters have been getting more attention compared to smart plugs, the present smart meter technology fails to address all aspects for effective load monitoring, such as prosumers being unable to make energy consumption/production changes, unable to ensure the security and privacy of metering data, unable to manage and store vast quantities of the metering data collected. In this regard, we see smart plugs as a potential complimentary solution that can improve the process of efficient and low-cost load monitoring. Until now, smart plugs have been a part of the smart homes but this review tries to present a smart plug as an integral building block of the smart grid environment as well.

Smart plugs can be an indispensable technology when it comes to seamlessly connect the end user to the utility with accurate information of energy consumption, leading to better services, energy saving and cost reductions on both ends.

In this section, the paper highlights various possible features to be included in a smart plug that facilitate not only the individuals but also make the process of load and energy monitoring easier for the utility as well. Some of these features have already been introduced in commercial smart plugs in the market. Commercial smart plugs offer single/limited features in their products. As shown in Figure 1, the use of separate plugs to access different features is inconvenient and expensive for the end user. It is noticed that any such available plugs with multiple features also tend to be cost intensive.

A large focus of the smart plug market remains on the aesthetic value of the smart plug instead of the technical capabilities. There is a substantial technical gap in the development of an all feature equipped smart plug which can be called actually smart in every respect. The next part details the range of possibilities when it comes to the functionalities of smart plugs and how each feature has been attempted using various research techniques. Here, this study presents the following features that are essential in a smart plug:

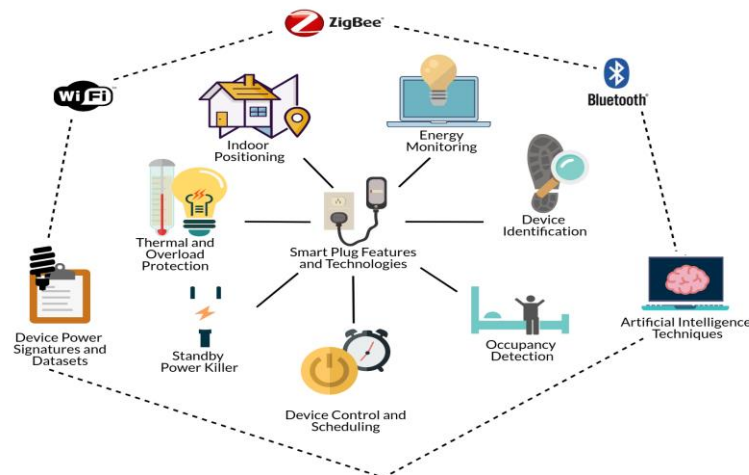


Figure 1. Features and Technologies used in the smart plug.

2.1. Energy Management Using Smart Plugs

Energy monitoring and its management are one of the most basic features and are the motivation for the development of smart plugs. All smart plugs in the market provide a feature where the energy consumption of the plugged-in device can be accessed on an hourly, daily, weekly, monthly and even yearly basis. This feature not only makes the consumers more energy aware but also helps them in understanding their consumption patterns. It can also help in identifying devices that are consuming high energy and can be replaced by more energy efficient devices. Utilities and appliance companies can use this data to recommend an upgrade and replacement for the older power-hungry devices. Usually, energy monitoring requires a current sensor and a voltage sensor or an Integrated circuit which can identify the current, voltage, power factor, real power and apparent power. For voltage sensing, the simplest technique involves stepping down the voltage to a low power level usually 5V. Current sensing can use conventional sensors such as ACS712 [20] or MEMS sensors which are gaining great popularity due to their compact size and high accuracy and sensitivity [18]. A very latest Hall Effect sensor can also be added in this line to measure electrical parameters.

2.2. Device Identification

Device Identification is a very interesting area of research currently being extensively explored in Load Monitoring and Energy Management systems. By identifying the devices being used in space, energy consumption can be efficiently monitored, scheduled and controlled. In recent years, device identification using Smart meter data have gained a lot of traction as a research problem [21–26]. Smart meter data uses disaggregation for device identification which has been successful to some extent but a unified approach to identifying all kinds of loads using these algorithms still needs to be figured out. It has also been pointed out that using smart plugs along with smart meter data can provide more accurate results and achieve a more efficient approach to device identification [22,27]. It should also be noted that the smart meter data disaggregation algorithms have not achieved the required accuracy and are still in the research phase. Apart from that, these algorithms require extensive training before implementation in real-time. Exploration of Semi-supervised and Unsupervised machine learning algorithms still needs to be systematically approached. A large amount of research still needs to be done for real-time identification of devices and smart plug data will prove to be a breakthrough.

A great advantage of the Device Identification feature is that it can enhance the accuracy of other sensors and features that can be fitted in the smart plugs. It will also provide users a way to control the consumption of their devices in real-time. Paradiso et al. [23] have pointed out that disaggregation algorithms require high-frequency data sampling for accurate device identification which might increase the implementation cost of the Smart metering hardware. An Artificial Neural Network (ANN) based approach for device identification was proposed using low-frequency data

sampling smart plug data [25]. Further, Zoha et al. highlight the issue of identification of low power appliances in disaggregation algorithms [21]. Most of the disaggregation algorithms are unable to identify and differentiate low power appliances. In this article, Hidden Markov Models (HMM) and Factorial Hidden Markov Models (FHMM) for identification of low power appliances in the presence of high-power loads have been explored. It is to be pointed out that such a continuous effort in Device Identification needs to be explored in conjunction with smart plug data so that the efficacy of a hybrid approach to device identification can be evaluated.

2.3. Device Scheduling and Control

While the energy management feature helps in monitoring the energy consumption, a device scheduling and control method surely gives authority to the users (consumers/prosumers) to manage their energy consumption. There are various possible scenarios for the need of device scheduling and control including the presence/absence of user, device standby power losses, device overloading, controlling energy bills and limiting energy usage [28,29]. The features discussed in this section also stem from the need for an efficient device scheduling and control. These scheduling and control methods have been suggested on a different basis, for example, occupancy driven domestic load control [30–33] and device control for prevention of standby losses [34]. The schedule and control mechanism can be incorporated for effective electricity usage based on the demand with respect to the time automatic control of different appliances to reduce energy usage during peak hours without consumer intervention. Examples include: (i) in the context of household appliance usage, scheduling and control process can be incorporated in such a way that the shifting of load from peak hours to off-peak zone consumption of energy in the household can be done during the low-priced time slots; and (ii) Classifying loads as energy storage system, non-interruptible loads and thermodynamic loads.

2.4. Occupancy Detection

One of the main motives for using a smart plug is reducing energy loss while electrical appliances are ON and this is where the feature of occupancy detection comes into existence. A large amount of energy can be saved by employing proper occupancy driven control in conjunction with smart plugs. Especially, high power consuming devices such as air conditioners, heaters, copying machines and televisions and so forth, which are used only in the presence of a user can be made more energy efficient using this feature.

Agarwal et al. pointed out that Heating, Ventilation and Air Conditioning (HVAC) systems are one major type of electrical load that can benefit from occupancy detection [18]. Authors suggested a stand-alone sensor for Occupancy detection which employs a Passive Infrared (PIR) sensor and a Reed Switch with the potential to save 10%–15% of energy consumption. While the system has been designed and tested keeping in view office space, its applicability to home spaces is still undefined. Since occupancy of space is not the only factor affecting energy management; the system can be improved upon by pairing it with other sensors and systems to increase the energy efficiency of a space. The important outcomes of Jin et al. [35] and Kleiminger et al. [32] for the occupancy detection have considered semi-supervised learning algorithms for presence detection and is termed PresenceSense. It means that even unlabeled/unstamped data can directly be used. The intended applications of PresenceSense include smart plug loads, space security and behavior modelling. They also used Wi-Fi, ultrasonic sensors and accelerometers in separately to establish the ground truths. These methods presented designing an occupancy detection algorithm for the simple and cost-effective implementation of smart plugs. However, a clear gap that Jin et al. have left to explore is the hidden relationship between occupancy and plug-in loads which needs to be addressed in a more systematic manner. Kleiminger et al. proposed the use of electricity data available from smart meters, digital meters, smart plugs and other monitoring devices for occupancy detection. They explored the occupancy of the home residents, the experiments conducted and performed in office space by Jin et al. [28]. Kleiminger et al. also achieved an accuracy of over 80% using HMM and other supervised algorithms with less than 80%

accuracy. While Jinet al. also have shown an accuracy of over 94% without any training in comparison to ground truths as well as other Power threshold models that are used for presence detection using power consumption. This is a positive indicator that semi-supervised and unsupervised learning algorithms need to be explored more when it comes to smart plugs.

2.5. Standby Power Killer

Standby losses in electrical devices are very much the concern with respect to the electricity bills in terms of energy losses [34–37]. Most appliance users tend to leave the device on standby; thereby switching off only a part of the electronic components. While this practice may be fine when the device has recurrent usage or has a high startup time which turns out to be a highly inefficient energy usage practice for longer periods. Constant improvements in electrical appliances are led to a lowering in energy consumption. At present, the standby losses still need to be addressed in day to day life, where the number of appliances grows exponentially as compared to the tiny growth rate of energy being generated. Mohanty of the *Agence de l'Environnement et de la Maîtrise de l'Énergie* (ADEME-French Environment & Energy Management Agency) has pointed out the energy losses incurred on a daily to yearly basis due to standby losses in home appliances and office equipment [37]. The survey has also quantitatively measured the losses for several countries as well as various types of appliances. The numbers clearly show that standby power losses cannot be neglected as has been done in the past if we intend on creating an energy efficient Electrical system.

The simplest way to counter the standby losses is to completely cut-off the power supply to the equipment which again requires human intervention and is very subjective and varies with each user. The other smarter way is to detect an appliance in standby and to switch it off automatically after a designated time. This feature can prove to be an indispensable one when it comes to smart plugs as one of the major focuses of the smart plug is energy saving and management. Commercial players have stamped their affirmation on the same by introducing smart plugs that are specifically meant for killing standby power. Tsai et al. demonstrated the design and implementation of a socket which can reduce the standby power to a negligible amount and even zero under certain conditions [35]. The design has been demonstrated using a Photovoltaic array and PIR sensor, which detects the user approaching the socket as well as switches off the device connected to the PV array in case of insufficient illumination. This technique can be effectively used in Off-Grid Systems for saving energy and can also be adequately modified for the traditional grid to prevent standby losses. A possible method will be a combination of the presence detection with the power signature of the device in standby mode. The power consumption pattern of a device in standby mode is significantly different than when it is being used and can be used to identify a device in standby mode.

2.6. Thermal and Overload Protections

Thermal Protection is an advanced feature in the smart plug architecture as some devices that are either continuously plugged in, being used in extreme conditions or used with plugs of improper rating can result in fire hazards due to overheating or current overload. Basically, a smart plug protects or shields appliances against a voltage surge/voltage spike (consequently a current spike). A simple temperature sensor integrated into the smart plug to actuate a relay can be used for taking preventive measures.

Energy fluctuations cause device failures. Traditionally, the overload protection is integrated on the device side. However, this can still lead to hazards like fire and short circuits in the devices. An overload protection feature at each socket can be an efficient way to not only prevent such hazards but also help in easier detection and identification of fault location and fault identification in the complete electrical system. This way smart plug can contribute to electrical safety along with energy management.

Shi et al. [6] proposed an online energy management system as a stochastic optimal power flow problem and real time Energy Management System (EMS) based on Lyapunov optimization.

Makonin et al. [38] presented the importance of making the “real” smart meter and defined what intelligence is needed to actually make a meter smart and have proper protection. Akhtar et al. [39] presented that “smart loads (SLs) could be effective in mitigating voltage problems caused by photovoltaic (PV) generation and electric vehicle (EV) charging in low-voltage (LV) distribution networks.” Tang et al. [40] developed a “real-time algorithm for Alternate Current (AC) system based on quasi-Newton methods to track the optimal power flow.”

2.7. Indoor Positioning

The indoor positioning feature allows locating the position of an object or a person inside a building. This feature potentially proves to be a very crucial and beneficial auxiliary feature which can enhance the accuracy of other features [11,13]. For example, if the location of the smart plug is detected inside the bathroom, then the smart plug can be used to easily identify and control devices such as water heaters and lights based on time of usage. Similar usage times and patterns can be easily inferred using this feature in other parts of any building (infrastructure) such as kitchen area, balcony, office spaces and classrooms.

3. Design and Implementation of Smart Plugs

A considerable amount of research is going on towards the design and development of smart plugs that not only packs maximum features and aesthetic appeal but also provides minimum user interaction. The physical form factor of the smart plug is an important factor when it comes to the acceptability of smart plugs by any user. Firstly, it should be small, compact and compatible with the traditional plug-in sockets. Secondly, it should not contain any parts which add to the hassle of installation and use. The design of commercial smart plugs available in the market is introduced by putting in a lot of thought into the design part and largely satisfies the issue of aesthetic appeal and form factor. Hence, an ideal smart plug will be an intelligent amalgam of various technologies that have been usually used independently until now.

3.1. Smart-Sensing Technology

The electronics and instrumentation part of any sensing technology essentially consists of sensor-packed circuit board with signal processing and computing capabilities. In the case of the smart plug, a sensor to detect the electrical parameters such as current, voltage, power and so forth, is necessary to facilitate the device monitoring. There are many commercially available current and voltage sensors as well ICs which enable this task. Here, it can be rightly added that MEMS sensors, which are becoming cheaper and easier to implement by the day, can prove to be a breakthrough in this regard [18]. Many other sensors such as the PIR sensor, temperature sensors also facilitate additional features in smart plugs. Sensor Fusion is one more approach that holds great potential in decreasing the physical form factor of any device and providing maximum functionality in a limited space. Sensor fusion allows combining and using limited sensor data to make useful inferences resulting in enhanced efficiency of the complete system in terms of design, cost as well as energy.

Depending upon the smart plug design architecture, it may or may not have a microprocessor/microcontroller to process the sensor outputs. On one side, having an onboard processing unit with a decentralized design makes the monitoring and control task easier, the limited computing capabilities might prove to be a hurdle in handling large amounts of data. The other possibility is to use a centrally controlled unit for all smart plugs in the network as a hub and to use a web or mobile application to control the smart plugs. A clear advantage of this method is a simpler design of the smart plug and the availability of more computing resources for the sensor data. This method limits the smart plug in the sense that it may pose issues due to communication delays between the smart plugs and the hubs. It also requires a more complex software development than the decentralized design where the onboard processing unit does most of the work.

The implementation of smart plugs has seen the use of systems with Arduino microprocessor units and Zigbee as a communication system in various researches works [41]. While open source technologies like Arduino make smart plugs an easy solution to implement with onboard computation abilities to some extent; they also tend to increase the cost and complexity of the solution. Also, tampering with open source hardware technologies is easier. Zigbee is another technology that is being widely used in smart plugs, both in research and commercial space, which has the potential to offer a simpler, robust and low-cost solution. Designing of special System-on-Chip (SoC) solution is an interesting option to be explored where only the required sensors are put on the board, saving space as well as power consumed by the device but they incur high prototyping cost. Some smart plug designs have attempted an implementation with an onboard processing unit such as Arduino as well as self-engineered setups [41]. With the help of edge computing platform smart plug can be integrated with the Arduino systems for better manage and control of household appliances.

3.2. Communication Systems

Another important aspect of smart plug architecture is communication among intelligent electronic devices (IEDs). In view of the recent developments, the options for a wireless communication protocol for device level monitoring are many [42]. These include the common protocols like Wi-Fi, Bluetooth, Zigbee and some newer ones such as Bluetooth Low Energy (BLE) and Z-wave. Some companies such as Insteon have also launched their own proprietary protocol for their home automation system. The selection of a suitable wireless communication protocol depends upon the area of application of the smart plug. For residential or individual use, Wi-Fi is a reliable option as the network is essentially free of any congestion most of the time. However, Wi-Fi, when used in Public or Commercial setting can be inefficient where the network traffic is high most of the time. Similarly, for critical device monitoring, such as in offices and industries, a more reliable protocol such as Zigbee or MQTT is suitable as they are highly scalable and capable of operating even in low bandwidth with a large number of devices in the network. Bluetooth Low Energy with its meshing capability has emerged as a high energy efficient option for smart plugs. The complete capabilities of BLE still remain to be explored.

3.3. Data Acquisition and Assessment

The capabilities of the smart plug can be attributed to what it can do with the acquired data. Any IoT device generates a continuous stream of data that needs to be analyzed to provide meaningful insights about the environment in which it is deployed. A significant amount of actionable information can be derived from the data stream which capable of making the device “Smart.” The data can be acquired physically such as in a Physical Database Storage or on the Cloud depending upon the resources available at hand. Another important aspect in the data acquisition phase is data visualization where middleware, web applications and mobile applications come into the picture. This software enables the end user to understand, monitor and control the smart plug functionality with an easy and interactive user interface. They play an important role in the effective implementation of the smart plug.

A major research effort is directed towards the analysis of smart plug data using Machine Learning and related algorithms. Some of the focus areas include Appliance identification, Presence detection, Demand Response management and Peak load management [21–24,27,29]. Another important issue that needs to be considered while implementing a smart plug is that despite the great advancement in Machine Learning and Artificial Intelligence, proper hardware to implement the Machine Learning algorithms is still in the development phase. Cost-effective hardware to efficiently implement and handle a variety of algorithms in a decentralized manner is still a research problem. Thus, the present implementation and design processes must take this into the picture and try to reduce the algorithm complexity to the minimum level, which the available devices can robustly handle. Cloud-based services can be used for data storage and algorithm implementations are a good alternative for handling the sensor data in smart plugs.

3.4. Data Analytics/Mining

The devices in the IoT ecosystem continuously generate a large amount of data but what drives an IoT application are the inferences and insights we draw from this enormous data stream. Likewise, the smart plug data can provide numerous versatile insights about the space in which the smart plugs are deployed. Data analysis and Machine Learning algorithms used for data analytics in smart plugs must consider the fact that the smart plug hardware has limited onboard computational power. Thus, the present implementation and design processes must focus on keeping the algorithm complexity to the minimum level, which the available devices can robustly handle. A centralized smart plug system with a central hub might provide greater processing power as compared to individual decentralized smart plugs but the costs and complexity of the system are also greater in a centralized system. Apart from that, real time response and the fluctuating and erratic nature of transmitted data over various channels is a challenge in the Internet of Things ecosystem. In the case of smart plugs, real-time response might be easier to tackle due to the limited size of the area in which they operate but the precise transmission of data is an issue that needs to be addressed for a good smart plug design. The smart plug adoption rate is bound to hit a plateau unless effective data analytics algorithms are developed to process the generated data efficiently and accurately. Data Analytics and Cyber Security are two major aspects to address for the success of using IoT in Smart City/Smart Grid applications. Some specific contributions done by the researchers are also discussed in Section 3.6.

3.5. Cyber Security

With the rise of the number of connected devices, the security of these devices is an equally rising concern. Security measures to prevent cyber-attacks have become an integral part of the IoT system design architecture. It is difficult to imagine the merging of the cyber and physical world without proper security protocols in place for all the connected devices present in any kind of space. The same is true with respect to smart plugs as they are expected to collect a variety of data in and around personal and work spaces and it can raise privacy violation concerns for the users if proper security measures are not in place.

When it comes to the security aspects of the smart plugs, there are a variety of threats and vulnerabilities that need to be addressed. Many research works have been reported in this direction with their focus ranging from Smart homes to Smart Grids. Song et al. [43] discussed privacy-preserving communication protocol for all IoT applications in Smart homes. The authors stressed the use of symmetric encryption keys for securing data transmissions and message authentication coded for data integrity and authenticity keeping in mind the low computing power available on the IoT devices. Humayed et al. presented a detailed survey of threats, vulnerabilities, attacks and controls in CPS (cyber physical system) covering Cyber, Physical and Cyber Physical aspects separately [44]. The various possible attacks and vulnerabilities have been listed out along with their control strategies for the kind of CPS, such as, smart grid, Industrial Systems, Medical devices and Smart cars.

Mesbah et al. [45] presented the security of smart meters against customer attacks which involve changing the readings of the meters by using linear error correcting block codes [45]. Tang et al. explored a new perspective of security analytics by a scheme to detect and counter the online data integrity attacks against the real-time electrical markets [40]. It is seen that a substantial amount of research is directed towards the detection, prevention and control of Security vulnerabilities in the smart grid at different levels. It is important to embody the security aspect at the time of system design to enhance the robustness of the system at the time of implementation.

3.6. Recent Designed Smart Plugs

Researchers are exploring different wireless technologies of IEEE 802 standards such as Zigbee, Wi-Fi, Bluetooth Low Energy (BLE) for the design of the smart plug. Various new techniques have been suggested for saving energy using the developed smart plugs. We discuss some of the interesting

works done with respect to design and implementation [25,26,41,46–53]. Table 1 summarizes the recent state of the art contributions toward the design and implementation of smart plug done by the researchers.

Table 1. Summary of Design and Implementation.

References	Protocols	Features	Limitations
Lukacet al. [25]	• BLE	- Controlled by smartphone app - Security features have been included	- Additional cloud functionalities can be included - BLE can also be used for presence detection-based control
Khaoet al. [26]	• Wi-Fi	Low measurement error compared to Standard meter measurement	Wi-Fi network can present reliability issues
Choi et al. [46]	• BLE	- Energy management using Presence Detection by BLE beacons - Control of devices using smart plug	Energy consumption also depends on other factors apart from the presence or absence of individual
Elma et al. [47]	• Zigbee	- Voltage control of devices instead of switching off - Lower Peak Demand Power	- For Passive loads only - May reduce the life of the equipment
Capone et al. [48]	• WiFi	- A novel architecture for the implementation of smart plugs - Bridges outdoor and indoor networks - All aspects of the system architecture have been touched in detail	Requires a separate energy management hub
Ganuet al. [50]	• Carrier Sense Multiple Access	- Design of smart plug for Peak load control - Decentralized device scheduling algorithm - Accounts for user preferences - No manual intervention required	- Security issues - No clear economic incentives for end users - Might require legislative changes for large scale implementation
Aftab et al. [41]	• WiFi	- smart plug design using open source - Real Time identification of Devices is claimed	No detailed explanation of dataset/techniques used in device identification
Patel et al. [52]	• Electrical Signals	Identification of electrical events using Switching noise in the devices	- Not applicable to all types of device - Low current devices may go undetected - Only for observation and data analysis of devices
Irwin et al. [53]	• X10 and Insteon	- Design of Power Line Monitor (PLM) to monitor device status - Development of Autometer-for accurate load monitoring	Only for monitoring the Power consumption

Lukacet al. have designed and implemented a smart plug using BLE for monitoring power consumption using a mobile app. The work also compares a few of the contemporary smart plugs with

the proposed device [25]. Thong Khaoet al. presented a smart plug solution that can monitor, as well as control, devices using a web-based application [26]. This system uses Wi-Fi as the wireless protocol and a bi-stable relay to control the devices. The measurement accuracy has been compared using a standard meter and an error of less than 0.5% is reported. Other aspects of the system such as hardware, software, the robustness of the system and so forth, have been explored in detail. A Smart-office energy management system developed by Choi et al. uses BLE beacons to detect user presence and control the devices in the user space using smart plugs [46]. A lightweight app and web service display the energy consumed as well as the energy saved. They also proposed an energy saving control algorithm to control the energy consumption of the device connected to the smart plug. The system was deployed and tested for a period of three months and the average ratio of energy savings was 31.3% and 15.3% for PCs and lights respectively. Elma et al. have proposed new use of smart plugs in their Home Energy Management control algorithm which controls the voltage across the appliances instead of switching them off [47]. This reduces the instantaneous power consumption in passive load resulting in lower peak demand. The system uses Zigbee communication protocol along with the chopper voltage control circuit to register a reduction of about 18% in the peak demand. The system, however, has some limitations such as there is a considerable increase in THD during voltage control using a Triac/Thyristor and the life of the appliance may also be reduced due to such control.

The work done by Capone et al. is relevant to the implementation of smart plugs where a novel architecture for a reduction in energy usage in homes is proposed [48]. The work proposes the use of multiple Energy Management Devices (EMDs) which form the basic block of the complete architecture and are connected by an EMD hub to the outside network and utilities. The smart plug can easily take the place of the said “EMD” and can be integrated in the proposed architecture. The development of similar architectures with schemes to exploit all the sensor data available inside an energy space can be a game changer in energy management. Irwin et al. have proposed a solution on the lines of a smart plug where the implementation of a Power Line Monitor (PLM) is advocated on each wall plug, which sends device status data to a controller every 10 seconds. The proposed PLM polls the power data continuously and disaggregates it using Machine Learning Algorithms. It can be said to be a localized NILM system. The nPlug developed by Ganuet et al. uses analytics to determine peak load periods, load imbalances [50] and can reschedule the operation of heavy loads in these periods to off-peak periods without any manual intervention by the user. This system specifically addresses the problem of peaking shortage in India. The authors also raise the issue of legislation and policy hassles and the possibility of tampering of the smart plugs which might be a bottleneck in the large-scale implementation of such products. Aftabet et al. introduced a technique for real-time identification of devices using smart plugs [41]. These proposed systems use an Arduino with ESP8266 for processing and communication over Wi-Fi. The paper uses a classifying technique to identify the device using their power consumption data. Another implemented design has been proposed by Patel et al. [52], where the developed system identifies the electrical events using noise or transition pulses while switching states in electrical equipment. The noise during the switching (on/off) of an appliance is detected and classified and mapped to an electrical event or device using Supervised Learning techniques.

Ling et al. raised an important concern by unfolding the security vulnerabilities in smart plugs [54]. The work takes a commercial smart plug (Edimax) and attempts to exploit its communication protocol and launch various attacks on it. It has been found that the system was vulnerable to all the attempted attacks, namely, device scanning attacks, brute force attacks, spoofing attacks and firmware attacks. They also described the detailed process of each of the attacks and the possible solution to remove the vulnerabilities against these attacks. With the adoption of smart plugs in the future, it is expected that the entire major device in any building will be ultimately connected through a smart plug. This means that any cyber-attack on the smart plug would result in the attacker taking control of the home devices making him capable of causing serious damage to property and individuals. It is to be noted that security measures in a smart plug need to be implemented at each level including Hardware,

communication and cloud level [43,44,54,55]. Any discrepancy at any level can be a threat to the privacy and safety of the user. At the Edge device and component level where the acquisition and generation of data take place, it must be ensured that a secure Firmware with regular updates and a secure edge gateway is implemented. Similarly, it is required that for the transport and end layer suitable security and authentication protocols must be adopted to ensure an end to end security. Hence, it is very essential to address the cybersecurity issues in smart plugs not only after manufacturing but more importantly when the smart plug is designed a prototype [43,44,55].

4. Market Space

Smart plugs have made their existence felt in the market space in the last decade. This section has placed special emphasis on highlighting the recently available smart plugs in the commercial market. Many companies have stepped in with a variety of products giving the consumers a plethora of choices to select from. These companies include some of the major players in the electronics markets, crowdfunded campaigns, startups as well as enthusiastic innovators. Although, Armelet al. pointed out that smart plug has a slow adoption rate but they had also advocated that the use of smart plugs along with the smart meters will offer an optimal solution for energy monitoring along with remote control [9]. Also, with more and more companies investing in the development of smart plugs, rising energy awareness among users and the focus of policymakers on smarter energy products, it is inevitable that the adoption rates are bound to increase in the coming decade. It is also being pointed out here that the smart technology-enabled devices in homes, offices and, industries have an even lower rate of adoption due to higher costs and installation and operation complexity.

Smart plugs are a simpler and low-cost alternative for these devices and hence, an easier way to adopt Smart technologies. The annual growth in the global smart plug market is anticipated to be around 38% from 2017–2021 [51]. The technology adopters can majorly be divided into three categories: Innovators, Early adopters and the early majority. Innovators being the people who are actively involved in creating and using technology, the early adopters are the ones who are the early customers of any technology and early majority are the customers who form the first sizable population to adopt the technology after seeing it being successfully used by innovators and early adopters. For the smart plug market, the early majority account for majority market share until now as these are the ones who are mostly tech-savvy consumers passionate and knowledgeable about the market. For any new market to capture a wide customer base, it is necessary that the above mentioned three segments are being properly addressed to establish credibility among the masses. The inability to gain the credibility of these three segments might result in any new technology is dying out quickly. Geographically, the market space can be divided into the Americas, the Asia Pacific (APAC) and Europe, the Middle East and Africa (EMEA) [56]. Among these three regions, the Americas are one of the fastest growing regions in terms of Global Smart Plug Market due to the high acceptance of advanced technology products.

In Table 2, we tabulate some of the most popular smart plugs and some new innovative designs available in the market. Some of the major players in consumer electronics like Belkin, TP-Link, D-link have also stepped into the smart plug market with a variety of devices [57,58]. Other companies such as Zuli, Insteon, iDevices, Leviton, Etekcity, Edimax and Crownstone are startups and crowdfunded projects which have successfully established themselves in the smart plug market. WeMo, Insteon and iDevices offer devices with one or two distinctive features per device such as Dimmer, Energy monitoring, Switches for Light control and others [59–61]. There is no unified solution for controlling and monitoring the energy and cost of each of these devices is quite high to implement for multiple sockets in any space. The other companies offer simple energy monitoring and device control features only with some devices like D-Link providing thermal protection and device scheduling as well [58]. An exception to this is Crownstone [62], which is a crowdfunded company that is manufacturing smart plugs with multiple features including occupancy detection, indoor localization, energy monitoring, device control, device identification and other features are still being added as the project progresses.

Crownstone gives value for money along with multiple features to the users. Most of these devices can be controlled by smartphone apps along with an added option of voice control using devices such as Amazon Alexa, Echo and Google Home Assistant.

The Wireless technologies used by smart plugs are Wi-Fi, Bluetooth, Bluetooth Low Energy, Z-Wave, Insteon Wireless. Z-wave is a low-frequency RF communication protocol developed by Zensys for home automation purposes and is being used by many other companies for home automation [63]. Insteon has its own wireless protocol which it claims has several advantages over the other existing protocols being used by other smart plugs [64]. Although, Insteonsmart plugs require an Insteon hub to setup the wireless network and communicate among the smart plugs which makes it more expensive and complex to implement. Some of the manufacturers are using Zigbee protocol but the absence of effective interoperability between various platforms has restricted it from becoming popular. Z-wave devices are also facing similar problems when it comes to interoperability.

It is observed that there is a considerable cost involved in setting up smart plugs for all the plug-in sockets in any space. Cost is an issue that is one of the major hindrances for widespread adoption. Apart from that, there are a very few smart plugs that offer multiple features. For any smart plug to be popular and widely adopted, the development of a multi-feature prototype must be a priority in the research and development agenda of any company. The market space is currently flooded with smart plug prototypes but the one that provides maximum features with a hassle-free experience to the user is bound to win. Table 2 compares the existing smart plug technologies introduced by different companies/startups based on the technology used; cost per unit and the control mechanism.

Table 2. Summary of commercially available smart plugs.

Company	Type of Devices Available	Technology	Cost (USD)	Control Mechanism	Pros	Cons
WeMo (Belkin) [59]	Dimmer, Mini Smart Plug, Insights Switch, Light Switch	Wi-Fi	50-100	App, Amazon Alexa, Echo, Google Home Assistant	energy usage through the WeMo app	more expensive
iDevices [60]	Dimmer Switch, Wall Switch, Wall Outlet, Outdoor Switch, Thermostat	Wi-Fi	30-80	App, Amazon Alexa, Google Home Assistant	Uses Alexa to turn electronics and lights on and off.	plug is only compatible with certain devices
Zuli [65]	smart plug	Bluetooth	60	Smartphone App	sensing feature is far more precise and reliable	Lower Definition
Insteon [61]	Insteon Hub, Plug in Devices, Wall Switches, Outlets, Keypads, Thermostats, Remotes	Insteon	129.8	Smartphone app, other Insteon device using the Insteon Hub	Dual Outlet	Higher Price Point
Leviton [64]	Smart Plugs	Z-Wave	49	App, Amazon Alexa, Echo, Smart-things, Google Home Assistant	Dual Plugs	Not For Higher Voltage Appliances
Etekcity [63]	Smart Outlets	Wi-Fi	30–40	System App	Remote Control Range	No Smartphone Access
Edimax [66]	smart plug with and without control function	Wi-Fi	50–70	Smartphone App	Set limits for energy usage on a daily, monthly or weekly basis	Higher Price Point
TP-Link [57]	Smart Wi-Fi Plug	Wi-Fi	35–50	Smartphone App	small and light It is easy to use and setup	does not offer energy monitoring reports
D-Link [58]	Smart Wi-Fi Plug	Wi-Fi	35–60	Smartphone App	automatic overheating protection	Lights are always on No Home Kit support
Crownstone [62]	smart plugs, Embedded smart plugs	Bluetooth Low Energy, Wi-Fi	45	Smartphone App	Smart Home Monitoring	Works only with the Crownstone devices

5. Applications of Smart Plugs

Smart plugs fall under an ILM (Intrusive Load Monitoring) type of application as pointed out by Ridiet al. [11], which exists at the plug level and hence is more localized in comparison to the ILM1 type sub-meters or NILM devices, such as smart meters, which are located at a few or single locations in space. They also have a better ability to interact with the environment in comparison to ILM3 type devices, which are usually embedded in the circuit. Basically, ILM 1 relies on sub-meters that typically measure the consumption, ILM 2 uses metering devices placed at the plug level, ILM 3 uses metering devices placed at the appliance level. On one side, where the NILM based devices, such as smart meters, can mainly be used only for energy monitoring and data collection along with some basic communication. Smart plugs, on the other hand, can be used for a wide spectrum of applications apart from energy monitoring and even complement NILM based devices.

Figure 2 shows various applications of future generation smart plugs. These smart plugs are too vital for mankind, particularly considering the future needs and living styles of people. Some of the possible application scenarios for smart plugs are discussed further. Some of these applications are currently in use and some others prove to be viable for further research and implementation.



Figure 2. Smart Plug Applications: Present and Future.

5.1. Energy Monitoring and Control

The most basic application of the smart plug is Energy monitoring and Control. The fundamental difference between Smart Plugs and the smart meters is that Smart meters are another type of device being used for energy monitoring but they do not provide the feature to control individual devices. Apart from that, smart plugs offer real-time insights with greater accuracy at device level whereas most of the smart meters use disaggregation algorithms to analyze the smart meter reading for measuring device level consumption. While smart plugs may have additional features to manage energy consumption on a daily basis, the insights provided by smart meters are mostly passive and require a longer cycle of observation and analysis.

5.2. Electricity Theft Detection

Electricity Theft incurs huge losses for utilities all over the world. The annual monetary losses in the top 50 emerging economies alone were estimated to be around USD 58.7 Billion [67]. With the traditional systems, it was comparatively easier to spot electricity theft manually but was highly inefficient owing to the vulnerabilities and malpractices in the system. With the increasing installation of smart meters, these incidents are becoming more and more discrete and difficult to detect. Smart meters are being hacked by tech-savvy malicious users to gain access and manipulate their electricity

readings illegally. Although there has been a lot of research on electricity theft detection using smart meter data (fine-tuned predictive models for calculating various losses), it has been difficult to implement the same in real-time [42,45,67–75]. With the implementation of smart plugs, the individual energy reading from any device can easily be compared with the smart meter data to infer whether electricity theft is taking place or not. Thus, smart plugs can provide valuable insights and a solution to the problem of electricity theft.

5.3. Energy Saving and Awareness

A certain feature of smart plugs such as standby power saving and occupancy detection will help to save energy without annual intervention by the user. The analysis of the energy savings made over a month or a year can then be included in the electricity bill to enhance energy awareness in the public domain. Also, the detection of faulty devices consuming excessive energy proves to be a benefit to both the user as well as utility. The user, on the one hand, gets to save on their electricity bill and on the other hand, the utilities can advertise up gradation and sale of new energy-saving devices. The utilities can easily provide the users with suggestions to improve their savings on energy bills by giving personalized recommendations and energy statistics on demand.

5.4. Efficient Smart Grid, Microgrid and/or Off-Grid Operations

One of the major goals of Smart grid technology is to achieve bi-directional communication between the generation end and the user end seamlessly. The present smart grid infrastructure having generation and distribution facilities in the grid must be established a communication infrastructure where the information exchange is frequent and two-way [2]. There is a clearly visible gap that needs to be bridged between the users and the distribution facilities. Smart meters are one of the devices, which are an attempt to bridge this gap but they pose considerable limitations concerning quality, frequency and accuracy of data. Wider participation of consumers in the real-time pricing of electricity based on direct communication between consumer and utility/service providers can help in managing load rejection better. Here, it is to be noticed that smart plugs can serve as the point of communication between the consumer and the utility for effective participation in the real time pricing process.

Microgrid and Off-grids will form a major part of the Smart Grid infrastructure in the near future [39,40,76–78]. These technologies are being evolved for minimal energy loss and continuous monitoring to ensure maximum efficiency. Many remote locations are being electrified and powered by off-grid systems where a conservative approach to energy usage is mandatory to cater to maximum users for maximum time.

There are various facilities bound to off-grid and microgrid systems such as motors, pumps, lighting, charging stations and so forth, which form the basic infrastructure in any location whether remote or accessible. The proper monitoring, scheduling and control of these facilities according to time of use, power available and other environmental conditions can go a long way in establishing efficient power supply systems.

Reliability is the main impact index to measure the effectiveness of any off-grid/grid integrated system. Smart plugs can play a vital role in the effective implementation of Microgrids/Smart grid. According to Reference [4], Demand Response and DER scheduling are important aspects of a smart grid that needs to be intelligently addressed. The algorithm suggested by the authors requires the device-level information to assess the time for which a certain device is unutilized. In such a scenario, smart plugs can prove to be a useful accessory. Moslehi and Kumar suggested that integrating the renewable sources of energy from consumer premises can be useful from the reliability perspective of the smart grid. At the office/home level, smart plugs have the potential to report the required data and control devices at lowered costs and increased benefit to the consumer as well. They also stressed the importance of addressing the volatility of renewable resources by harnessing data using ICT [4]. The volatile aspect of the renewable resources, which include Demand Response, availability, forecasting and scheduling can be brought down to an acceptable level. Smart plugs, if properly customized to suit

the type of renewable source being handled, can log important data for analysis, forecasting, scheduling and time-based, event-based or availability-based control of the connected devices.

In off-grid based systems, Smart plugs can prove to be a great energy management tool. They can be used at various points in the off-grid system to monitor and control the energy usage, collect energy data and set schedules for the operation of connected devices for better demand response and efficient utilization of resources. At present, the smart plugs are mostly being used at the home or office level. Their implementation at the higher end of the hierarchy of the Energy ecosystem that is, at the substation, utility, microgrid and grid level is still to be explored. Core research to customize the smart plug to the needs of the utility, substations and microgrids can be instrumental in achieving the goal of a smarter grid. The smart plug-based system is modular, easy to replicate, scalable and customize so that they can be beneficial in the long run for a utility leading to a substantial reduction in cost and time of implementation [5]. Thus, the complete chain of the Smart grid components involving the generation, distribution and user can be seamlessly connected resulting in optimal operation of each component by benefitting from each other's data and insights. Consequently, smart plugs can prove to be an important building block towards the fruitful implementation of a Smarter Grid.

5.5. Building Big-Data Framework

NILM has been a widely researched topic in recent years. There are very few elaborate datasets available to establish the ground truth for carrying out uniform research [68,69]. It is very difficult to compare the research findings of any group of researchers unless they are using a common dataset for evaluating their algorithms. The huge variations in research data used for developing, validating and testing algorithms is one of the major issues in the real-world implementation of research in the area. The data used by disaggregation algorithms for NILM is either artificially fabricated data or the dataset is very narrow to include the complete research scenario. Other issues are the unavailability of finer accurate device level data to establish ground truth and excessive noise in the smart meter data. There is also a problem of obtaining high-frequency sampling data from designed/upcoming smart plugs which is more immune from noise interference. Smart plugs can be used for establishing research data which can then provide a reliable way to evaluate and simulate NILM environments [11].

5.6. Other Auxiliary Applications

Apart from the general energy management-based application of the smart plug, the sensor data in smart plugs may be used for realizing many other applications. The occupancy detection feature is very useful for security purposes as well as for Elderly care [79,80]. The thermal and overload protection also provides an added security feature against fire hazards. Indoor positioning helps the smart plug to react instinctively to the presence of the user. The smart plug features can also add to the comfort of the user in any space by providing an automatic environment and device control. Henceforth, a smart plug with multiple sensors can be effectively used to increase the efficiency of any space in terms of energy, safety and comfort. Further research needs to be focused on integrating more and more features in the smart plug to enhance adaptability.

6. Conclusions

The review presents the various paradigms in smart plug technology. Smart plug technology will be widely used for monitoring and control energy consumptions in any spaces that incorporate electrical devices. A lot of work is continuously being done to test and integrate newer communication protocols and features into the smart plug for use in a variety of scenarios in the EnergyEcosystem. It is also observed that the applications of smart plugs are not limited to energy management and will only increase with the integration of more intelligence. With the introduction of new efficient and cost-effective IoT technologies in the future, the smart plug is expected to be in high demand in the coming years and this work intends to be a positively aggressive initiation of the future work of the group. The future work of the group is focused on developing cost-effective IoT based Energy

management systems for off-grid systems with a special focus on smart plugs. We also intend to make contributions to Device identification in smart plugs and Electricity Theft detection in the future. We firmly believe that the smart plug can prove to be a vital component in smart energy management systems leading to an even smarter grid and Smart Cities.

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