OVERVIEW OF DEMAND MANAGEMENT IN SMART GRID AND ENABLING WIRELESS COMMUNICATION TECHNOLOGIES

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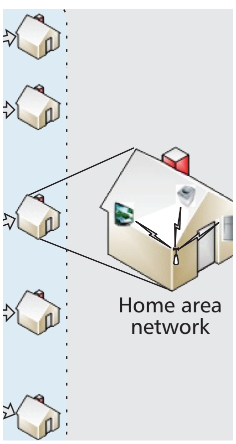

The authors provide an overview of demand management with a particular focus on the necessary enabling wireless technologies. They review various mechanisms and algorithms for the optimal demand management in smart grids using these wireless technologies.

ABSTRACT

There are significant challenges as well as great opportunities for research at both policy and technology levels on the efficient use of energy. Most existing power generation and distribution systems are based on a century old mechanism where power grids are managed by vertically integrated utilities. Intelligent power grids known as smart grids are required as the demand for energy continues to grow and more and more emphasis is being placed on the supply of renewable energy. The main ingredient of smart grids is the integration of information and communication technology (ICT) into the grids to monitor and regulate power generation and demand. This article provides an overview of demand management with a particular focus on the necessary enabling wireless technologies. Various mechanisms and algorithms for the optimal demand management in smart grids using these wireless technologies are also reviewed.

INTRODUCTION

The electricity supply industry has been facing significant challenges in terms of meeting the projected demand for energy, environmental issues, security, reliability and integration of renewable energy. Currently, most of the power grids are based on many decades old vertical hierarchical infrastructures where the electric power flows in one direction from the power generator to the consumer side and grid monitoring information is handled only at the operation side. It is generally believed that a fundamental evolution in electric power generation and supply system is needed to make the grids more reliable, secure and efficient. This can be achieved by enabling the future generation electricity network smarter and intelligent by embedding bi-directional information and communication architecture with power grids.

Various countries around the world such as the US and several European countries have already launched development projects on what is known as smart grids. For example, by 2030, the US DoE Smart Grid R&D Program [1] aims to achieve 20 percent reduction in the nation's peak energy demand, 100 percent availability to serve all critical loads at any time and 20 percent of the electricity capacity from distributed and renewable energy sources. The European Smart Grids Technology Platform has also set similar targets with an emphasis on highly interconnected distribution networks and the integration of renewable energy to meet the EU target on carbon emissions reduction by year 2020 [2].

There are various definitions for smart grid. For example, the main highlight of the EU definition is that a smart grid is an electricity network that can intelligently integrate the behavior and actions of all users to ensure sustainable, economic, and secure electricity supply. The definition of US DoE states that a smart grid uses digital technology to improve reliability, security, and efficiency of the electricity system. Regardless of these different definitions, the main ingredient of the smart grid is the application of information and communication technology in power grids. Figure 1 illustrates a possible overall smart grid architecture. It is a highly integrated and complex, yet flexible and reliable network with various centralized and distributed energy sources. As shown in Fig. 1, the power flow direction is no longer just downhill from the bulk power plants to consumers. Instead, dynamic flows can start from any generation sources and end up anywhere in the grids. The energy can be stored and released back to the grids even at household level. The integration of ICT enables not only the operation control center to make informed decisions and optimize the energy flow, but it also provides opportunities for consumers to participate in the energy demand management to reduce the cost of their energy.

Demand management is the key to the operational efficiency and reliability of smart grid. Facilitated by the two-way information flow and various optimization mechanisms, operators benefit from real time dynamic load monitoring and control while consumers benefit from optimized

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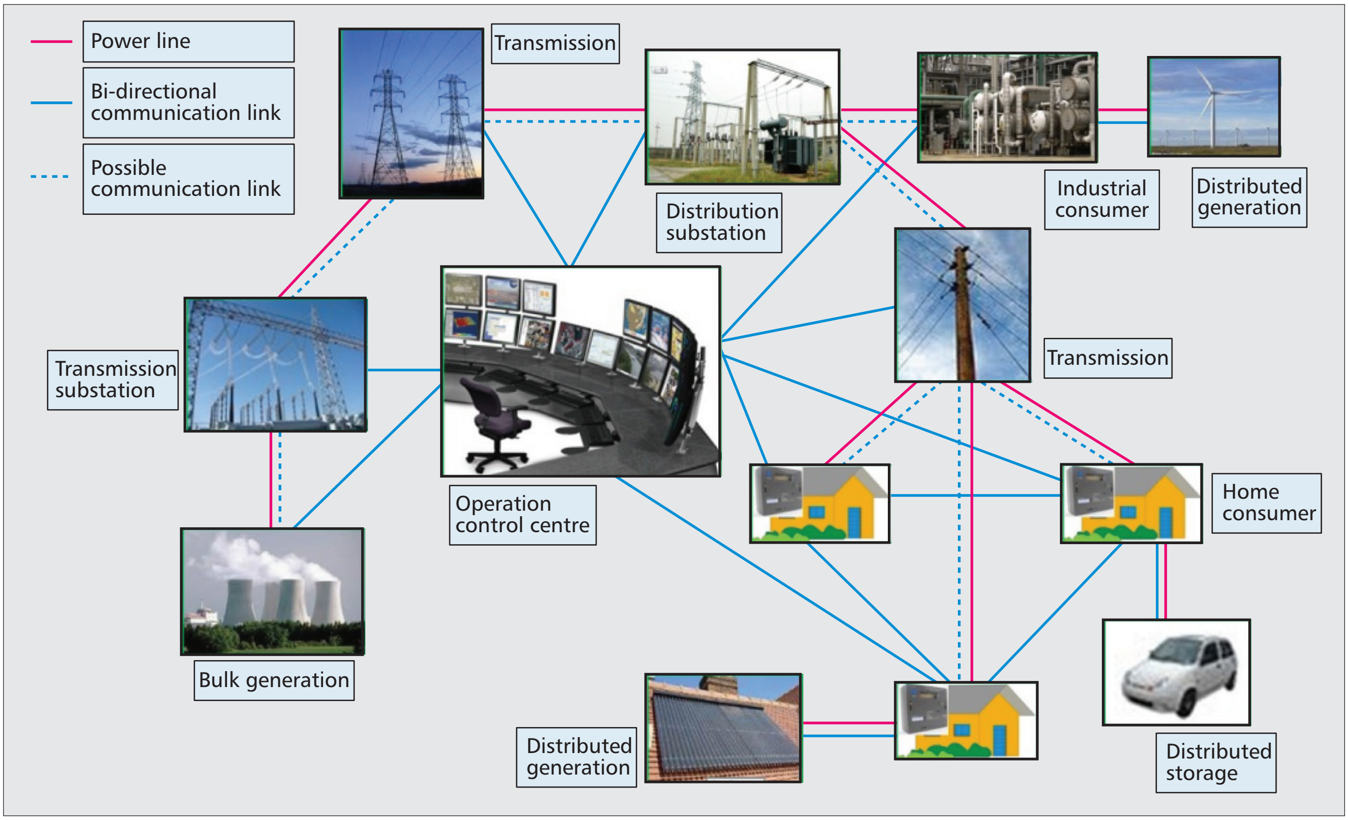

Figure 1. *Smart grid architecture.*

use of energy. In this article, we provide a comprehensive overview of demand management in smart grid with a focus on the enabling wireless technologies. We first present survey on demand management and associated research challenges. We then discuss major features of various candidate wireless technologies required to facilitate demand management. The features and enabling mechanisms in terms of consumption scheduling, real-time response and load balancing are also discussed.

Overview of Demand Management in Smart Grid

Features

Demand management mainly consists of load monitoring, analysis and response. In conventional power grids, the two sides of the electricity demand and supply system are basically disconnected, as such demand management is performed exclusively by the utility operators using mainly the raw data based local operation monitoring and state estimation. These approaches have significant drawbacks in terms of high response time (delay) and inaccuracy. The development of smart grid provides demand management with advanced features to enable many new essential functions and applications as follows:

Bi-Directional Coordination — In smart grid, demand management is expected to be a combination of centralized and distributed schemes. Monitoring and control activities will not only be based at the operation centers but can also be distributed across the whole network. Every node at the demand side of the network will be able to manage its own demand and consumption optimally according to the current supply condition. These activities will be acknowledged by the supply side utility operators via effective bi-directional information exchanges. Taking advantage of the full visibility of the demand condition of the grids, operators can alter their supply policies such as price rates dynamically. Both sides of the electricity market can participate in the demand management and achieve a bi-directional coordination to fulfill customers' requirements while responding to the current circumstances of the grid. This will reduce the management cost of the grid operators and will potentially lead to a win-win situation for the utility operators and the consumers.

Data Gathering and Information Processing — The advanced instrumentation technology enabled by real time sensing and data communication will be the most important interface of the power grids for monitoring the demand and supply. For this purpose, the advanced metering infrastructures (AMI) have been proposed to gather and convey real time raw measurement data. Advanced signal processing techniques spanning from data compression, data mining and optimizations will become important tools to extract useful information from the raw data and to generate appropriate demand and supply control messages. Monitoring specific performance parameters such as potential demand and local back-up supply capability will enable grid opera-

The NANs and HANs of AMI communications infrastructure are particularly suitable for wireless deployment, largely due to the ease and low cost of adopting wireless instead of wired solutions.

tors to conduct more effective and accurate demand management. The communication architecture will facilitate the data processing and analysis to be performed either locally or distributively to reduce the workload of transmission and central controls.

Real-time and Online Processing — Considering the highly dynamic nature of the energy supply from, for example renewable resources, in the electricity grids and the huge impact that can be caused by possible control delays, it is important to handle the dynamics of the supply and demand in a timely manner. As for bi-directional management in smart grid, effective communications is of paramount importance. Modern communication and Internet technologies will ensure prompt and transparent exchange of information in the network. For example, after detection of a potential outage, both the consumers and control authorities in the impacting area will be notified immediately. Early actions can be taken before further disturbances are spread. Local area data processing and demand assessment is subject to a minor delay of seconds so that associated control can respond effectively. These activities are expected to be performed online using various user interfaces. Every participant of the activities will be responded and acknowledged transparently.

Proactiveness — The success of the smart grid lies in the full participation of the consumers. The smart grid should enable everyone to have access and participate in demand management. Importantly, the consumers should be given incentives for participating proactively and coordinating with the operators and other stake holders. To achieve this, an efficient and transparent exchange of information system facilitated by advanced communication architecture and attractive electricity consumption and price plans are required. Proactive participation of the demand side provides the operators not only the opportunity to respond in real time to the supply and demand, but also to predict the future demand more accurately and devise appropriate actions on the generation and supply of energy.

Challenges

There are various perceived challenges spanning from policy level to technology level including social and behavioral aspects. The policy level challenges include capital investment, enforcement rules on grid operators to provide considerable incentives to consumers, standardization of electrical appliances and third party engagement of consumer raw data. The social and behavioral aspects include trust and engagement of consumers in the demand management. The technological level challenge mainly spans the integration of high quality and low delay two-way communication infrastructure with the power grids. There are various state of the art communication technologies available, however, it is the choice of the most appropriate technology and the integration of all the components of the smart grids that will form the important challenge. To balance the supply and demand, similar techniques as used in communication networks for managing capacity of the network and the resources can be used. For example, optimization techniques using distributed strategies and game theory can be developed, as discussed in the succeeding sections.

Wireless Technologies

To facilitate demand management, suitable communications technologies must be chosen to address various requirements in the different parts of the AMI. The neighborhood area networks (NANs) and home area networks (HANs) of AMI communications infrastructure are particularly suitable for wireless deployment, largely due to the ease and low cost of adopting wireless instead of wired solutions. The backhaul network connecting the AMI headend and the data aggregation points (DAPs) can either be wireless or wired. The AMI communication architecture is illustrated in Fig. 2.

The link between the DAPs and consumers requires NANs with a coverage in the range of thousands of meters. Each DAP can connect to hundreds of smart meters (SMs). As a result, a key requirement of candidate wireless solutions is coverage of wide area, which can also be achieved through a mesh network architecture or relay stations. Additionally, the wireless network must be able to provide a certain level of reliability as well as low enough latency not only to satisfy demand side management (DSM) requirements but also to serve all other AMI applications. According to communication requirements from OpenSG [3], this translates to a minimum reliability figure of 99.5 percent and a latency requirement of less than 1 second, which is a relatively relaxed figure as compared to the commercial broadband requirements.

On the other hand, HANs which facilitate energy management and planning within customer premises, require a relatively smaller coverage area. The requirements are also relatively less stringent as there are less control messages and information exchange between the smart meter and smart appliances (and plug-in hybrid electric vehicle (PHEV)). In general, the HAN requires a minimum reliability figure of 99.5 percent and a latency requirement of less than 5 seconds [3].

Neighborhood Area Networks

Candidate technologies for NAN have to provide coverage radius of over a thousand meter. Reliability of communication channels between the DAP and the smart meters dictates that the spectrum used will have to be exclusive or interference free. Consequently, the most suitable candidates need to be licensed or leased wireless solutions. A comparison of the characteristics of different NAN technologies can be found in Table 1.

WiMAX — Implementations of IEEE's 802.16 standard for metropolitan networks [4], commonly referred to as WiMAX (worldwide interoperability for microwave access), is a leading candidate for providing connectivity between DAPs and SMs. WiMAX is based on orthogonal division multplexing access (OFDMA), which assigns slices of the frequency spectrum to different users [5], avoiding interference among the users and increasing the spectral efficiency of the system. Although WiMAX is not being widely adopted as a wireless broadband platform, it does not diminish its chance of being a candidate as some utilities are expected to set up dedicated DAPs. As a result, WiMAX is more attractive in the sense that its structure is much less sophisticated as compared to rival cellular standards such as 3GPP Release 8 (commonly known as Long Term Evolution (LTE)). Additionally, amendment *j* to the standard added multihop relay capabilities [6], which can enlarge the coverage area using low cost relay stations.

UMTS/LTE (2G/3G Cellular) — Current cellular technologies such as UMTS and LTE [7] also provide attractive solutions for providing NAN coverage. Relaying functionality had also been incorporated in 3GPP Release 10 (commonly known as LTE Advanced) [8], which will allow extended coverage using relay/repeater stations. However, the utilities have to be willing to overlay DAP-SM communications over existing communication infrastructure. Although the advantage of overlaying is a lower setup cost since the existing infrastructure can be used, the utility operator will have to work with the telecommunication operators to set up the network which can be contentious due to security and privacy concerns.

IEEE 802.22 — An alternative candidate to mainstream broadband wireless is the IEEE 802.22 wireless regional area network [9], which uses white spaces in the television spectrum. The IEEE 802.22 standard proposes to use cognitive radio technologies to exploit unused spectrum in the frequency spectrum allocated to television broadcast. As the spectrum used is not dedicated, the latency in data transmission could be higher as compared to other solutions mentioned earlier.

Home Area Networks

Wireless solutions for HANs have a slightly different set of requirements, which are not as stringent as those for NANs. In general, the message arrival rate within a customer premise is not as high as that between SMs and DAPs. Additionally, the data volume is also much lower. A comparison of various wireless candidate technologies for HAN is provided in Table 1.

WiFi — IEEE's suite of standards for wireless local area networks, IEEE 802.11 or WiFi, is the most commonly deployed wireless standard within homes. As such, WiFi devices and chips are relatively cheap, making it an attractive solution. Amendment s of the standard also incorporates mesh networking capability.

Zigbee — Zigbee is one of the leading candidate technologies for networking of devices in HANs. The specification builds upon the IEEE 802.15.4 standard, and is tailored for mesh networking. Zigbee also has various profiles to support different applications, such as Smart Energy. Zigbee Smart Energy 2.0 profile, which adds many more features such as the support for PHEV, will be ratified by the end of 2011.

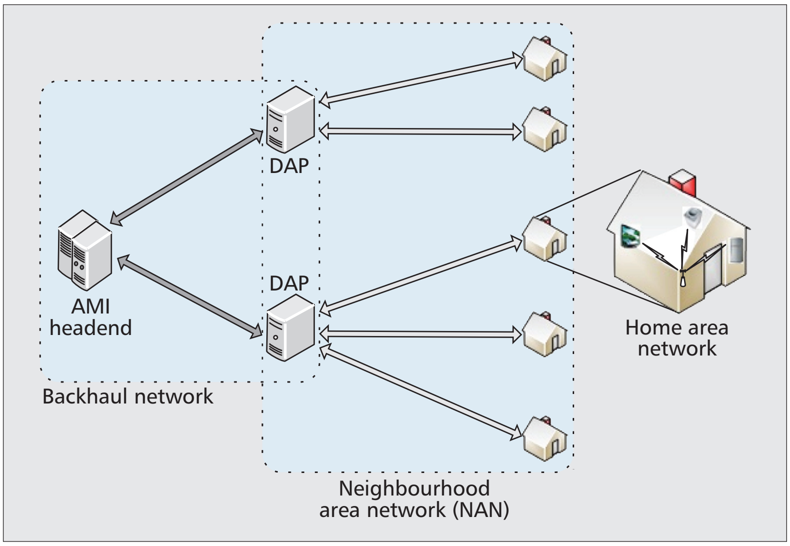

Figure 2. *Smart grid architecture.*

Bluetooth — The Bluetooth specification was designed for personal area networks. The specification supports functions such as mesh networking. Furthermore, the specification ensures less latency as compared to the two previously mentioned standards through the use of a time division multiple access (TDMA) like medium access scheme. Both WiFi and Zigbee uses contention based carrier sense multiple access (CSMA) which can result in large latency if many devices are in operation.

Developments of Demand Management Approaches and Proposed Mechanisms

The success of smart grid lies in the design of flexible and robust demand management techniques underpinned by the deployment of ICT infrastructure mentioned earlier. Apart from improving the legacy load control approaches, the main contributions of recent research have been in the demand side consumption scheduling, dynamic pricing and load balancing using distributed energy resources (DER).

Demand Side Consumption Optimization

Demand side consumption optimization is an important feature to manage the (peak) demand on the main grid and to maintain system reliability and stability. It has been an active research topic for many years. For example, some approaches in terms of peak clipping and flexible load shape shifting and related management mechanisms have been outlined in [10]. However, it is the recent advancement of communication technology that has facilitated an entirely new set of approaches and methods to perform demand side management on a real time basis. The operators could apply direct response and control mechanisms through local or remote

As an analogy to the design of hierarchical topology based Internet routing, finding the most suitable system architecture of consumption management system in smart grid is an important research topic.

Coverage	Technology	Range	Latency	Reliability	Cost & Ease of Deployment
NAN	WiMAX	30km	Low	High	Medium/Medium
	UMTS/LTE	30km	Low	High	Medium/Low
	802.22	30km	Medium	Medium	High/Medium
HAN	WiFi	200m	Medium-High	Low-Medium	Low
	ZigBee	100m	Low-Medium	Medium	Low
	Bluetooth	100m	Low	Medium	Low

Table 1. *Comparison of candidate NAN and HAN wireless technologies.*

control systems which directly control the energy usage of different appliances in the customer premises either coarsely by ON/OFF switching, or by changing operational parameters such as the temperature of hot water tank or heating system. For indirect approaches, incentive based management such as dynamic pricing or social interaction can be adopted. The latter approach provides more management flexibility and enables proactive consumption optimization by the distributed consumers, which might turn out to be more cost-effective and efficient. It suits better for managing real-time/daily consumption and reducing peak loads. However, it has stricter requirements in terms of metering technologies (to support local analysis and computation) and communication security. The centralized direct management schemes are more suitable for emergency response to prevent outages.

As an analogy to the design of hierarchical topology based Internet routing, finding the most suitable system architecture of consumption management system in smart grid is an important research topic. For example, a three step optimization methodology using a decision tree structure was considered in [11]. The root node acts as a global planner which tries to achieve an overall control of the load profiles. The root node can be the control centers at the utility side. It decomposes the profiles in subparts and assigns them over its follower nodes in the hierarchical structure. Follower nodes will take the responsibility to plan its part of the consumption using similar optimization techniques as the root node and will further decompose the work into the leaf nodes. The leaf nodes are directly linked to the controllers, e.g. smart meters, located at the consumers' terminals. Communications between all the nodes are essential to support the networked coordination.

As shown in Fig. 2, the AMI architecture suits very well for the management structure. The cost-effective and short-range Zigbee/Bluetooth based wireless sensor networks can be deployed at the demand side to support exchange of information between the leaf nodes and the appliances. In the middle level which represents NAN, the low latency and high reliability 3G/4G wireless solutions can be adopted. High capacity wired technologies are suitable to handle mass data flow at the top level between DAP and AMI headend. However, the total amount of communication workload is reduced because of the hierarchical decomposition of responsibility. Besides, the hierarchical decomposition supports scalability because the deployment of leaf nodes are reasonably independent of other components of the tree.

The structure presented in [11] was designed primarily for implementing global optimization to regulate consumption. Indeed, mathematical optimization is expected to be the heart of global consumption scheduling algorithms. For example, decentralized algorithms based on game theory provides a flexible optimization framework for demand side management.

In [12], an energy scheduling framework based on convex optimization technique was proposed to schedule power consumption of individual appliances to achieve the goal of peak load reduction. The power requirements in terms of the minimum standby power and maximum operating power of the appliances were formulated into convex constraints. Both centralized and decentralized game theoretic frameworks were proposed. The authors showed that, under the concave game settings, the participating users have the potential to quickly move towards a unique point (*Nash Equilibrium*) at which the consumption cost is optimized. Coordinated scheduling can be achieved using HAN/NAN communication technologies mentioned earlier, and local computations are required for conducting the optimization.

In practice, not all the appliances' consumption requirements can be easily formulated into convex forms. Some of the appliances may have their own fixed consumption patterns to follow which means once such an appliance is scheduled for operation, it has to work according to its own power consumption profile until the end of operation. Hence it is necessary to classify the appliances into non-shiftable (fixed operation), power-shiftable (schedule the operation power) and time-shiftable (schedule the operation time) groups.

We define non-shiftable appliances as those that the scheduler cannot change the operation time or power consumption profile. For example, a fridge is normally required to operate continuously for the whole day and a light bulb will consume a certain level of power when it is switched on. Power shiftable appliances are defined as those whose power consumption pat-

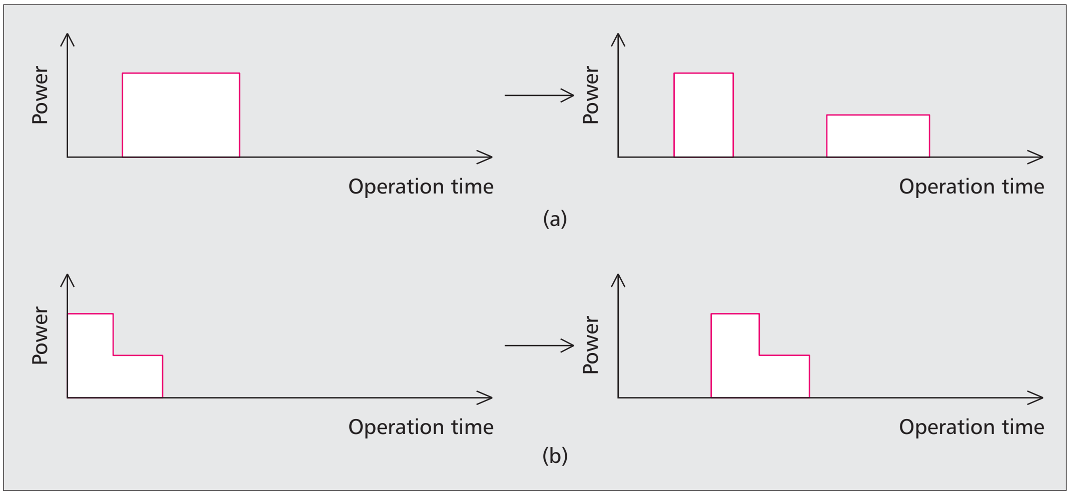

Figure 3. *Illustrative examples of power and time shiftable operations.*

Time-shiftable appliances are those that the consumers can tolerate postponing the operation. For example, a washing machine or a dish washer. However, for these appliances, the power may not be shiftable.

tern could be changed if required, as shown in Fig. 3a. For example, a flexible battery charger. Time-shiftable appliances are those that the consumers can tolerate postponing the operation. For example, a washing machine or a dish washer. However, for these appliances, the power may not be shiftable. For instance, the operation of a washing machine could be postponed. However, when it is required to start, it will draw power according to its own consumption pattern as shown in Fig. 3b and this can not be changed. The energy scheduling algorithm should consider separate constraints for each class of appliances, as explained in the following scheduling algorithm [13].

For a power-shiftable appliance a with a standby power α and a maximum operation power β, the scheduling requirement is written as $\alpha \leq x_a \leq \beta$, where $\boldsymbol{x_a} = [x_{a,1}, x_{a,2}, \ldots, x_{a,N}]^T$ denotes the scheduled power consumption vector over the day for the appliance and N determines the time resolution. For example, $N = 24$ for hourly scheduling and $N = 1440$ for minute based scheduling. The parameter $x_{a,t}$ denotes the power consumed by the appliance a at time t. In addition, we will also require a constraint on the total energy requirement, for example, $\sum_{t=1}^{N} x_{a,t} = l_a$ where l_a is the total energy requirement for the operation of the appliance a.

A time-shiftable appliance b can have a preset power consumption pattern $\mathbf{p}_b = [p_{b,1}, p_{b,2}, \ldots, p_{b,N}]^T$. We can only postpone the operation of b, but the power consumption pattern should remain the same, as shown in Fig. 3b. Hence the scheduling result $\mathbf{x}_b$ has to be exactly the same as one of the cyclic shifts of the pattern $\mathbf{p}_b$. All possible shifts for the vector $\mathbf{p}_b$ can be put together in a matrix form as

$$\mathbf{P}_b = \begin{bmatrix} p_{b,1} & p_{b,N} & \cdots & p_{b,3} & p_{b,2} \\ p_{b,2} & p_{b,1} & \cdots & p_{b,4} & p_{b,3} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ p_{b,N} & p_{b,N-1} & \cdots & p_{b,2} & p_{b,1} \end{bmatrix}. \quad (1)$$

We define a binary integer vector $\boldsymbol{s_b} = [s_{b,1}, s_{b,2}, \ldots, s_{b,N}]^T$ as the switch control for the time-shiftable appliance b. There is only one non-zero element in the vector s_b which is equal to one. Now the schedule plan for a time-shiftable appliance b can be written as $\mathbf{x}_b = \mathbf{P}_b\mathbf{s}_b$, $\mathbf{1}^T\mathbf{s}_b = 1$. The vector $\mathbf{s}_b$ is an optimization parameter which chooses the appropriate column of $\mathbf{P}_b$ to optimize the energy consumption.

Using these definitions, we could formulate the optimization problem as to minimize the peak load L subject to the requirements of all the appliances as follows:

$$\begin{aligned} &\min_{L,\mathbf{x}\in\mathbb{R}+,\mathbf{s}_b\in\mathbb{Z}+^{N\times 1}} \quad L \\ &\text{s.t.} \quad \sum_a x_{a,t} + \sum_b x_{b,t} \leq L,\ \forall t \in 1,2,\ldots,N \\ &\qquad \alpha \leq \mathbf{x}_a \leq \beta, \sum_{t=1}^{N} x_{a,t} = l_a,\ \forall a \qquad (2) \\ &\qquad \mathbf{x}_b = \mathbf{P}_b\mathbf{s}_b,\ \mathbf{1}^T\mathbf{s}_b = 1,\ \forall b. \end{aligned}$$

The above problem can be solved using mixed integer linear programming (ILP) [13]. As an example, we consider an hourly consumption scheduling, i.e., $N = 24$, for a group of four households. Every household is assumed to have a similar set of appliances, however with different consumption requirements. Assume the total daily requirement is 43 units. Without optimal scheduling, it is likely that many appliances may be operating simultaneously because users may have similar consumption behaviors. The overlapping loads could generate undesirable peaks. As illustrated in Fig. 4 (left), the loads are high in the evening with a peak of 3.72kWh while they remain low in the day time. Appliances scheduling will reduce the peak demand through coordination between households and adjusting the operation time and the power of shiftable appliances.

Figure 4 (right) depicts the optimal hourly consumption scheduling result using the ILP optimization in Eq. 2. The optimization schedules appliances to minimize the peak load L over $t = [1, 2, \ldots, 24]$. As seen, there is no significant peak and the load allocation is fairly balanced. This is because the shiftable consumptions are reallocated optimally through-

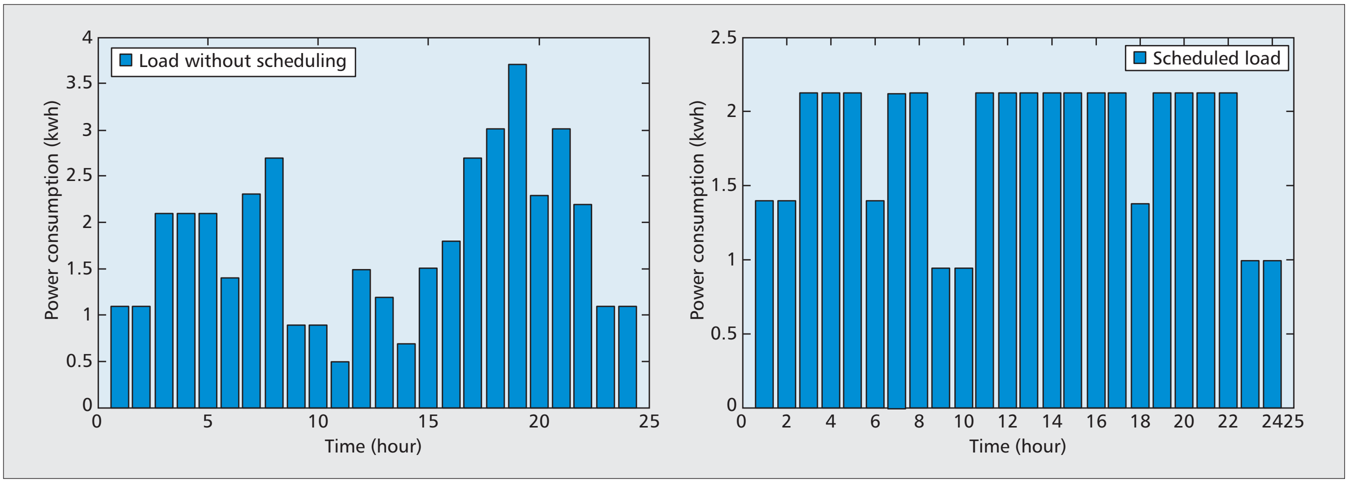

Figure 4. *Hourly load over the day. Left: without scheduling, right [13]: after scheduling.*

out the day. The optimized hourly peak load L is 2.14kWh and the peak to average load ratio is 2.14/(43/24) = 1.19, which means the peak load is just 19 percent higher than the daily average. In contrast, without scheduling, the peak to average load ratio is 2.07. The optimization is able to control the peak load at a reasonable level. With a dynamic price plan, the ILP formulation can also be applied to incentive based scheduling to minimize the energy cost which will in turn attempt to balance the consumption loads.

The scheduling of appliances may introduce discomfort to the consumers mainly due to possible delays introduced by shifting the operation of the appliances. A successful scheduling should therefore ensure that the appliances are scheduled according to certain user preference. User preference can be formulated into the optimization problem using additional constraints. Also, considering the discomfort as a cost of inconvenience, this can be factored into the overall optimization cost. However, the reduction of user discomfort is expected to increase the peak load and probably the economic cost. Therefore, the best strategy is to provide incentives to the consumers and encourage them to participate in the demand management. A robust load balancing algorithm should consider various pricing profiles by multiple utility providers and quantify consumer behavior using numerical means to optimize both the peak loads and incentive to consumers.

Dynamic Pricing

Generally, issuing dynamic pricing policies as user incentive is the most effective way to achieve indirect demand management for the grid side operators and controllers. Dynamic pricing mainly consists of time-of-use (ToU) pricing, critical peak pricing (CPP), time block based pricing (TBBP), and real-time pricing (RTP), as listed in Table 2.

ToU and CPP rates have already been included in many utility contracts/tariffs in the current electricity markets for load control purposes. In order to account for the dynamic demand in smart grid, pricing policies should be updated frequently. It is believed that a combination of time block based pricing and ToU/CPP rates could be a possible solution for the early stage of smart grid development with limited ICT deployments. Some economically driven consumption optimization algorithms, such as that in [12], consider this kind of pricing schemes. However, the performance of such pricing mechanism will highly depend on the accuracy of the demand estimation/prediction and risk assessment. Self-learning algorithms can be used for demand prediction. Various risk control mechanisms used in business research can also be adopted in the design of pricing policies.

RTP is believed to be robust in terms of responding to the dynamics even when there is unpredictable energy demand in the grid. The main challenge of implementing RTP is the expectation of a high quality communication infrastructure for real-time monitoring purposes. Latency will be the primary concern in choosing the communications solution for RTP. In order to support continuous and mass flow of data, the throughput of the communication network should also be very high. Finally, the power consumption of the communication infrastructure itself has to be managed optimally.

Distributed Energy Resource (DER) Management

In addition to balancing the supply and demand, the smart grids when integrated with the distributed energy sources will enable the consumers to choose different type of energy sources and suppliers as well as to optimally use and sell back the locally generated and stored energy. The optimal use of available energy at different times can help reducing the dependency on the central supply. The grid side utilities can balance the load by choosing the supply from different generation systems especially at peak demand periods. For example, the work in [14] discusses how various energy supplies can be aggregated and dispatched. The idea of load-based services can bring true benefit for the access of varying energy generation from green resources (such as wind and solar) and smart charging of PHEVs.

Pricing policy	Characteristics	Cost & ease of deployment
Time-of-use pricing	One-off issuing rates depending on the time of use Limited performance for dynamic demand control	User behavior and load estimation required Low ICT requirements
Critical peak pricing	One-off issuing rates depending on particular events Critical rate for pre-defined peak times (or loads) Limited performance for dynamic demand control	Hard to define critical events Low ICT requirements
Time block based pricing	Monthly/weekly/daily updating rates ToU rates or load-sensitive rates Enhanced performance for dynamic demand control	Load prediction and risk control required Non-real-time ICT required
Real-time pricing	(Near) real-time updating rates Advanced performance for dynamic demand control	Advanced real-time ICT required High communications power consumption

Table 2. *Dynamic pricing schemes.*

Residential DER management based on instantaneous supply conditions (both from the central energy source and the distributed energy sources) is also an important research topic. For example, various households in a neighborhood area can share locally generated power and draw power from the central energy source only when it is required. The authors of [15] developed a decision-support algorithm using particle swarm optimization (PSO) to support this kind of schemes.

Conclusions

The main ingredient of smart grids is the integration of ICT into the grids to monitor and regulate energy generation and demand. The smart meters and sensors will be deployed in various parts of the grid, starting from the generation, through distribution, and all the way to the household level. These will be interconnected through both wired and wireless connections. Due to the consideration of cost effective implementation, wireless solutions are preferred at the NAN and HAN levels and wired connections could be used for backhaul networks. In addition to the integration of renewable energy, one of the main goals of the smart grids is to perform demand management to reduce peak loads. This requires acquision of real time data from various points in the grid and optimization of the power supply and demand. In order for the demand management to be successful, consumers should be given adequate incentives for full participation. This article covered various candidate communication technologies and mathematical optimization algorithms to enable demand management. As communication is an underpinning technology for the success of smart grid, we envisage that smart grids will be an exciting research area for communication engineers for many years to come.

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