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Methodology Article

Autonomic Internet of Things for Enforced Demand Management in Smart Grid

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Abstract: Recent research in the field of Internet of Things (IoT) has concentrated on the adaptation of the autonomic computing theory to make IoT self-sufficient and self-managing. The smart grid is one popular IoT application which can greatly benefit from the adoption of autonomy. In this paper, we propose the idea of enforced demand management (EDM) in smart grid as an implementation of the autonomic computing framework. Instead of allowing all consumer appliances to be active, the smart grid can actuate and control selected appliances remotely and autonomic-ally. This will allow the smart grid to be able to exercise some control over the load and consequently the demand it faces during peak hours of usage. Subsequently, the smart grid will be able to enhance efficiency and reliability. Furthermore, cellular network requirements for enabling such a method are also highlighted for the case of Long-Term-Evolution (LTE).

Keywords: Smart Grid, Internet of Things (IoT), Wireless Sensor Networks (WSN), Autonomic Computing, Demand Response

1. Introduction

The smart grid is a promising technology to upgrade the electrical power grid using intelligent information and communications technology to produce a smarter power system. Smart grid provides a bidirectional flow of electricity and information between power source and the facilities [1]. Methods in the smart grid allow to advance configurability, reactiveness and self-management, which improve efficiency, reliability and safety of the system [2]. The smart grid merges advanced sensors, communication technology, and control methods into the current electric grid at transmission and distribution levels [3]. Many problems are faced in the design of smart grid technology, and factors such as dynamic pricing and distributed generation are to be kept in mind. Specifically, in operation of smart grid, demand side management and demand response are problems that many researchers are trying to solve [4].

By nature, the smart grid can be considered as the most important application of the Internet of Things (IoT) since the smart grid can receive telecommunication and information by its support [5]. The integration of different sensing devices, radio-frequency identification (RFID) technologies, remotely based sensors and smart objects makes up the IoT [6]. IoT aims to establish connections between every object using the Internet, and allow for innovative applications using web services. These connections include human-to-machine and machine-to-machine (M2M) connections that can be either wired or wireless. IoT covers all areas of life like health, education, transportation, security, home services, and, in our case, the power grid [7].

Each customer or consumer of the smart grid can be represented as a data-providing entity, generating extensive amounts of data that needs to be classified, managed, analyzed and processed. This rises up to be one of the core challenges that current IoT technology faces due to the extremely large amount of smart grid customers. Nodes in the smart grid, such as smart meters, will further contribute to number of connected devices in IoT; the numbers of which are expected to touch 30 to 50 billion devices by 2020 [8].

In this regard, the main advantage offered by IoT is that it enables opportunities for actuation in the smart grid. Traditionally, information about power consumption and power generation is sensed and transmitted to a central entity for decision making. The added feature of actuation will allow for remote control of any connected node over the smart grid using the Internet. Obviously, the popular problem of scalability still exists in such a setup, and so does the problem of security [9]. As the system increases in size, human capacity will fail to manually manage and control the system, especially as we consider billions of nodes and connections. This calls for a self-managed smart system with an efficient algorithm that can automatically control the input and output signals according to given priorities to result with an efficient, cost-effective performance.

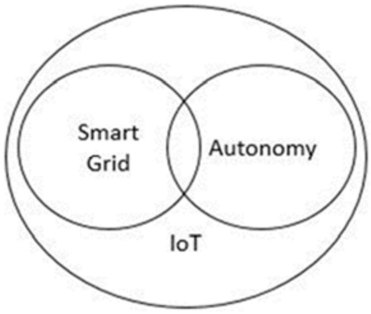

Figure 1. *Venn diagram showing the relation between IoT, autonomy and the smart grid technology sets.*

One of the innovative methods to solve this is by re-designing the smart grid in an autonomic way. The term “autonomic” is derived from the principles of autonomic computing that was introduced by IBM in 2003 as a new paradigm in managing complex information systems [10]. An autonomic system is defined as a dynamic system, or system of systems that can work without any intervention by humans [11]. Intelligence in such a system is manifest through the properties of self-management, self-operation, self-configuration, self-optimization and self-decision. The key objective of autonomic computing in this research is the management of house appliances in a way to reduce utilization of power, and thereby reduce demand of electricity during peak load hours [12]. This will boost the competence and consistency of the smart grid distribution network which still remains a critical goal for utilities.

The traditional methods utilizing manual management are impractical. Autonomic computing provides an efficient way of handling the large number of device by reducing user involvement. Inefficiencies of manual maintenance can be overcome by the intelligent and dynamic management schemes, which are autonomic in nature [10]. The process of decision making can be simplified with autonomy for functions of device management, access management, and identity management. With the adaptation of IoT technology with the smart grid, the smart grid components can be mirrored in the same way as IoT autonomic components and controlled using the autonomic framework [12].

Smart grid and autonomic schemes form two application sub-sets of IoT. Schemes based on autonomic computing are applicable in a growing number of IoT projects as it generally leads to automatic smart systems and devices with minimal human intervention. Figure 1 shows the relation between the three. Currently, not all of smart grid technology is autonomic. However, the addition of autonomic principles can offer a tremendous advantage to the smart grid.

The most important contribution of this paper is the idea of enforced demand management (EDM). This paper is organized as follows. Section 2 summarizes the research areas. Section 3 presents the proposed EDM methodology and Section 4 presents network infrastructure requirements. Finally, Section 5 concludes the discussion.

2. Research Areas

Before the idea is discussed in detail, it is important to summarize few supporting technologies. In this section, the motivation is developed to further appreciate the concept of EDM, by highlighting current problems in the smart grid, and the role of IoT.

2.1. Smart Grid Enabling Technologies

2.1.1. Wide Area Networks (WAN)

WANs are popular because of the restricted capabilities of wired communication setups in areas with dynamic requirements such as constrained geographic subareas [13]. Therefore, a wireless smart grid communication system is important as it can minimize the cost of equipment, installation and maintenance rather than using wired networks [14]. The actual structure of smart grid communication consists of multiple layers of sub-structures and protocols [13]. These protocols span the entire scope of the smart grid from home area networks (HANs), transmission networks as well as WANs.

HANs are a small scale of networks that occur within the locality of a house. HANs are typically implemented to connect multiple, intelligent devices in order to provide energy efficiency, management and user initiated demand response. Meanwhile, neighborhood area networks (NANs) are defined as services, or outdoor access networks which connect multiple HANs to local access points [15]. WANs (traditionally termed as backhaul networks) are large scale and cover the metropolitan, regional, international and also communication between the NANs and the utility systems.

2.1.2. Machine to Machine (M2M)

In M2M communication, a large number of smart devices communicate automatically using both wireless and wired systems [16]. In this communication paradigm, devices and servers share information and make decisions automatically, as they are able to explore the environment and learn how to take advantage of the each other’s data [17]. In M2M communication in smart grid, smart meters act as primary data generation devices using mobile type communication

(MTC) protocols. Typically, these devices send data to the smart grid server (MTC server) through universal mobile telecommunications system (UMTS) as an operator network [18].

From a networking perspective, the smart grid is essentially a huge sensor network comprising of meters, appliances and electrical facilities. By utilizing the technology of M2M, several aspects of smart grid such as data management, providing quality of service, efficiency of network and protocols, security, device management and demand response can achieve significant improvement in quality [17].

Complex entities inside the smart grid lead to big challenges in developing remote management procedures as well as demand response activities that are directed to the peak hours' problem. By shifting user demand from "on peak" to "off peak", the smart grid can lower the peak demand which eventually decreases cost. Designing communication architecture in this scenario is a huge challenge as it should be suitable for all devices in the smart grid [19].

2.1.3. Sensing and Actuation

Cooper and James [20] have stated that data in IoT and smart grid can been categorized into different areas. One such area corresponds to command data that can be used to control remote devices connected to the Internet. There are a few requirements to be considered such as how to represent the state of the device, and how to control the device depending on its functionality. This calls for a feedback system that can operate over the Internet. Subsequently, many obstacles arise such as the delays involved in sensing the input and the transmission delays, especially for a real-time system where the system can experience a constant stream of data. Examples are smart homes and energy monitoring systems [21]. Additionally, a standardized language for communication is essential to allow easy integration between systems, and easy control over existing devices. Here, IoT protocols offer a wide variety of help with a growing number of light weight communication standards and open source community.

A feedback system also allows us to track down the changes that the system has been facing, and the ability to control each part of the system remotely promotes efficiency to the system [22]. This is done with the help of the previous data generated and also in accordance to user interaction. The architecture of the controlling devices can follow different styles based on the complexity and logic behind each specific sensor network connected to the smart grid.

2.2. Demand Side Management

Demand side management (DSM) has been defined as planning, implementing and monitoring activities with the goal to affect consumer's use of electricity. This is done to receive desired change in the utility's load shape or time pattern magnitude of utility's load [23]. Broad load shaping objectives is a convenient term for DSM from utility's point of view, which can be interconnected and flexible programs that shifts the demand during peak periods. We can consider DSM as an essential ingredient for the smart grid, as we need to shape user's energy consumption to seek social benefits and to implement social objectives. To implement social benefits, we need to collect information about users and their energy consumption behavior, which is the actual challenge.

So far different techniques of DSM have been offered, such as voluntary load management programs [24] and direct load control [25] but smart pricing is the one of the most efficient tools offered. This tool mostly concentrates on cooperation by users to encourage them to consume wisely and more efficiently. Increasing the price of electricity according to the peak periods makes users willing to flow DSM programs in order to receive discounts in their bills. Flat pricing, peak load pricing and adaptive pricing [26]-[27] are some of the several methods that has been proposed recently. The general idea of all of these methods is that at the low demand hours, users will receive lower price and at the high demand hours, higher price will be charged. This encourages consumers to conserve energy at high demand hours. However, many of the users after applying these methods didn't notice the difference in the prices as their consumption wasn't high enough in the first place [28]. Another option in DSM is direct load control (DLC), where, based on an agreement between the utility and the customers, the utility remotely controls the operation of certain appliances in a household.

2.3. Demand Response

During peak hours, the demand increases beyond what the supply can provide. This makes electricity prices during peak hours more expensive than normal hours. With significantly high demand, a blackout can be caused unless a counter measure is taken beforehand. One of the solutions to this problem is demand response. It basically describes programs that encourages users to be more energy efficient by willingly reducing the load during peak hours for an exchange of benefit. This helps the electrical system lower the load significantly during peak hours and thus reduces the prices for the users and the prices for maintaining the electrical load during peak hours [29].

3. Enforced Demand Management

The following subsections contain the design requirements for the idea of EDM.

3.1. Design Requirements

3.1.1. Feedback System

To make the demand response more rewarding, IoT can be integrated to facilitate easier control over various appliances. However, to ensure efficiency, this needs to be implemented through an effective, reliable and scalable platform. Also, appliances need to use a protocol that can last with the changing technologies. We assume that generally most appliances last for 10+ years. In [30], it is suggested to make appliance's software modular-based in order for appliances to integrate the demand response concept with the IoT. Another idea is to add an external device at the power source to enable control. There's more than one method to it, for example intrusive and non-intrusive sensor networks may work as actuators as well, provided that the smart grid can identify the devices, and process and transmit the information securely.

A feedback system has the ability to track the recent changes that has occurred to the system, and various types of details regarding the appliances' conditions and output. Using the information taken, a decision can be taken to utilize the demand for the supply given.

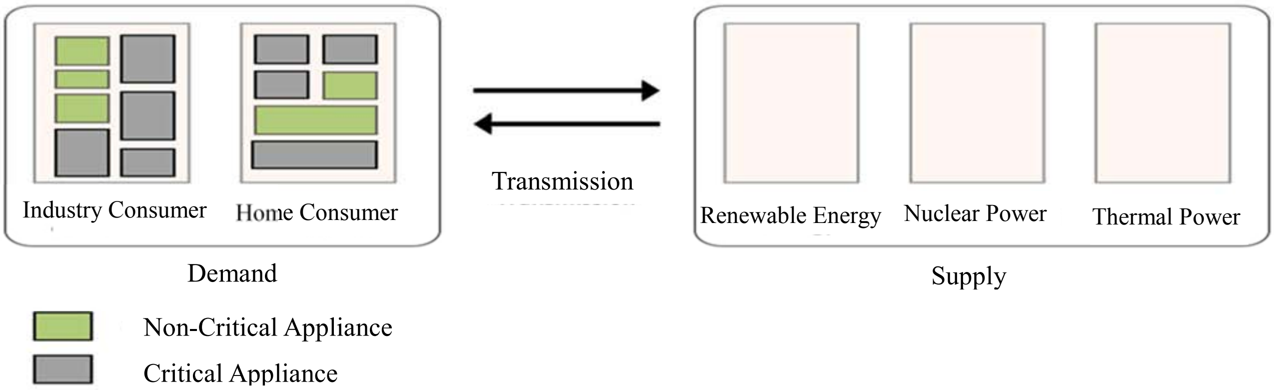

Figure 2. *Demand side critical and non-critical appliances in the smart grid transmission network.*

3.1.2. Minimized Human Interaction

In order for the system to work efficiently while providing quality, security and ability to manage huge amounts of data, human interaction needs to be minimized and replaced by a smart algorithm and supporting devices to monitor the state of the system. This is a way that can help to reduce resources and errors. This will result in an effective solution that increases the positive outcome of demand response.

3.1.3. Selected Devices and Appliances

While bearing in mind the significant positive results of demand response, some devices can't just be switched off randomly. These kind of devices are termed as "Critical Devices" and switching them off suddenly or lowering their usage of the load can lead to unpleasant consequences and even appliance damage. For example, switching off the main air conditioner while it's being used is not recommended and it is better to control an alternative for load shedding. Instead, "Non-Critical Devices" can be selected by either following a planned and detailed endorsed database or by manual configuration. Only a set of selected devices will follow the enforced demand response plan. This should provide convenience for the users while significantly improving the demand response especially if we consider a huge smart grid with thousands of nodes representing residential homes, industrial elements, and other high load consuming components. However, this method is only recommended for consumers that are able to meet a minimum requirement of saving depending on the type of user.

Figure 2 presents industrial and home consumers as demand generators and electricity generation companies as suppliers. This system has bidirectional communication and transmits both electricity and data between the two stakeholders. Using a feedback system, the electric company has information about critical and non-critical appliances in the demand side which will help the system to make smarter choices that are efficient and at the same time will satisfy consumers.

3.1.4. Business Compensation System

To ensure convenient service while attracting users to the system, incentives need to be created in order for the system to achieve its objectives. The more the user saves and helps the smart grid during peak hours, the more reward they can get. These rewarding mechanisms can be:

- Decreasing the load during peak hours has significant positive impact on the supply, but it cannot be done without the help and cooperation of demand. To achieve that, different packages of benefits can be introduced to the consumers that may include financial benefits or lowered rates at different times of the day.
- Manual configuration can be done by the users to select the specific set of devices to be affected during peak hours. This allows for flexible and potentially a higher level of participation, since different users may have different preferences that may result in different rewards, which will drive their motive, including of course energy efficient methods.

3.2. Autonomic Decision Making

The theory of autonomic computing revolves heavily around the monitor, analyze, plan and execute (MAPE) control loop [31]. Autonomy through the control loop is implemented by two components viz. an autonomic manager and an autonomic managed resource. The MAPE control loop is not a sequentially constrained process, but is a structural arrangement of its constituent sub-processes. Adapting the theory of autonomic computing means to follow the architectural elements suggested by the autonomic control loop.

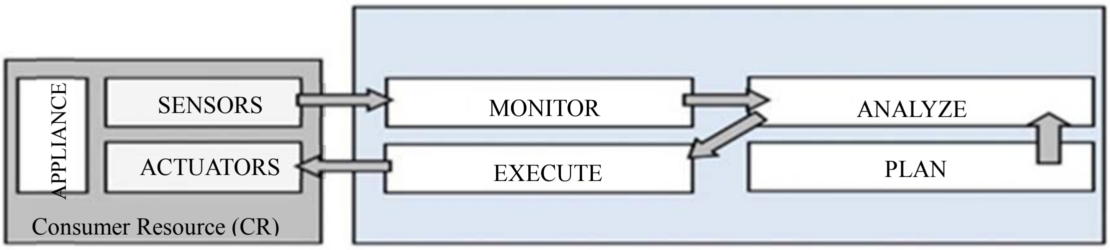

Figure 3. *The smart grid autonomic manager and the consumer managed resource as agents of the MAPE control loop.*

Figure 3 presents two components, 1) the smart grid autonomic manager (SGAM), and, 2) the consumer resource (CR). SGAM takes on the core functionalities of the MAPE control loop, whereas the actual sensing and actuation is done in the CR. The CR is geographically placed close to the appliance to be remotely controlled. It could either be an agent running in the appliances software, or an external hardware responsible for the power supply to the appliance. In either case, the CR should be able to provide feedback to the monitor module in the smart grid.

During a given time of the day, or upon failure in electricity generation, the smart grid can chose to implement EDM. Let's consider the following scenario in a local neighborhood comprising 1000 households. If the smart grid can enforce a specific non-critical appliance (such as a fridge) to be switched off in 1000 houses for a given short time duration, it would definitely have an impact on the total demand faced by the smart grid. The smart grid could then take 100 different houses and enforce the demand in a similar manner. By doing this, the functionality of the fridge is not compromised as the temperature wouldn't fluctuate much in a short duration. Obviously, fridges which can be turned off in such a manner will be preferred; perhaps not smart fridges. Since, it is the consumer who would be selecting the appliance based on a standard procedure, the risk to the appliance would be minimal. Eventually, the smart grid will be able to exhibit a level of automation in execution.

4. Network Infrastructure Requirement

Cellular M2M technology has been around in the market since year 1995 and Global System for Mobile Communication (GSM) communication is the dominant mobile technology. Most of the early M2M applications are built using GPRS/EDGE connectivity. Until the year of 2015, 124 countries have deployed the LTE service and 18 countries have scheduled for LTE service [32]. LTE-M, an evolution of LTE optimized for IoT in 3GPP RAN with its' first released in Rel-12 in Q4 2014 and further optimization in Rel-13 in Q1 2016, has emerged as the LTE solution for M2M application. However, the device cost is still significantly high and not suitable for massive IoT deployment. Thus, Narrowband IoT (NB-IoT) is introduced in 3GPP Rel-13 to further address improved indoor coverage, support for massive number of low throughput devices, low delay sensitivity, ultra-low device cost, low device power consumption and optimized network architecture for supporting M2M communication.

NB-IoT is deemed suitable for smart metering and smart grid management. The targeted throughput for downlink (DL) is 250kbps. Meanwhile, the targeted throughput for uplink (UL) is 20kbps for single tone and 250kbps for multi-tone. A further 5dB improvement in link budget compared to LTE-M allows the indoor signal penetration of smart meters that usually placed in the basement. Cutting the complexity of transceiver by lowering the peak rate and limiting the channel bandwidth to 180 kHz further reduces the cost of LTE module to be less than USD 5. The battery life is further improved by allowing the device to go into sleep mode more often. The device will only wake up if necessary. Optimizing the core network architecture supports more connected devices per cell and subsequently allowing less number of base stations to cover a wider geographical area with many smart meters. Low cost authentication method coupled with embedded SIM in the LTE NB-IoT module is further implemented to reduce the energy consumption and cost of deployment.

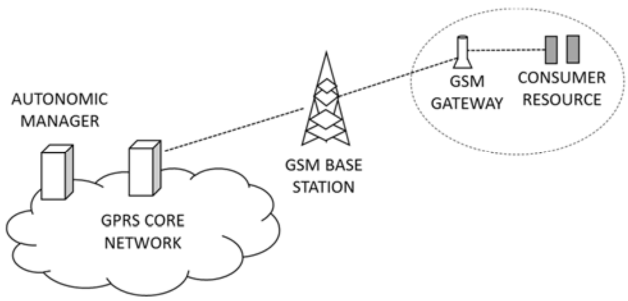

Figure 4. *Smart Metering using Traditional Cellular Network.*

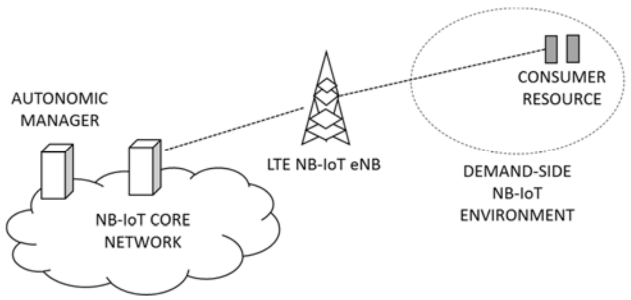

Figure 5. *Coverage Expansion and Demand-Side Management Support using NB-IoT.*

As illustrated in Figure 4, a smart meter for GSM requires a GSM gateway as packet concentrator to achieve communication for the most basic IoT smart grid application. Data from all the smart meters will first aggregate at the GSM gateway before sending to GPRS core network. In this typical GSM deployment, the smart meters usually communicate using Wi-Fi, Zigbee and etc. The coverage is limited up to 100 meters. An autonomic manager can exist in such a setup. For NB-IoT deployment, all the smart meters equipped with NB-IoT connectivity module can directly communicate with LTE eNB. The coverage range is even better than the current cellular technology. Data from the smart meter is sent to NB-IoT core network directly and the intermediate gateway can be eliminated. In addition, the advantage offered by NB-IoT will be to allow demand-side management if the NB-IoT modules are installed at the appliance level instead of just limiting to the smart meters such as shown in Figure 5.

The new work item [33] is going to be started in Q3 2016 to further enhance the Rel-13 NB-IoT design. Positioning is one of the features for Rel-14 NB-IoT so that traffic reporting can be sent together with location. If faulty is detected on the smart meter, the repair process can be speed up. Besides, multi-cast support is going to be introduced to allow firmware or software upgrade instead of in-field device replacement. LTE resources for NB-IoT are further optimized to reduce the number of signaling before UL transmission. Even with these enhancements, the ultra-low cost and complexity of the Rel-13 NB-IoT UE will still remain.

Future 3GPP standardization efforts can include items for supporting EDM in a smart grid environment.

5. Conclusion

In this paper, we proposed the idea of EDM as a method to enable DLC automation. Instead of allowing all appliances to be active, the smart grid can actuate and control selected loads remotely. This will allow the smart grid to be able to exercise some control over the demand it faces during peak hours of usage. This idea is a result of the recent advances in IoT which have focused on the adaptation of the autonomic computing paradigm to make IoT self-sufficient. Furthermore, network support from LTE NB-IoT technology was also discussed.

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