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A study of the communication needs in micro-grid systems

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Abstract

The demand for increased power delivery, the extensive incorporation of distributed generators, such as the ones utilizing renewable energy sources, and the adoption of modern electronic devices with processing and communication capabilities, are transforming the power grid into a smart grid. In this work, we provide a brief review of smart grids and, particularly, an integral subsystem, the so-called smart micro-grid, as well as the associated communication technologies, operations and challenges. Furthermore, we outline a very useful connection between techniques that are able to extract information about the consumption signals of domestic appliances by utilizing the theory of sparse coding and the compression of this information when its transmission is required to a remote site. This connection can lead to compression methods that are suitable for transmitting device consumption signals, which constitute one of the most frequent type of smart-grid traffic.

1 Introduction

The modern way of life and the continuous growth of the population, set a challenge on the electrical energy that must be delivered by the power grids of today. Along with the increased demands for energy, the reduction of the manufacturing costs of the processing and communication electronics have created a new generation of smart devices and appliances that set a challenge on the capacity of the associated communication networks. The power delivery networks of today take on a whole new form: The communication requirements, traditionally restricted to transmitting power/voltage and current measurements to some operation center that estimates the “state” of the network and, in turn, sends proper control signals back to the various components of the network, have been extended in various ways.

Modern "smart-grids" [1], [5] support operations that may (a) inform the consumers about the current price of energy and enable automatic demand/response, (b) send energy usage measurements/statistics from sensors built-in the devices of each consumer (household, industry) to some operation center (that can analyze and categorize certain behaviors into groups), (c) send and receive messages to orchestrate the supply/demand/capacity of renewable and other distributed sources / energy storage facilities, etc. Furthermore, the overall network organization has changed (e.g., incorporation of micro-grids) since local distribution systems that include generation, storage and load capabilities and are able to work isolated or connected to the main grid, have started to appear.

Several excellent survey papers and technical studies have appeared in literature, over the past few years, dealing with the communication requirements of the smart grid, in general. On the ground of these studies, in this paper, we will focus on the communications issues of smart micro-grids. In particular, this work attempts to:

- Provide a brief description of the smart micro-grids and typical operations/services that are envisioned.
- Report suitable communication architectures and technologies that achieve the above requirements.
- Identify several open research issues that should be tackled, focusing mainly on cognitive radio systems, which have gained significant interest recently as a candidate technology for smart micro-grids.
- Outline a connection between the so-called non-intrusive load monitoring techniques and the compression of consumption signals of domestic appliances, based upon sparse coding, with the aim to efficiently transmit this information at some data processing / aggregation center.

2 The smart micro-grid

One key entity that has been introduced into the so-called smart-grid, towards its modernization, is the smart micro-grid [3]. It is a power system that covers the electricity needs of small areas, such as university campuses, small islands and parts of a city, and it is capable of operating either connected to the main-grid or in an independent mode (also, known as islanding mode). The micro-grid [4] consists of distributed energy generators, storage devices and loads, while it is supported by an appropriate information and communication infrastructure.

The smart micro-grid is expected to provide advanced monitoring and control operations, as well as new applications and services to the end-user. In more detail [5], energy management applications in residential, commercial and industrial premises can provide a cost-effective utilization of heating, cooling and various other energy-hungry loads. Also, a micro-grid can employ demand-response programs for load reduction during peak hours. Moreover, the effective incorporation and control of distributed generation based on renewable sources of energy, as well as electric vehicles, are also possible. The micro-grid can provide adaptive protection and islanding schemes, to increase the reliability of the provided power, while protecting itself from imbalances that can propagate from the main power grid. Finally, novel services and applications allow end-users to also sell energy to the main grid, aggregate the micro-grid assets to be more competitive in energy markets and utilize pricing signals for the reduction of energy consumption and costs.

3 Communication infrastructure

The various new services offered by the smart micro-grid, rely upon the transmission of large amounts of data. A communication infrastructure for supporting the required data exchange of these applications, among end-users and other stakeholders of the grid (e.g., operators, aggregators, etc.), is therefore a central subsystem of the smart micro-grid. Although there is, yet, no consensus on the best architecture of such a network, a common network hierarchy decomposes this subsystem into a Home Area Network (HAN), a Neighborhood Area Network (NAN) and a Wide Area Network (WAN) [5].

Various communication technologies have been studied for each network [5]. Among them, the choice of wired power-line communications, although it seems as a natural candidate, suffers from significant electromagnetic interference [2]. On the other hand, wireless communication technologies, with smaller costs for installation and maintenance, offer also increased reliability and are well-suited to many smart micro-grid applications. Well established wireless technologies, such as cellular systems, WiFi, Zigbee etc., are expected to be integrated into 5G wireless systems, which will be able to support the traffic requirements of the smart grid.

The scarcity of the available spectrum below 6 Ghz and the associated costs for licenced access of the spectrum, have made researchers consider also other approaches. In particular, the research on the communication technologies for smart micro-grids has also considered cognitive radio systems [9], which operate using dynamic spectrum access, and offer the potential to mitigate the spectrum inefficiency problems that arise in other wireless solutions. Recent research has focused, on (a) studying various architectures of cognitive radio based smart grids, (b) spectrum sensing approaches that result into better utilization of the spectrum, (c) various medium access control (MAC) mechanisms, (d) possible routing protocols, (e) interference mitigation schemes and (f) security and privacy issues.

4 Challenges

The smart micro-grids of the future will comprise a great number of communication nodes. For the efficient transmission of the produced information, the involved communication systems should be reliable, secure and guarantee privacy [6], [7]. Furthermore, they should utilize the available communication resources efficiently by exploiting methodologies for reducing the amount of data, e.g., by compression [8] in order to avoid transmitting redundant information, and modern wireless technologies, such as cognitive networks [9], which due to their inherent intelligence, are quite flexible and adaptable to different communication environments and conditions. In the following, we provide some interesting research topics that can be pursued.

As the number of devices that participate in smart micro-grids increases, the relevant smart operations are increasingly adopting a decentralized approach [10], rather than a centralized one, leading to a subsequent increase in vulnerability and security risks of transmissions. To achieve high levels of security, reliability and privacy, transmission schemes should be capable of detecting and handling eavesdroppers and malicious behavior [11]. The adopted schemes could utilize ideas from information theory (such as the notion of secrecy capacity [12]), multi-agent approaches [13] and game-theoretic modeling, while taking into account the constraints that are imposed, e.g, by critical micro-grid operations (e.g., power balance control) with low latency requirements.

For energy management and demand response purposes, the power consumption signals of the domestic appliances of multiple houses are gathered at a remote concentration center for supporting decision making procedures [15]. The amount of data, however, could be excessive which could exhaust the available resources of the communication infrastructure, meaning that compression techniques should be employed. Sparse coding and dictionary learning algorithms [14] can lead to novel compression techniques, which are particularly suited to the considered consumption signals. It is interesting to point out that such techniques are compatible with techniques that are proposed for the problem of the so-called non-intrusive load monitoring [16] and we are going to elaborate further on this in the following section.

The high number of communication nodes has also another implication, when wireless communications are employed. In particular, the unavailability of spectrum, as well as the costs that are associated with its access, may lead to communication blockage, negatively affecting the perceived quality of service. Cognitive systems could increase the spectrum efficiency, being able to perform spectrum sensing in a wide frequency range [9]. To exploit the high number of nodes, cooperative spectrum sensing strategies [17], especially tailored for smart-grid communications, would lead to increased detection performance.

As a final direction, efficient, of low-complexity, interference management schemes are required for the harsh interference conditions that exist in the environment, where smart micro-grid data are transmitted [9]. The main sources of interference that should be targeted, are electromagnetic interference, produced by electricity flows (especially, near generators and high voltage cables), the utilization of multiple communication technologies, and the density of communicating devices. The proposed schemes could employ, among others, new advances in the theory of interference alignment / management, approaches that select appropriate interference free channel resources (in all three dimensions, namely, space, time and frequency) and distributed techniques, like relaying and cooperative beamforming.

5 Compression of consumption signals

As already mentioned in the previous, some of the services offered by the smart micro-grids require the collection of the consumption signals, of each device and per household. This process involves two steps: (a) The computation of the individual consumption signals, at each house, and (b) the transmission of these signals to some data processing node. Although these two steps seem quite different, we will see that there is a clear connection between these two problems which can be solved under a common framework.

The computation of the individual consumption signals, given the aggregate consumption signal for all the appliances in a house, is a problem known as "non-intrusive load monitoring" or "energy disagreggation" [18]. In a more general setting, some of the domestic appliances could be "smart enough" to report their consumption signal. For such appliances, the individual consumption signal is, thus, known. However, in order to compute the individual consumption signals for the "non-smart" devices too, the solution of an optimization problem must be computed [16], [19]. Among the various approaches, recently, approaches that utilize dictionaries and sparse coding have appeared [20], [21].

The latter methods use properly selected "dictionaries" of signal patches, and analyse the agregate consumption signal using a small subset of patches, per time instant. This way, the optimization problem associated with this analysis has twofold implications: (a) The aggregate signal is decomposed into individual consumption signals, inferred by which patches are involved in the analysis, and (b) a compressed, sparse coded version of the aggregate and the individual consumption signals is computed. Thus, each house that employs such a disagregation algorithm can also send the consumption signals in a compressed form, under the mild assumption that the communicating ends have agreed upon a common dictionary, at some initialization phase.

6 Concluding remarks

In this work, a brief review of smart micro-grids was provided, along with the most suitable communication technologies. Furthermore, the associated operations and challenges were mentioned. Additionally, we outlined a connection that can lead to compression methods, based on sparse coding, suitable for the consumption signals of the individual domestic appliances.

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