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"A Review On Different Energy Efficient Communication In Smart Grid"

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ABSTRACT –

Electricity is a core utility for the functioning of society and for the services provided by information and communication technologies (ICTs). Several concepts of the smart grid, such as dynamic pricing, distributed generation, and demand management, have significantly impacted the operation of ICT services, in particular, communication networks and data centers. Ongoing energy-efficiency and operational expenditures reduction efforts in communication networks and data centers have gained another dimension with those smart grid concepts. In this paper, we provide a comprehensive survey on the smart grid-driven approaches in energy-efficient communications and data centers, and the interaction between smart grid and information and communication infrastructures. Although the studies on smart grid, energy-efficient communications, and green data centers have been separately surveyed in previous studies, to this end, research that falls in the intersection of those fields has not been properly classified and surveyed yet. We start our survey by providing background information on the smart grid and continue with surveying smart grid-driven approaches in energy-efficient communication systems, followed by energy, cost and emission minimizing approaches in data centers, and the corresponding cloud network infrastructure. We discuss the open issues in smart grid-driven approaches in ICTs and point some important research directions such as the distributed renewable energy generation capability-coupled communication infrastructures, optimum energy-efficient network design for the smart grid environment the impact of green communication techniques on the reliability and latency requirements of smart grid data, workload consolidation with smart grid-awareness, and many more. Smart grid has modernized the way electricity is generated, transported, distributed, and consumed by integrating advanced sensing, communications, and control in the day-to-day operation of the grid.

Key Words: Data centers, distributed generation, dynamic pricing, energy-efficiency, green communications, renewable energy, smart grid, sustainability.

1. INTRODUCTION

The objective of this paper is to develop a comprehensive survey on the smart grid-driven approaches in energy-efficient communications and data centers, and the interaction between smart grid and information and communication infrastructures. Although the studies on smart grid, energy-efficient communications. Increasing electricity prices, diminishing fossil fuels and rising concerns on Greenhouse Gas (GHG) emissions have called for the modernization of the power grid, in which Information and Communication Technologies (ICTs) are playing the key role. Smart grid adopts the cutting-edge technology in generation, transmission, delivery, consumption and storage of electricity. ICTs bring significant innovations in these areas, as sense, communicate and control functionalities are becoming the standard practice in smart grid deployments. Meanwhile, modernization of the grid brings forward new concepts such as Time of Use (ToU), real-time pricing, distributed generation, demand management which impact the Operational Expenditures (OPEX) and emissions of the information and communication infrastructure. In particular, communication networks and data centers, being the largest power consumers and GHG emitters among other ICTs, benefit from smart grid-driven techniques to enhance energy savings and emission reductions. For the past decade, telecommunication companies have been seeking ways to reduce their electricity bills as well as their energy consumption and emissions. The research in the field of energy-efficient communications targets communication networks with less OPEX, less power consumption and less emissions with minimal service degradation. To this end, vast amount of research has been performed in energy-efficient wireless, wire line and optical communications. Nevertheless, ToU, demand management, renewable-dominated supply selection or briefly smart grid-driven techniques can further bring down the bills; reduce the amount of energy consumption and emission release of the operators.

Besides telecommunication companies, data center operators are impacted by high electricity prices and carbon costs. Combined electricity demand of telecommunication networks and data centers is reported to be equivalent to the demand of the fifth largest country. Therefore, green data centers have been another major research track in the past several years. To this end, smart grid-driven techniques have been implemented through price- or emission-aware workload consolidation and migration as well as renewable powered data centers.

Implementation of wireless communications and data centers in connection with the smart grid is illustrated in Fig. 1 including the power flow in the grid. Electricity is transported to the consumers over the transmission and distribution system similar to the legacy grid, while in addition, consumers can become power generators and sell power the grid according to the novel distributed generation practices of the smart grid. In the smart grid, all of the entities are connected through communications. In the figure only wireless technologies are presented but as will be discussed later on in this paper, using optical and wire line communications is also possible. In the figure, data collected from sensors and meters are fed into the utility headquarters and stored in cloud data centers.

2. SMART GRID: OVERVIEW

Smart grid integrates advanced sensing, communication and control functionalities in the power grid's operation, for the purpose of enhanced efficiency, reliability, security and reduced emissions. The legacy grid involved sensing, communication and control functionalities to some extent; however the advances in ICTs have necessitated bottom-up modernization of the cyber and the physical elements of the power grid. Smart grid aims to increase its efficiency by integrating renewables into the energy mix, employing smart demand management and by adopting techniques to reduce the losses over the power lines.

Meanwhile, smart grid aims to enhance its reliability without falling into the pitfalls of the traditional approaches, i.e. over provisioning of the resources. Reliability corresponds to 100% availability of the electricity as well as protection against power quality fluctuations and operation in isolated mode in unexpected circumstances such as natural disasters or terrorist attacks. In addition, smart grid desires to have improved security. Security of the physical smart grid infrastructure refers to the security of the utility assets such as substations, overhead power lines, towers, generators, batteries, as well as the customer equipment, e.g. smart meters, smart thermostats that may be controlled by the utility while security in the cyber domain refers to secure communications and secure software tools that preserve the corporate, infrastructure and customer information. The readers who are interested on a detailed survey on smart grid security are referred.

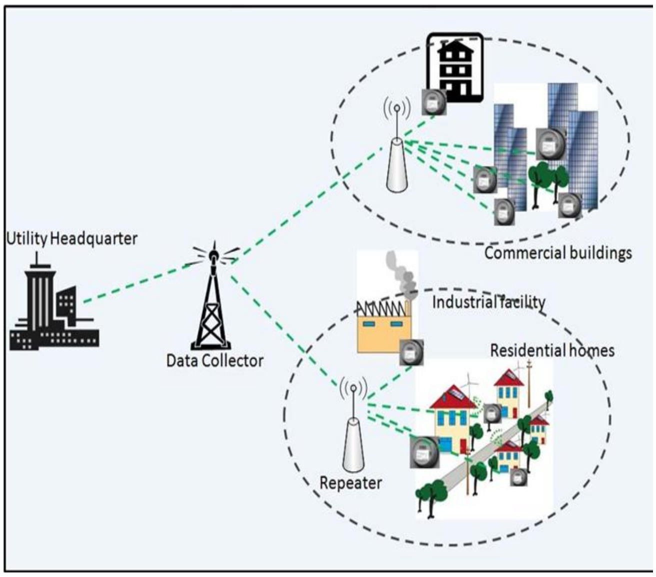

Fig 1: A Typical AMI network

Advanced communications enable smart grid to device variable pricing policies such as ToU and real-time pricing. The variable pricing of electricity can be either based on historical demand data or real-time demand and supply condition. In either options, electricity has higher price during high demand than the price set for low demand periods. ToU uses the seasonal and daily demand information collected over the years and real-time pricing uses the hour-to-hour market price of electricity. With the installation of smart meters, variable pricing and corresponding billing actions have become feasible in the smart grid.

Variable pricing policies lead to price-following demand management. In legacy demand response programs, utility operators used to call large-scale customers such as industrial plant operators or building operators and ask them reduce their consumption during critical grid conditions by offering some incentives. This type of demand response is not convenient for small-scale customers nor for dynamic pricing, therefore in the smart grid price-following has demand management become the common practice. In this context, smart grid adopts diverse communication technologies to support remote smart meter reading and price-following demand management.

The network of smart meters is known as the Advanced Metering Infrastructure (AMI). AMI may be implemented using a wide variety of communication technologies that allow remote configuration, meter reading and appliance control. For instance, IEEE 802.15.4g is being developed for the utility-to-meter communications while IEEE 802.11b/g is another standard available in many smart meters. Cellular, Worldwide Interoperability for Microwave Access (WIMAX) and narrow-band wireless communications are also among the utilized technologies for AMI. Furthermore, cognitive radio using TV white spaces has emerged as an alternative to costly cellular communications, especially for coverage in rural areas. In addition, the technique known as Power Line Communications (PLC) emerges as a strong candidate for the AMI. A typical AMI using cellular communications is presented. In a broader context, AMI is seen as an ideal application of Machine-to-Machine (M2M) communications while M2M communications will also become useful for self-organization of micro grids, remote control of home appliances, and interaction of distributed renewable energy generation resources and so on.

As for price-following demand management, the past several years have seen a tremendous interest in the development of residential demand management techniques. In general, based on prediction of consumption patterns, consumer demands are shifted to less expensive timeslots to reduce energy expenses of the consumers and to reduce the peak-to-average ratio of the grid. Several studies apply optimization models while others use neural networks or game-theory. Furthermore, sensor networking technology has been considered as an integral part of residential demand management. As communication technologies are getting more and more integrated in the smart grid, reliability of communication and its impact of smart grid applications has been a relevant research direction as well.

The novelties included in the developing smart grid are not limited to pricing policies and demand management. Energy flow from the customers to the grid or energy transactions among communities or advanced monitoring solutions for the transmission and distribution systems are among the new concepts of the smart grid. For instance, wide area measurement and situational awareness components are gaining large deployment opportunities. In the U.S., there is a momentum for dense deployment of phasor measurement units (PMUs) and other wide area measurement instruments in the power grid1. Close to 1000 PMUs are planned to be up and running in substations and power plants in the U.S. in the near future.

Efficient integration of renewable energy, in parallel with the governments' targets of reducing GHG emissions, is another driving factor for an enhanced grid. The energy sector is one of the major GHG emitting sectors, therefore utilizing resources such as solar, wind, tidal or biomass will significantly reduce its emissions. Among those renewable resources, solar and wind power are available in most of the parts of the world while their contribution to the energy mix of today's power grids is fairly low. This is due to their intermittent nature since, without efficient storage or backup capacity, fluctuation in their generation output may risk the operation of the grid. According to a US-based independent system operator (ISO), 9000 MW of wind generation requires an additional of 1150 MW of capacity for regulation and ramping purposes. Once again, advance sensing, communication and control functionalities help the in-tegration of such intermittent energy resources. For example, sensors collect weather-related data, feed them to the grid operators through near-real-time communications and control actions are implemented for dispatching more power from other sources, ramping or load shedding. Besides, the challenges of renewable energy generation, management of large-scale, distributed generators emerges as a significant problem where researchers from the NSF future renewable electric energy de-livery and management (FREEDM) systems center seek solutions for. In relation to renewable energy integration, convenient energy storage is essential where advanced storage technologies are becoming an integral part of the smart grid. Distribution automation is another important feature that will transform the legacy grid into a smart grid.

Finally, the smart grid technologies are closely related to Electric Vehicle Charging Infrastructure (EVCI) since Electric Vehicles (EVs) require a reliable and digitized grid for battery charging. The past couple of years have seen a significant amount of studies addressing the challenges of charging EVs from the power grid, as well as using EV batteries for the benefit of smart grid. The former is known as Grid-to-Vehicle (G2V) energy flow while the latter is called Vehicle-to-Grid (V2G) energy flow [68]. EV charging is challenging because it is expected to be aligned with the evening peak demand, adding to the stress on the grid that is already operating close to its operational limits. Thus, uncontrolled vehicle charging is overload transformers and harm utility equipment, degrade power quality, increase power losses and cause voltage problems. The coordination of vehicle loads, and utilization of vehicle batteries for ancillary services have been studied in several works such as. For a more complete survey of electrification of transportation interested readers are referred to. The interaction of smart grid with the transportation industry is out of the scope of this survey.

3. ENERGY-EFFICIENT COMMUNICATIONS AND THE SMART GRID

Energy-efficiency has been an integral part of networks that consist of battery-run nodes such as sensor nodes or mobile phones while energy-efficiency of network equipment powered from mains such as base stations, switches, routers has not been under the spotlight until recently. In parallel to the increasing number of subscribers and their diverse demands, electricity bills of network operators have been skyrocketing. As a result, a significant amount of academic and industry efforts have been put into reducing the energy consumption of core and access network equipment. Along with the traditional electricity costs, large amount of GHG emissions of communication networks is foreseen to add more costs to the operators with the forth-coming carbon taxes and caps. Price-following demand management of smart grid can be employed by the communications infrastructure to reduce electricity bills where this can be also extended to emission-following load management of the equipment. On one side smart grid-driven approaches impact the way energy-efficient communication technologies are implemented, on the other side smart grid involves dense communications and it is impacted from energy-efficiency techniques. This section summarizes the works that study the mutual impacts of smart grid and energy-efficient communications. We have grouped these studies under wireless, wire line and optical networks and for each type of network, we focus on the appropriate smart grid domain. Energy-efficiency of battery-run, hand-held devices and Wireless Sensor Networks (WSNs) are beyond the scope of this survey since their energy-efficiency aims at increasing the lifetime of the network or the device considering their limited battery power.

The smart grid can be roughly divided into three domains in terms of communication coverage and functionality; Smart Grid Home Area Network (SG-HAN), Smart Grid Neighbor-hood Area Network (SG-NAN) and Smart Grid Wide Area Network (SG-WAN). SG-HAN is a single residential unit with smart appliances, an energy display, power consumption control tools, storage, solar panels, small-scale wind turbines, electric vehicles and a smart meter. A SG-NAN corresponds to a group of houses possibly fed by the same transformer. Advanced Metering Infrastructure (AMI) collects smart grid data from the premises in a SG-NAN and aggregates the meter data before they are sent to SG-WAN which connects SG-NANs to the utility operator. From the utility perspective, besides metering, equipment in the field needs to be monitored and con-trolled. Hence the equipment in the field are managed by a separate network which is called as Smart Grid Field Area Network (SG-FAN). The geographical scale of a SG-FAN is similar to SG-NAN therefore similar communication technologies are applicable for both. These network domains can be implemented using a variety of communication technologies. For instance, due to their wide coverage fiber optic, UMTS, LTE/LTE-A may be more convenient for SG-WAN while IEEE 802.11, IEEE 802.15.4, PLC would be more suitable for SG-NAN and SG-HAN. In [76], the authors provide a comprehensive survey on routing techniques and applications in each of those domains. In the following sections, we will provide a survey of energy-efficient wireless, wire line and optical communications tailored for each smart grid domain.

3.1 Energy-Efficient Wireless Communication

Wireless communications can be employed in a wide range of smart grid applications including, meter data collection, demand management, substation and power line monitoring and protection. For the sake of clarity, in the next three sections, we present wireless communications that are used or planned to be used in SG-WAN, SG-NAN, and SG-HAN, respectively.

3.2 Energy-Efficient Wireless Communications for SG-WAN:

In wireless communications, energy-efficiency is generally quantified by the "bits-per-joule" metric which corresponds to throughput versus unit energy consumption [13]. Here, the definition of throughput may include the whole transmitted bits or it may only refer to the actual data that excludes headers, signaling bits, duplicate packets and transmission errors. Furthermore, the majority of the studies in the domain of energy-efficiency focus on optimizing transmits power and ignores the circuit power and power needed for cooling the equipment. Al-though a holistic metric and an approach is not available in the literature, even focusing only on energy-efficient transmission has resulted in significant power savings.Third generation (3G) and fourth generation (4G) cellular networks are expected to be densely used in the SG-WAN. They provide the convenience of using the existing infrastructure and wide coverage with high data rates. For instance, KEPCO KDN Co. offers a transmission line surveillance system that uses laser scans to monitor the surroundings of power lines and sends an SMS notification in case of an alarm. Another industry example comes from Qualcomm Inc. and Echelon Inc. who are using Verizon's and T-mobile's infrastructures, respectively, to provide cellular connectivity for smart meters. Furthermore, with the adoption of high data rate Long Term Evolution (LTE) and LTE Advanced (LTE-A) technologies, the cellular networks will be able to carry the high-volume PMU data. The peak data rates for LTE is around 300 Mbps at the downlink and 80 Mbps at the uplink with 20 MHz channel bandwidth and 4 × 4 Multiple Input Multiple Output (MIMO) antennas. On the other hand, with 70 MHz channel bandwidth and 4 × 4 MIMO antennas, LTE-A's targeted peak downlink transmission rate is 1 Gbps and the uplink transmission rate is 500 Mbps. In addition to their high speed, LTE and LTE-A employs the relaying technique to extend the typical cell diameter. Relaying technique is specifically useful for connecting geographically spread smart meters in rural areas.

3.3 Energy-Efficient Wireless Communications for SG-NAN:

SG-NAN is one of the crucial domains that glue utility net-works with the customer networks. It carries a large volume of heterogeneous data and supports a large number of devices. Similar to SG-WAN, 3G, 4G and WIMAX can be utilized in the SG-NAN. In addition, IEEE 802.11 family of standards offers promising deployments for urban SG-NANs.

Recently, several IEEE 802.11 standards have adopted power saving mode (PSM) in their operations. IEEE 802.11b and IEEE 802.11s utilize PSM to allow wireless nodes sleep when they are not receiving or transmitting. IEEE 802.11b is widely used for residential premises therefore it is also preferred for SG-HANs while IEEE 802.11s, the mesh standard has been considered as a promising candidate for the electric vehicle charging network. In, the authors study the performance of IEEE 802.11s in an admission control scenario for electric vehicles. PSM can be considered for IEEE 802.11 based SG-NAN communications however the drawback of the PSM is the additional delay which is the common tradeoff in all sleep-based schemes. Delay-tolerant SG-NAN data may not be impacted from PSM however; communications for controlling real-time operations may experience service degradation. For instance, in an electric vehicle charging network connected via IEEE 802.11s, increased delay due to sleeping nodes can cause severe damages to the distribution system if a control command from the utility that restricts charging happens to be delivered with extensive delay. For this reason, the impacts of PSM over the smart grid operation need to be further explored.

3.4 Energy-Efficient Wireless Communications for SG-HAN:

Zigbee is one of the widely adopted smart home and smart energy standards in SG-HANs. Presently, there are various Zigbee certified products for home automation and several smart meter vendors such as Landis+Gyr, Itron and Elster have manufactured Zigbee-enabled smart meters. ZigBee Alliance has also developed Smart Energy Profile (SEP) to support the needs of smart metering and AMI, and provide communication among utilities and household devices. Zigbee is a short-range, low-data rate wireless technology that is based on the IEEE 802.15.4 standard. Zigbee has been initially designed for power-constrained sensor networks; there-fore energy efficiency is an intrinsic property of Zigbee. It employs duty-cycling to increase the network lifetime. In the authors utilize a Zigbee-based WSN for demand management in the SG-HAN.

3.5 Energy-Efficient Wire line Communications:

Wire line communication technologies may be used to implement a SG-HAN and SG-NAN. In this context, PLC and Energy Efficient Ethernet (EEE) are among promising wire line communications. PLC uses low voltage power lines as the communication medium for data. PLC is already being used by some utilities for load control and remote metering. Energy efficiency of the PLC has been studied in [103] and a spectrum sensing scheme has been introduced to reduce its power consumption. In [104], the authors have extended this work to include resource allocation. Transmission parameters have been selected carefully to mitigate interference in contrast to the former approach of passively avoiding interference. Interference mitigation relies on a signal detection function whose durations are optimized with a limitation on power budget. Another energy-efficient PLC scheme has been proposed in where the authors have energy-efficiency as a bound for infinite transmissions and introduce a green resource allocation scheme. The scheme optimizes the quantity of information allocated to each channel when parallel channels are available. As a PLC standard tailored for smart grid applications, Home Plug Alliance has recently adopted power saving mode within its Green PHY 1.1 definition. A central coordinator is responsible for sleep/wake up schedules of connected devices in order to avoid devices waking up at different times.

3.6 Energy-Efficient Optical Networks

Fiber optical networks offer high speed, large bandwidth and high degree of reliability that has enabled them to be widely deployed as the basic physical network infrastructure. Optical networks have been traditionally implemented in a hierarchical structure consisting of core, metro and access domains. In general, a core network provides nationwide coverage with a few hundreds to a few thousands kilometers of optical fibers. A metro network provides coverage for a metropolitan area with optical fibers of a few tens to a few hundreds of kilometers length. Meanwhile access networks reach the customer and run between the service provider and the customer which typically uses optical fibers of a few kilometers in length. Energy-efficiency has found its way into all of those three domains including energy-efficient components, transmission, network design or applications. Optical communications may be used in SG-WAN or SG-NAN where the former is implemented by core technologies and the latter with metro or access technologies. SG-HANs can be implemented by visible light technology which is a fairly new, high data rate communication technology [109]. However, this is out of the scope of this survey since energy-efficiency of visible light communications nor its use in smart grid has been explored so far.

3.7 Energy-Efficient Optical Communications for SG-WAN:

A single core network equipment is one of the most power hungry elements of the telecom optical networks [17]. A core IP router port consumes approximately 1000 W, whereas the maximum power consumption of an optical network unit

(ONU) operating in the access network is around 5 W [110]. Therefore significant research efforts have been put into addressing the energy efficiency of the core network.

In smart grid, information flow between ISOs in distant regions utilizes the core network infrastructure. For instance, wide area measurements taken under the control of an ISO, can be delivered to another ISO for protection purposes. Although smart grid data will be carried over the same core infrastructure with all other traffic and it is difficult to have smart grid specific energy-efficiency measures, energy-efficiency techniques will have direct impact on the QoS of smart grid applications. For this reason, this section will cover general energy-efficiency techniques in core optical networks and include several studies that consider the renewable energy and ToU-based energy-efficiency improvements. Since utilization of renewable energy and ToU are part of the big smart grid picture, those works stand out as examples of the interaction of smart grid and energy-efficient core optical communications.

3.8 Energy-Efficient Optical Communications for SG-NAN:

Most of the smart grid communications is within metro and access networks reach. Utility headquarters and offices are already connected via fiber optical networks while with the fast adoption of Fiber-to-the-Home (FTTH) technology; the number of residential subscribers are increasing. In addition, hybrid technologies are emerging as promising candidates for metro and access convergence. Thus, metro and access optical networks emerge as a strong alternative for SG-NAN communications.

Although a single access network equipment consumes much less power than a core router port, access equipment are large in quantity, hence they consume significant amount of power in total. According to [18], access networks contribute to 70% of power consumption of all networks. For this reason, energy-efficiency of access networks has been an active research area in the past several years. According to [123], Passive Optical Networks (PONs) and point-to-point optical networks have been found to be the most energy-efficient access technology in comparison to digital subscriber line (DSL), hybrid fiber coax-ial (HFC) networks, fiber to the node (FTTN), Universal Mobile Telecommunications System (UMTS) using wideband wide-band code-division multiple access (W-CDMA) and WiMAX. Further energy savings in Ethernet Passive Optical Networks (EPONs) have been studied in several works. The general approach has been putting ONUs to sleep similar to putting BSs to sleep in wireless networks. ONUs can be put to sleep either depending on the traffic volume or link speeds between ONUs and Optical Line Terminal (OLT).

4. CONCLUSIONS

Information and Communication Infrastructures (ICTs) are among the major power consumers and Greenhouse Gas (GHG) emitters. In particular, the power consumption of communication networks and data centers in total is comparable to consumption of large countries. Consequently, the Operational Expenditures (OPEX) of communication networks and data centers are growing with increasing electricity prices and emerging carbon caps and taxes. For this reason, recently vast amount of efforts have been put into enhancing the energy-efficiency of ICTs. In addition to traditional approaches, smart grid-driven techniques have found their way to provide OPEX reductions. Dynamic pricing schemes, distributed generation, demand management, fine-tuned monitoring of faults and disturbances are new concepts brought by the smart grid and they can be effectively utilized to reduce the bills, consumption and emissions of ICTs.

In this survey paper, we have focused on the studies that investigate the challenges and opportunities arising from the interaction of the smart grid with green ICTs. We have provided a comprehensive survey of the smart grid-driven works in energy-efficient communication networks and data centers. We have first given a brief introduction to the smart grid and introduced the fundamental concepts that have emerged with the smart grid. Next, we have elaborated on the use of energy-efficient wireless, wire line and optical communications in different do-mains of the smart grid such as Home Area Networks (HAN), Neighborhood Area Networks (NAN) and Wide Area Networks (WAN). Then, we have surveyed the studies that take smart grid factors into consideration while managing data center's power consumption, emissions and electricity bills. Finally, we have outlined the lessons learned and the open research issues regarding smart-grid awareness in energy-efficient ICTs. In addition, we have pointed out new research directions.

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