Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities

Zhong Fan, Parag Kulkarni, Sedat Gormus, Costas Efthymiou, Georgios Kalogridis, Mahesh Sooriyabandara, Ziming Zhu, Sangarapillai Lambotharan, and Woon Hau Chin

***Abstract*—Optimization of energy consumption in future intelligent energy networks (or Smart Grids) will be based on grid-integrated near-real-time communications between various grid elements in generation, transmission, distribution and loads. This paper discusses some of the challenges and opportunities of communications research in the areas of smart grid and smart metering. In particular, we focus on some of the key communications challenges for realizing interoperable and future-proof smart grid/metering networks, smart grid security and privacy, and how some of the existing networking technologies can be applied to energy management. Finally, we also discuss the coordinated standardization efforts in Europe to harmonize communications standards and protocols.**

***Index Terms*—Smart grid, smart metering, demand response, interoperability, standards, wireline and wireless communications, renewable energy, security, privacy.**

I. Introduction

CLIMATE change and greenhouse gas emissions have become a recognized problem of international significance in recent years. Renewable energy sources offer a key solution to this problem; however, their integration into existing grids comes with a whole new set of barriers, such as the intermittency of generation, the high level of distribution of the sources and the lack of proven distributed control algorithms to manage such a highly distributed generation base.

Historically, the electrical grid has been a *broadcast* grid (i.e. few-to-many distribution), where a few central power generators (i.e. power stations) provide all the electricity production in a country or region, and then 'broadcast' this electricity to the consumers via a large network of cables and transformers. Based on load forecasting models developed over time, the utility providers generally over-provision for the demand (considering peak load conditions). If the demand increases above the average, they may have to turn on the peaker plants[1] which use non-renewable sources of energy (e.g. coal fired plants) to generate additional supply of energy to cope with the demand. The provisioning for peak load approach is wasteful when the average demand is much lower than the peak because electricity, once produced, has to be consumed as grid energy storage is expensive [2]. Secondly, setting up and maintaining the peaker plants is not only environmentally unfriendly but also expensive. Also, given the increasing demand for energy, it may be difficult, perhaps impossible in the longer run, to match the supply to this peak demand. What is attractive in such a situation then, is to match the demand to the available supply by using communication technology (two way communications between the grid and the customer premises) and providing incentives (e.g. through variable pricing) to the consumer to defer (reschedule) the load during times when the expected demand is lower so as to improve utilization of the available capacity. This necessitates the flow of metering information from the customer premises to the grid to identify the demand, and control information (e.g. pricing information) in the other direction to coerce the customer into adapting their demand. As mentioned earlier, since the legacy grid is a broadcast grid, this motivates the need for a communications infrastructure and protocols to support the aforementioned functionalities.

While the legacy grid has served well for the last century or so, there is a growing need to update it, from the points of view of both the aging infrastructure and the new environmental and societal challenges. As a result, national governments and relevant stakeholders are making significant efforts in the development of future electrical grids or Smart Grids. A smart grid is an intelligent electricity network that integrates the actions of all users connected to it and makes use of advanced information, control, and communications technologies to save energy, reduce cost and increase reliability and transparency. Development of this new grid will require significant efforts in technology development, standards, policy and regulatory activities due to its inherent complexity.

A proper demand management through the smart grid technology has the potential to yield significant savings in the generation and transmission of energy. This is mainly due to the reduction of number of peaker plants needed to

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Z. Fan, P. Kulkarni, S. Gormus, C. Efthymiou, G. Kalogridis, M. Sooriyabandara and W. Chin are with Toshiba Research Europe Limited, Telecommunications Research Laboratory, 32 Queen Square, Bristol, BS1 4ND, UK (e-mail:zhong.fan@toshiba-trel.com).

Z. Zhu and S. Lambotharan are with Advanced Signal Processing Group, Department of Electronic and Electrical Engineering, Loughborough University, Leicestershire, LE11 3TU, UK.

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[1]Peaker plant is a standard term used in the power grid community. Peaker plants are switched on to meet a shortfall in supply, on a timescale varying from a few seconds up to a few minutes [1] (cf. Table 1 in this document).

cater for peak demand that occurs only a small percentage of time. For example, it has been reported in [3] that in Europe, five to eight percent of installed capacity is used only one percent of the time. By deferring the peak demand to off peak times, the capacity and transmission cost could be reduced up to 67 billion euros in Europe [3]. An annual potential value generation up to 130 billion dollars by 2019 has been forecast by McKinsey in [4] for a fully deployed smart grid in the US. The work in [5] states that even a conservative estimate of potential saving due to grid modernization is 40 billion dollars per year. In addition to the direct savings, there are many important economical and societal benefits such as reduction of CO2 emissions, integration of renewable energy, elimination of regional blackouts and reduced operational costs via for example automated meter readings.

Many countries are currently making massive investments on smart grid research and development. For example, the smart grid is a vital component of President Obama's comprehensive energy plan: the American Recovery and Investment Act includes $11 billion in investments to "jump start the transformation to a bigger, better, smarter grid". One of the key elements behind the current intensive work program towards smart grid in the United States is tightly linked with the need to modernize their power system. In particular, the lack of electricity distribution network reliability under stress conditions was born out of under-investment in the infrastructure combined with growing energy demand. This was emphasized in a series of major supply disruption events (e.g. the North-East blackout), widely seen as a wake-up call to address network stability by increasing inter-connectivity, local and wide area control. Also, there are growing expectations on the integration of a wide range of renewable energy sources with the power grid. Therefore the US DoE Smart Grid Research and Development Program [6] has set the following performance targets for 2030: 20% reduction in the nation's peak energy demand; 100% availability to serve all critical loads at all times and a range of reliability services for other loads; 40% improvement in system efficiency and asset utilization to achieve a load factor of 70%; 20% of electricity capacity from distributed and renewable energy sources (200 GW). There are also a number of huge industrial research projects currently underway, for example, the IBM GridWise project [7] and the smart grid trial in New Mexico [8].

Europe, by contrast, presents a highly interconnected, mesh distribution network exhibiting more robustness than the US system. Energy network development is in a period of stability within the European Union (EU). There is a program of large investments in updating the distribution network already agreed at the EU level [9], which is decreasing the pressure for rapid decisions towards adoption of disruptive new technology. The biggest concern in Europe is in the integration of renewable power generation to meet the 2020 targets for reduction of CO2 emissions from fossil power generation. The intermittent nature of these energy sources places demands that existing transmission and distribution networks have not been designed to meet. Considerable effort will be needed so as to become less dependent on conventional and foreign sources of energy. The important role of smart grids is mentioned in the European Commission's 2020 strategy document [10], in the EU Smart Grids Technology Platform [9], and also highlighted in the new initiative on Future Internet research (FI PPP, [11]) as a key application. A recent example FI PPP project on smart grid is FINSENY led by Siemens [12]. The EU, through the technology development platform, has established a carefully planned approach to the implementation of smart grid technologies in the medium to long term. Establishing work on standardization, research projects involving academia with industries (utilities and manufacturers), and demonstration/pilot projects are the current priority.

Smart grids and smart metering are expected to contribute significantly towards improving energy usage levels through the following four mechanisms:

- Energy feedback to home users through an IHD (In-Home Display) - Accurate energy consumption, coupled with real-time pricing information is expected to reduce energy usage within the home, especially as energy prices continue to rise.
- Energy consumption information for building operators - to assist with the detailed understanding and optimization of energy requirements in buildings.
- The inclusion of distributed micro-generation based on locally-distributed clean, renewable energy sources such as wind and solar.
- Real-time demand response and management strategies for lowering peak demand and overall load, through appliance control and energy storage mechanisms (including electrical vehicles).

To enable the above functionalities, an effective, reliable, and robust communication infrastructure has to be in place. This paper provides an overview of the following important issues of smart grid communications: communication infrastructure, network architecture, demand response management, security and privacy challenges, and standardization activities. Compared to other recent surveys on smart grid (e.g. [13] and [14] which are mainly from an academic perspective), our primary aim is to provide a coherent picture of the current status of smart grid communications, especially focusing on research challenges, standardization, and industry perspectives. We would like to point out that since the smart grid is a vast area, the main focus of this paper is on smart grid communications. For overviews on other aspects of smart grid, e.g. technologies on the transmission side and control center of the smart grid, please refer to [15] and [16]. Furthermore, this article mainly provides a technical perspective of the smart grid. For a business or economic perspective, the readers are referred to [17].

The rest of the paper is organized as follows. Section 2 discusses several research challenges and opportunities in smart grid communications. Section 3 addresses the important issue of security and privacy and Section 4 presents our vision of applying some existing networking technologies to solve energy management problems. Section 5 provides a brief introduction to the standardization activities in Europe and conclusions are drawn in Section 6.

II. Communication Challenges and Issues

While communications technology is seen as an essential enabling component of future smart grids, there are a number

TABLE I
COMMUNICATION REQUIREMENTS AND CAPABILITIES OF THE DIFFERENT TYPES OF NETWORKS

Type of Network	Range	Data Rate Requirements	Potential Technologies
HAN	Tens of meters	Application dependant but generally low bit rate control information	ZigBee, Wi-Fi, Ethernet, PLC
NAN	Hundreds of meters	Depends on node density in the network (e.g. 2Kbps in the case of 500 meters sending 60 byte metering data every 2 minutes per NAN)	ZigBee, Wi-Fi, PLC, cellular
WAN	Tens of kilometers	High capability device such as a high speed router/switch (a few hundred Mbps to a few Gbps)	Ethernet, microwave, WiMax, 3G/LTE, fibre optic links

of challenges that must be addressed in order to have fully robust, secure and functional smart grid networks. Some of these challenges are discussed below. It is important to note that these challenges are very much intertwined, i.e. they affect each other and must be considered as parts of a bigger problem/challenge. We begin by first giving an overview of smart metering communications which is a major component of the overall smart grid communications architecture. This is then followed by a discussion on several different related research issues [18].

A. *Smart metering communications*

A smart metering communication system consists of the following components: smart meter which is a two-way communicating device that measures energy consuming at the appliances (electricity, gas, water or heat); Home Area Network (HAN) which is an information and communication network formed by appliances and devices within a home to support different distributed applications (e.g. smart metering and energy management in the consumer premises); Neighborhood Area Network (NAN) that collects data from multiple HANs and deliver the data to a data concentrator; Wide Area Network (WAN) which is the data transport network that carries metering data to central control centers; and Gateway which is the device that collects or measures energy usage information from the HAN members (and of the home as a whole) and transmits this data to interested parties. Table I indicates the typical communication requirements and the potential technologies that could be employed to realize the different types of network mentioned above. For a comprehensive survey on communication protocols for automatic meter reading applications, please refer to [19].

Figure 1 shows a typical smart metering architecture that is being reflected in the European standards development process. Note that this is just an example and not a definitive final architecture. At the most basic level, the home will be equipped with a series of smart meters, one each for electricity, gas, water and heat (if applicable), according to the facilities available at each home. These will be connected to a metering gateway in the home, which may or may not be part of an existing home gateway device. The HAN through which they communicate with the metering gateway may be multi-standard. This is mainly due to differing meter locations and power availability; for example, gas and water meters may have to use only battery power. Multiple HANs are further connected into a NAN via a wireless mesh network.

In Figure 1, the smart metering gateway is connected to both the utility (via a WAN) and the distribution control system (DCS) because the utility company may not necessarily own the DCS, especially in countries such as the UK where there is so much competition and fragmentation - a home in London could be supplied by a Scotland-based utility with the local distribution infrastructure being owned by another company. The utility is mainly responsible for services like billing, service management and tariffs, and the distribution control system is responsible for demand response, commands to disable certain devices/appliances, renewable energy integration, etc.

During the European standardization process, it became evident that a single application data model is required to enhance the interoperability of the different meters and databases used to store their information. One such model which has been receiving a lot of attention is the Device Language Message Specification/Companion Specification for Energy Metering (DLMS/COSEM) model [20][21][22], which is currently being modified to address all of the additional functionalities that have been mandated.

Optionally, home devices and appliances may also be part of the HAN, whilst any home automation system(s) may be connected to the same HAN and interface with the smart meters. The in-home display (often called the Customer/Consumer Display Unit - CDU), which is being considered strongly to be mandated in the UK Smart Metering Implementation Project, is an example of this. In the future, it is expected that home automation systems will gather detailed energy usage information from the smart meters and also from sub-meters attached to specific devices and appliances, so that a number of sensors and actuators can be brought together within the home to optimize the energy consumption of the home as a whole. This aspect of smart metering and home automation is crucial to the realization of the targets of CO2 emission reduction that the EU has set.

There are a number of options currently for the communications outside the home, i.e. between the metering gateway and the power distribution network, utility, operators and any other authorized parties. The obvious candidates are wireless cellular technologies and various home broadband solutions. However, it remains to be seen if utilities will be willing to trust the reliability and independence of these solutions. It is more likely that a mixture of a wide range of technologies will be used, including proprietary solutions for the last-mile access to the metering gateway. Data concentrators/aggregators have been discussed (see Figure 1), which could be deployed around residential areas. Given a wireless mesh network between metering gateways and/or smart meters, these aggregators

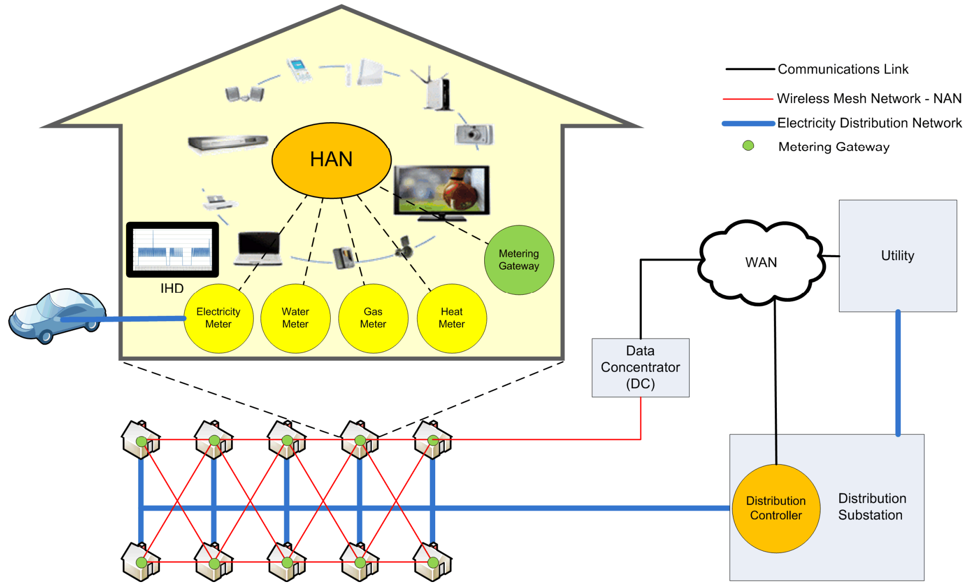

Fig. 1. Typical smart metering architecture

could gather all of the required data at periodic intervals and then send them over to the utilities through fixed line communications.

B. Interoperability

A key feature of smart grids is the interconnection of a potentially large number of disparate energy distribution networks, power generating sources and energy consumers. The components of each of these entities will need a way of communicating that will be independent of the physical medium used and also independent of manufacturers and the type of devices. The communication architecture of the future smart grid is yet to be defined. As a result, multiple communication technologies and standards could coexist in different parts of the system. For example, short-range wireless such as Bluetooth or UWB could be used for the interface between meter and end customer devices, IEEE 802.15.4 (ZigBee) and IEEE 802.11 (Wi-Fi) could be used for smart meter interfaces in the home and local area network, and cellular wireless (e.g. GPRS, UMTS, or 4G technologies like 802.16m and LTE) could be used for the interface between meters and the central system [23][24]. To this end, interoperability is essential for smart metering devices, systems, and communications architectures supporting smart grids. This has been emphasized by the recent EU M/441 Mandate on smart meters [25].

It can be envisaged that in a complex system such as smart grid, heterogeneous communication technologies are required to meet the diverse needs of the system. Therefore, in contrast to conventional telecommunication standardization such as IEEE 802.11n or 3GPP LTE, the standardization of communications for smart grid means making interfaces, messages and workflows interoperable. Instead of focusing on or defining one particular technology, it is more important to achieve agreement on usage and interpretation of interfaces and messages that can seamlessly bridge different standards or technologies. In other words, one of the main aims of communication standardization for smart grids is ensuring interoperability between different system components rather than defining these components (meters, devices or protocols) [26].

In this context, generic application programming interfaces (APIs) and middleware are useful enabling technologies. The success of commercial deployment of smart metering and smart grid solutions will significantly depend on the availability of open and standard mechanisms that enable different stakeholders and vendors to interoperate and interface in a standard manner. Open interfaces serve many purposes and provide additional benefits in multi-stakeholder scenarios such as smart energy management in home and industrial environments. Further, open APIs provide the means for third parties not directly associated with the original equipment manufacturers to develop a software component which could add functionality or enhancements to the system. On the other hand, smart energy management solutions require access to more information, ideally from different service providers and devices implemented by different vendors. Such information should be available and presented in a usable format to interested parties. Timing and specific configuration of measurements and controls are also critical for dynamic scenarios. Since support for different technologies and some level of cooperation over administrative boundaries are required, proprietary or widely simplified interfaces will not be sufficient in these scenarios. This situation can be improved by standard generic API definitions covering methods and attributes related to capability, measurement and configurations. The design of such APIs should be technology agnostic, lightweight and future-proof.

C. Scalable internetworking solutions

Wireless sensor networks (WSN) research should be extended to smart grid and metering. WSN has been an active research topic for nearly ten years and has found many applications [27][28]. Smart grid/metering appears to be a major application for WSN, especially related to Internet of Things and machine-to-machine (M2M) communications [29]. Existing industry efforts include IETF 6LoWPAN [30] and ROLL [31][32][33]. Based on smart metering user scenarios, the overall M2M network architecture, service requirements, and device capabilities are yet to be defined. Recently ETSI has established a new M2M technical committee to address these issues [34].

Internetworking between cellular networks and local area networks (e.g. WLAN) has received a lot of attention because of the need for seamless mobility and quality of service (QoS) requirements [35]. Topics such as intelligent handover and connection management have been extensively investigated. In the context of smart grid, due to the extremely large scale nature of the network, the characteristics of the metering and control traffic carried in the network are not clearly known. For instance, it could be the case where 100,000 smart meters generate meter traffic data every 10 minutes. As a result, how to design and provision a scalable and reliable network so that this data can be delivered to the central utility control in a timely manner is a challenging task. As traffic will be traversing different types of networks, interoperability is the key. Further, some of the traditional research topics may need to be revisited to cater for smart grid traffic, e.g. resource allocation, routing, and QoS. This is because the traffic that will be generated by e-energy type applications will likely be quite different to the traditional browsing/downloading/streaming applications that are in use today, with a mix of both real-time and non-real-time traffic being generated and distributed across different parts of a smart grid [36].

Interworking of communication protocols and dedicated smart metering message exchange protocols such as DLMS/COSEM [20] is an open research issue. The DLMS/COSEM standard suite has been developed based on two concepts: object modelling of application data and the Open Systems Interconnection (OSI) model. This allows covering the widest possible range of applications and communication media. Work has already started in the industry trying to address the issue of carrying DLMS data over various networks such as GPRS and power line communications (PLC) networks (for an overview of PLC and its applications to the smart grid, please refer to [37][38]). Recently, the DLMS User Association also established a partnership with the ZigBee Alliance and the two organizations are working on tunnelling DLMS/COSEM over ZigBee networks to support complex metering applications. Inside IEEE 802.15.4, the 802.15 Smart Utility Networks (SUN) Task Group 4g [39] is working on a PHY amendment to 802.15.4 to provide a global standard that supports smart grid network applications with potentially millions of fixed endpoints.

Recently a number of studies on efficient networking technologies for energy management have been published in the literature. A routing protocol for Advanced Metering Infrastructure (AMI) based on the framework of IPv6 routing protocol for low power lossy networks (RPL) is discussed in [40]. An ETX (expected transmission count) based rank computation method has been proposed for DAG (directed acyclic graph) construction and maintenance in RPL. This method enhances the unicast reliability of AMI networks. Simulation results have shown that the proposed mechanism produces satisfactory packet delivery ratio and end-to-end delay. In the near future, electric vehicles (EV) are envisaged to be a major application in the smart grid, and [41], among others, has outlined architectures for vehicle-to-grid (V2G) communications. The communication requirements and data flows between the EV and the grid (with distributed energy source generators) have been discussed, and Session Initiation Protocol (SIP) [42] is considered as a suitable solution for the establishment of communications. V2G networks have also been studied in [43], focusing on the message structure (based on ISO/IEC 15118-2) and message exchange sequence between the EV and the server over an IPv6-based PLC communication network.

D. Self-organizing overlay networks

Because of the scale and deployment complexity of smart grids, telecommunication network systems supporting smart grids are likely to rely on the existing public networks such as cellular and fixed wired access technologies, as well as private and dedicated networks belonging to different administrative domains. The purpose of such networks can be seen not only as a communications medium to exchange monitoring and control information, but also as an enabler of new services and applications. In many ways, the complexity and heterogeneity characteristics of smart grid communications networks will be similar to that of a wireless radio access network supporting voice and data services. However, stakeholder expectations, QoS requirements and load patterns will be significantly different from those of a typical mobile voice/data network because of the nature of the applications and services supported. Both will share, at least partially, problems related to managing and operating a complex and heterogeneous network where tasks such as network planning, operation and management functions, and network optimization are important. We believe that a self-organizing network overlaid over existing infrastructure could be the way forward to support wider deployment of smart grid systems. Such a self-organizing network should support functions such as communications resource discovery, negotiation and collaboration between network nodes, connection establishment and maintenance to provide the performance guarantees required by smart grid/metering applications. Recently, novel network architectures such as cloud-based systems have been proposed for smart grid data collection and control [44][45].

E. Home networking challenges

Research on home networking has so far focused on providing multimedia applications with high QoS, zero-configuration, and seamless connectivity to home users. With the advent of smart grids, new features and system design principles have to be considered. For example, consider how to integrate smart meter or M2M gateway functions into the home gateway (e.g. WLAN access point or femtocell base station) in a cost-effective manner. Clearly, smart metering adds a new dimension to home networks, complicating the issue of interference management and resource provisioning.

With potentially every device and appliance in the home supplying energy related information to the smart meter/home gateway (and by extension, possibly to the energy supplier as well), it is easy to envisage an order of magnitude increase in the number of devices in each home that are able to communicate with each other and with the outside world. Today's homes may have 2-3 computers (desktop, laptop, smart phone) that are connected to the home network and to the Internet. Tomorrow's smart grid/smart meter homes could have 20-30 or more appliances and devices connected to the same network. Although the preferred (wireless) networking standards for these devices have not yet been established, it is clear that there will be many more devices connected to whichever network is used. Although there has been much discussion in the networking community over the years of having "an IP address for every possible device" in the home, the convergence of energy provisioning and communications may be the catalyst for this to actually become a reality.

Along with the many new devices that will be connected to home networks, new kinds of applications will undoubtedly emerge. The prime (and easy to envisage) application is the one of energy consumption monitoring within the home and other areas (offices, etc.). In this direction, there are proposals for load monitoring and real-time control from the utility companies' perspective. However, energy monitoring has the potential to grow into something far more significant than just measuring the energy consumed. With the current concerns over climate change and the very important need for energy efficiency in all areas, it follows that fine-granularity monitoring of energy usage in the home and other areas will become a necessity and much research will be required in automating methods for energy usage reduction in the home. Given that there is much perceived wastage in the way in which the appliances and devices are used today (e.g. leaving devices on standby, inefficient usage of washing machines and refrigerators, inefficient use of heating and cooling), there is plenty of scope for realizing automated methods for reducing energy consumption.

III. Smart grid security and privacy issues

Analyzing and implementing smart grid security is a challenging task, especially when considering the scale of the potential damages that could be caused by cyber attacks [46]. For example, protection against unauthorized access and repudiation is a vital requirement for usage and control data communicated within the system, assuming that critical system functionalities require that the data are trusted by both the utility providers and the customers. To provide such security services might not be trivial as it may involve the integration of different information security domains such as secure communication protocols, tamper-proof hardware/software and regulatory frameworks on access control. The need for protecting smart grid data cyber security emerges from the need to interconnect smart grid components with a two-way communication network so that energy suppliers and customers can exchange information in an interactive, real-time manner. This capability could assist in enabling features such as load shedding, consumption management, distributed energy storage (e.g. in electric cars), and distributed energy generation (e.g. from renewable resources). Also, as previously discussed, the network could be implemented using a variety of media ranging from fibre optic broadband to ZigBee/WLAN, etc. Considering the need for fine-grained monitoring of smart metering data, the security of an advanced metering infrastructure is of paramount importance.

The security challenges of a smart grid system depend heavily on the system architecture. For example, consider the smart metering architecture in Figure 1. Some logical components (such as the distribution controller and the utility control services) may communicate via a hard-wired tamper-proof link (e.g. implemented within a simple physical controller) or may communicate using shared networks (e.g. when there is physical fragmentation). Each case imposes different security challenges such as protection against single point failures or protection against multiple points of attack. For example, the sink of a particular network can be identified based on timing analysis of messages that are sent from there [47]. This could potentially allow an adversary to launch an attack against the distribution controller which would have serious impact on customers in the whole area. To this end, security services should be provided through multiple layers of security so that potential attacks result in minimal damages.

More generally, smart grid security risks and vulnerabilities can be identified by using a top-down or a bottom-up approach. The top-down approach analyzes well-defined user scenarios such as automated meter reading (AMR) and billing, while the bottom-up approach focuses on well-understood security attributes and features such as integrity, authentication, authorization, key management, and intrusion detection. A classification of smart grid risks and vulnerabilities recently published by NIST can be found in [48] while a comprehensive specification of AMI security requirements has been documented by OpenSG in [49].

A. Cyber-physical security

Smart grid cyber threats, such as the Stuxnet worm [50], have the potential to breach national security, economic stability and even physical security. Power stations and SCADA (supervisory control and data acquisition) systems have always been targeted by hackers. The move from closed control systems to open IP networks opens up a new range of vulnerabilities. For example, data integrity and authentication may be compromised through network attacks such as man-in-the-middle spoofing, impersonation, or Denial of Service (DoS) attacks. Similarly, data security may be compromised by sabotage/insider attacks such as viruses and Trojan horses. The latter threat becomes significant considering the potential openness of the system and its interconnections with different networks such as NANs and the Internet.

Once an entry point is found, it becomes easier for the attacker to cascade an attack down the smart grid. For example, compromising the real-time pricing channel may result in energy theft or malicious remote control of appliances. Hence, rigorous hardware/software security is required to ensure the validity of different communicating parties such as head-ends and smart meters. If an attacker takes over the head-end, then he might be able to send smart meters a demand response command interrupting supply. The interruption can be made permanent by also commanding all the meters to change their crypto keys to some new value only known to the attacker [51]. The impact can be enormous: millions of homes could be left without power until they are locally replaced or rehashed with authentic keys, people suffer, health and safety could be jeopardized, and businesses could lose millions. Smart grid cyber-security needs to a) prevent such attacks from happening and b) have a recovery/survivability mechanism in case of (successful) attacks.

Communications security involves the design of a key management crypto-system. This could for example be based on existing systems such as Public Key Infrastructure (PKI) and Identity-Based Encryption (IBE) [52][53]. IBE, in particular, may be attractive for smart grids as it can be deployed without prior configuration, as the identity (ID) of a device is used to generate unique keys. This allows easy deployment of low powered devices such as sensors because they may start sending secure messages without the need to contact a key server. In general, a mixture of hierarchical, decentralized, delegated or hybrid security schemes may be feasible. Preferably, a candidate scheme should include secure bootstrapping protocols, i.e. it should provide effective means to initialize new devices. Further, critical security operations, such as key updates, should preferably employ group key management techniques, such as *defence in depth* techniques used in nuclear or military control systems, to mitigate the impact of compromised head-ends (or trusted people).

For more information on different smart grid cyber security attacks and threat impact, interested readers are referred to the NIST guidelines [48].

B. Privacy

Frequent smart metering data collection and analysis can help improve energy efficiency, as discussed in previous sections. Smart meters are expected to provide accurate readings automatically at requested time intervals to the utility company, the electricity distribution network or the wider smart grid. However, this comes at the cost of user privacy. That is, the information contained in such data may be used for purposes beyond energy efficiency, which gives rise to the smart grid privacy problem. In particular, frequent data collection from smart meters reveals a wealth of information about residential appliance usage, as discussed in [54].

In general, data privacy concerns the security of data that is linked with, or infer information related to, the life of individuals. The use of access control mechanisms, e.g. secure authentication, authorization and confidentiality services, cannot address the problem of smart grid data privacy holistically. This is because these data need to be disseminated to many different stakeholders within the grid. As discussed in [55] the consequences of the smart grid privacy problem are hard to understand, because a) the full range of information extraction possibilities are not known, and b) the concept of smart grid privacy is still not well defined. A good reason of why the problem of data privacy should not be underestimated can be found in a paper on digital inclusion and its ramifications [56].

Currently, the smart grid privacy problem is highlighted by Non-intrusive Appliance Load Monitoring (NALM) technologies that use energy measurements to extract detailed information regarding domestic appliance. Since the original work [57] there has been a wealth of research in the construction and upkeep of appliance libraries and detection algorithms [58]. Recent results suggest that even when household power profiles are aggregated, the use of household appliances can be identified with high accuracy [59]. The authors of [60] have described a fine-grained energy monitoring system that generates device level power consumption reports primarily based on the acoustic signatures of household appliances. Their experiments demonstrate that the system is able to report the power consumption of individual household appliances within a 10% error margin.

An example of appliance detection can be seen in Figure 2. In general, the granularity of events that an algorithm may be able to successfully detect depends on the frequency of smart meter readings. The frequency range can vary, depending on the utility, but in general this could be as high as every few (1-5) minutes. Such detailed energy usage information could lay bare the daily energy usage patterns of a household and enable deduction of what kind of device or appliance was in use at any given time. Further, the authors in [61] suggest that data mining techniques can be used to reveal trends of personal behavior in the metering data even if relatively low data sampling rates (e.g. every 30 minutes) are assumed.

From the above it becomes clear that the smart grid privacy problem is important and solutions are needed. There are two classes of privacy protection schemes: a) regulatory-based ones and b) technological-based ones. Current standardization activities focus on developing regulations and policies to help protect smart grid privacy. In the USA, NIST has acknowledged that the major benefit provided by the smart grid, i.e. the ability to get richer data to and from customer meters and other electric devices, is also its Achilles' heel from a privacy viewpoint [48]. Further, the American National Association of Regulatory Utility Commissioners (NARUC) [62] has drafted a resolution stating that: "utility customer information can be used to differentiate utility services in a manner that creates added value to the customer". On the other hand, "a balance has to be carefully considered between the appropriate pro-competitive role that utility customer information can play in new and developing markets and the privacy implications of using that information".

In Europe, the European Commission has set up a Task Force on smart grid aiming to develop a common EU smart grid vision and identify key issues that need to be resolved. In response, three Expert Groups (EGs) have been set up, one of which, EG2, aims to identify the appropriate regulatory scenarios and recommendations for data handling, security and consumer protection. One of the EG2 recommendations is to use anonymity services to help protect privacy. For example, smart metering data can be separated into low frequency attributable data (e.g. data used for billing) and high frequency anonymous technical data (e.g. data used for demand side management). In this case, the main challenge resides in anonymizing the high-frequency data, which are required for efficient grid functionalities, while making sure that the reliability, the effectiveness and the security of these functionalities are not compromised.

A number of technological solutions have further been proposed as follows.

- Anonymization. An example of this direction is studied in [63] where a secure escrow protocol is proposed to securely anonymize the ID of frequent metering data sent by a smart meter.
- Aggregation. In [64] the authors introduce two different solutions for the smart grid data privacy model. One solution uses a third trusted party as a data aggregation proxy. The other solution adds random value from a particular probability distribution to the data.
- Homomorphism. The use of homomorphic encryption can corroborate smart meter data privacy as discussed in [65]. This paper develops a method for a number of meters that have a trusted component and enjoy a certain level of autonomy. A trustworthy system provides guarantees about the measurements for both grid operators and consumers.
- Obfuscation. In [66] a cooperative state estimation technique is introduced that protects the privacy of users' daily activities. The proposed scheme can obfuscate the privacy-prone data without compromising the performance of state estimation.
- Negotiation. In [67] the authors introduce the concept of competitive privacy between the utility that needs to share the data to ensure network reliability and the user that withholds data for profitability and privacy reasons. The resulting trade-off is captured using a lossy source coding problem formulation.
- Energy management. In [68] the authors introduce a battery management algorithm that changes home energy consumption in a manner that helps protect smart metering privacy.

Although there is still much more research to be done in this area, it appears that smart grid privacy is a sensitive topic which can be approached in a number of different angles. Future protection schemes is likely to be a combination or evolution of the solutions introduced above, depending on the system cost and the need for privacy in different societies.

C. *Secure integration*

The most widely discussed smart grid security challenges concern the protection of smart metering data against unauthorized access and repudiation. This is an important requirement without which AMR data will not be trusted by either the utility providers or the customers. Solutions are required on different levels: end to end secure communication protocols need to be used, hardware components (e.g. smart meters) need to withstand physical attacks, the grid needs to detect forged/hacked components, and smart meter software should be bug-free [69].

We believe that AMI communications security requirements can be addressed by combining existing cryptographic protocols and tamper-proof hardware solutions, by exhaustively testing equipment and software against all sorts of attacks, and by adopting an open architecture for further testing and secure updating. Also, as discussed in the previous section, it is equally important to develop mechanisms for protecting smart metering data against insider attacks. The use of open smart grid interfaces, as previously described, will create a gateway for multiple third parties (stakeholders) to access and process AMR data. We need to make sure that such insiders will access smart metering data in an authorized manner and will only use this data in an *acceptable* manner.

Our vision is that security policies and legislation are not a panacea for privacy as they do not thwart attacks such as data privacy concessions: history teaches that legitimate techniques for mining and exploiting data evolve quickly when there is a clear financial incentive. Hence, the problem of smart meter data access and usage needs to be further reviewed within different security domains:

- Enforcement: Smart metering data should belong, in principle, to the users. For example, a digital rights management system could be used to allow utility providers to use the data in an acceptable manner. Any use of personal data (acceptable or unacceptable) should not be repudiated.
- Concealment: Users may use power routing algorithms in a manner that conceals events extracted from their energy usage activities [68].
- Reaction: There should be mechanisms that will detect (in retrospect) misuse of smart metering data. These mechanisms should have regulatory support for countermeasures (e.g. penalties) against malicious parties.

The common challenge in all the above cases remains to design a system that will balance the trade-off between security and performance, i.e. use adequate security strength while minimizing its power usage and cost overheads. In the future, smart grid/metering communications may potentially integrate with heterogeneous network systems, Internet applications, etc. For example, a roaming smart grid customer may wish to use power energy in remote areas and link this usage to his smart metering profile. This integration can be used for billing or other personalized services. In such an example, it will be necessary to establish secure communication protocols between different parties such as a home smart meter, a mobile phone, a smart roaming power appliance and the customer. The customer may additionally wish to allow third parties get access to personal smart metering information in exchange for services such as free entrance to facilities, or the customer may wish to remain anonymous. One can envisage further challenges arising as smart grid communication systems integrate with other communication systems: home entertainment systems, medical communication systems, and traffic monitoring communication systems (e.g. via GPS), just to name a few.

In the above scenarios it becomes clear that integration of services and interfaces gives rise to a whole new range of security and privacy vulnerabilities and requirements. In such complex computing, communications and energy management environment, it is important to understand how security risks are cascaded, i.e. how the compromise of one system leads to compromise of a downstream system. Risk analysis should be able to detect both proactive and reactive system anomalies and take appropriate measures such as creating appropriate

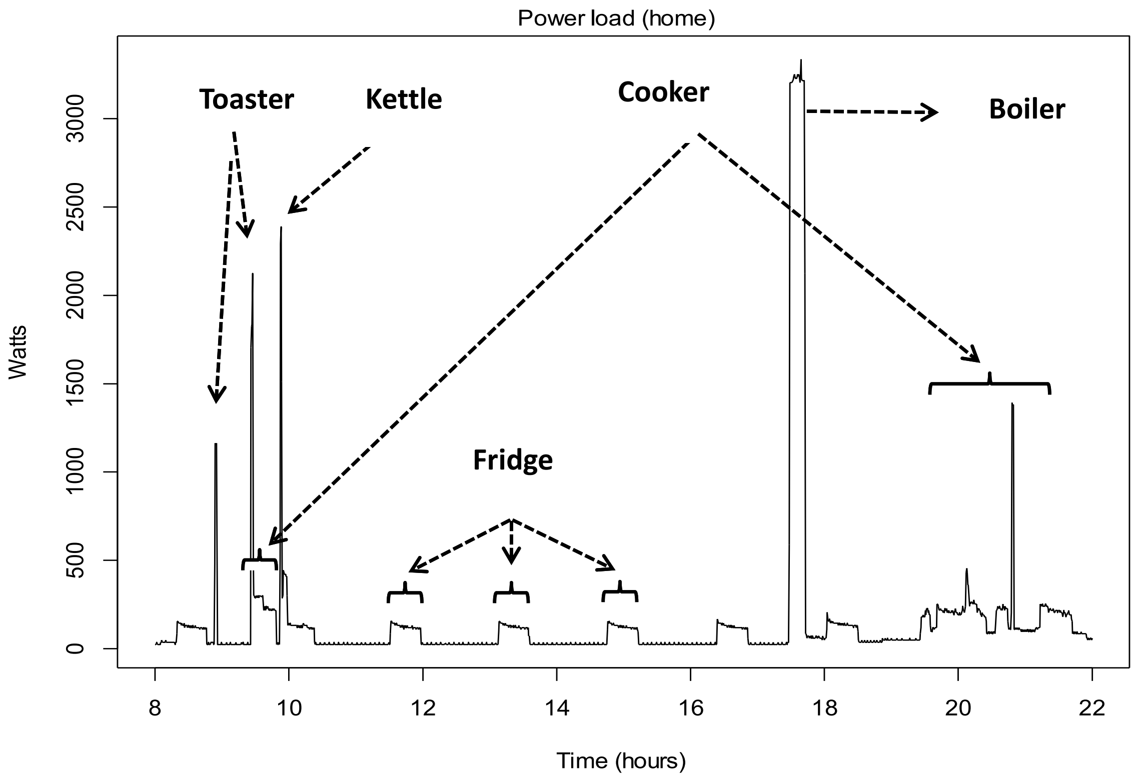

Fig. 2. Household electricity demand profile recorded on a 30-second time base from a one-bedroom apartment

logs and alerts. Further, the extrapolation and combination of multi-domain information such as energy consumption data, location information, lifestyle information, and other personal information increases the potential both for richer applications and services as well as security threats and damages. Indeed, future integration of systems and services requires transparent and secure protection mechanisms, more than ever before.

IV. Energy management - building on lessons learnt from communications networking research

In previous sections we have discussed research challenges for communication engineers posed by the smart grid. On the other hand, technologies developed in communication networking can help to solve various problems in energy management too. We elaborate on this interesting topic in this section. One of the main problems currently faced by the energy suppliers is the fluctuations in energy demand, which are expected to be further exacerbated when plug-in electric vehicles become a reality in the near future. In a situation like this, the approach traditionally adopted by the energy supplier is to take the peak consumption into account and create enough reserve energy supply (potentially upgrade existing infrastructure) to meet this uneven energy demand. This is similar to the over-provisioning approach adopted by the communications network service providers. Even though this approach addresses the problem of meeting the demand, it results in inefficiencies by creating a waste in the system since the demand on average is much less than the (estimated) peak energy requirement. Installing power plants to cater for the peak demand is not only expensive, but also may not be practical as the demand often keeps outpacing the supply. A coordinated effort to shift the power load from peak to off-peak times will lead to better generator utilization and fewer standby sources of energy which translates into reduced cost to the utility provider and less damage to the environment.

A compilation of energy consumption statistics of typical household electrical appliances can be found in [70]. This data suggests that most of the hard hitters, e.g. storage heaters, dish washers, washing machines, etc. can be rescheduled to operate during the odd hours, e.g. after midnight or early morning, when the overall demand is low. The next step is to identify how to determine the demand at the consumer level, distribution system level, and the aggregate demand taking into account all the distribution systems. This requires bi-directional communication mechanisms between the grid and the consumer premises - facilitating the consumers to notify their demand requirements to the grid and for the grid to feedback availability/pricing information to the consumers. Based on the information obtained from the consumer side, the utility providers can ascertain demand per distribution system and hence the aggregate demand. Subsequently, considering the capacity and the demand, the utility provider may identify target operating points for each distribution system. These could then be conveyed to the distribution systems following which the distribution systems could then translate these into individual targets for the consumers connected to it. Such target operating points clubbed with the consumer preferences could then factor into the decision of load scheduling at the consumer premises.

We can look at this problem as one involving balancing the load so as not to exceed the available capacity which, in essence, is similar to the traffic engineering problem in the Internet where traffic load balancing is analogous to electrical load balancing. We observe parallels between the two problems in that, mechanisms to estimate the demand are analogous to available bandwidth estimation and the concept of a traffic engineering management server spreading traffic across different paths is analogous to the energy management system distributing the available supply appropriately to the different distribution systems. Common to both are concerns of fairness (i.e. how to share the available capacity amongst the different users/consumers?) which could build upon the numerous studies on fairness in the communications networking area.

On a similar note, we observe that the problem of meeting the operating targets assigned to consumers is similar to the resource scheduling problem; essentially how to schedule the different devices within the house so that the net consumption conforms to the operating target. Figure 3 [71] depicts the interaction between a power management system (PMS), aggregate consumer load (CL), generation plant (GP), and spinning reserve (SR) when a peak is detected in a smart grid. The aggregate power consumed by the PMS customers needs to be brought into a power budget (budget) assigned to the PMS by the smart grid. When a peak event is detected (e.g. certain threshold being breached), the PMS could send its customers a schedule request to match the demand to the available supply by rescheduling non-critical loads to off-peak periods. This could possibly result in some reduction in demand. If, however, the demand still exceeds the allocated power budget, the PMS could send a request to the GP to increase its output by the amount of difference between the re-scheduled power demand and the budget of the PMS (diffPower). It may be likely that the GP may not be able to fulfil this demand in which case it could request the SR to allocate extra power to the GP to meet the power demand of the PMS customers. On the other hand, if the demand (subsequent to customers rescheduling some of their loads) drops below the budget allocated to the PMS, a request to reduce the power output could be sent to the GP in order to conserve energy. This ensures better utilization of the available resources by simply shifting power demand to the low demand periods thereby leveling the load.

Finally, it may be likely that it is impossible to satisfy the demand in which case the energy supplier may have to resort to controlled (partial) outage. The decision of who does and doesn't encounter outage could be based on the different preferences and priorities of the different consumers depending on their roles in the grid. It is envisaged that the prioritization could be done in a hierarchical manner wherein the consumers are grouped into different service classes at the time of registration (initiation of service). For example, hospitals/emergency services should never encounter outage whenever possible, whereas service to other low priority consumers may be compromised. Load shedding should happen in such a way so that loads are disconnected according to the service classes assigned to them. The consumer in each service class could further prioritize their appliances according to their preferences which help the scheduler to make scheduling decisions for the consumer in an outage event where the outage can be avoided by merely re-scheduling non-critical loads in the lowest priority service class (e.g. residential). This is analogous to the QoS paradigm in computer networks where some of the traffic is dropped or delayed (using the priority assigned to the packets) due to lack of bandwidth. Different classes of priorities could be assigned to different types of buildings according to their perceived importance. Further, having sub-classes can facilitate more granular load scheduling decisions.

Apart from the aforementioned approaches, we also observe a number of similarities between the smart grid resource allocation problem and well-known problems from communications and networking research.

Load Admission Control: One of the popular mechanisms for resource management in the communications networking world is admission control wherein a flow/connection is admitted in the network only if resources are available to serve it. Intuitively, this could be an interesting approach to explore in the context of energy management. This could potentially work as follows: the utility could allocate target operating points to each distribution system connected to it. Prior to connecting the load, the energy management gateway at the consumer's premises could send a load request to the Power Management System connected to its distribution system. This could contain both the load that is desired and the priority of the load. If the sum of the incoming load request and the current aggregate load is less than the target operating point, the load request could be granted. Otherwise, if the priority of the load request is low, a response could be sent to the consumer to reschedule the load. If the priority of the load request is high, then the PMS could send a message to the noncritical loads connected to it, asking them to respond if any of them would be willing to be rescheduled. Once the responses are received, it could choose the first of the responses which can relinquish load equivalent to the demand of the pending request. The PMS could then instruct this consumer to reschedule (providing a cheaper tariff as a reward) and approve the load request which is pending. After approving the pending request, the PMS would update its current aggregate load by adding the recent request's requirement.

As elaborated in the earlier sections, the priority of different loads will vary depending on the individual customer preferences. Hence, it should be possible to adjust the priority of each load according to the customer's perceived priorities. This can be achieved using the home energy management gateway (HEMG) device which will provide the necessary functionality to assign preferred priorities to customer loads. Although load admission control requires more information exchange between HEMG and PMS which may raise privacy concerns, this exchange can be anonymized using privacy measures such as that introduced in [63].

Load Scheduling: There are similarities between the load scheduling problem in smart grids and scheduling and resource allocation problems in communication networks. For example, in Orthogonal Frequency Division Multiple Access (OFDMA) wireless systems [72], mathematical optimization algorithms are used to determine optimum power allocation and frequency band selection to satisfy different data rate requirements for various users. This has similarities in smart grids where loads

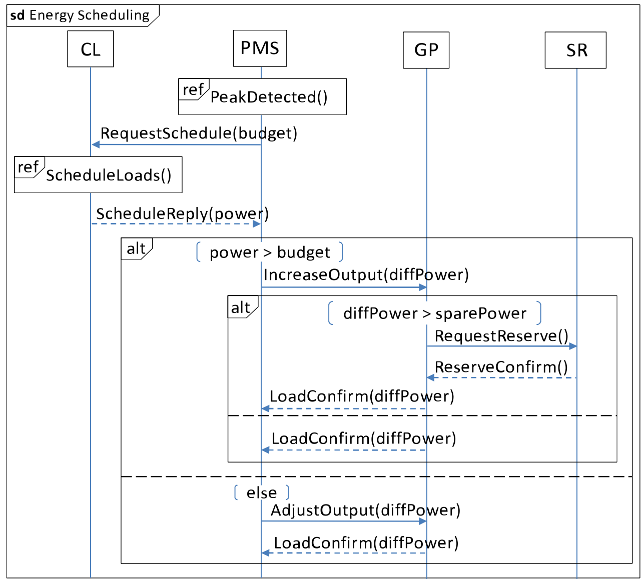

Fig. 3. Example of an energy management scenario

need to be allocated to various users at different time slots to optimize resource utilization and to improve energy efficiency. The solutions to load balancing in smart grids can be obtained based on the optimization approaches used in communication networks.

Cooperative Energy Trading: It is envisaged that a future smart grid will include many micro generation plants. We envisage a cooperative energy trading scheme where the energy trading happens between energy users in a local open market. A local market could consist of micrograms that operate their own micro generation plants as well as being connected to the macrogrid [73]. The idea here is a better utilization of the available power resources by cooperatively using available generation resources. This approach is very similar to the cooperative communication [74] philosophy where the nodes in a wireless network try to increase their throughput and network coverage by sharing available bandwidth and power resources cooperatively. The consumers with micro generation plants create a market for trading energy within their local consumer group. They cooperatively use energy generated by the local micro generation plants to curb their dependence on the macrogrid supply. This approach will both increase the efficiency of the macrogrid and possibly fetch a better price for micro generation electricity. If the micro generation output in a cooperative energy area is greater than the total power consumption (surplus power), the same cooperative trading concept can be applied to the micrograms that are in close proximity (e.g. neighboring micrograms). This approach could greatly reduce the transmission costs by localizing energy distribution in a hierarchical manner.

To summarize, the lessons learned and the optimization approaches adopted in communication networks can be used in energy management problems in smart grids. While solutions to resource allocation in communication networks are well established, adopting these within the context of smart grids may not be trivial. Nonetheless, this could be a good starting point as these concepts could potentially offer invaluable insights into the design of reliable and efficient smart grids [71]. There has been a recent surge of interest in extending the optimization approaches used in communication networks to demand management in smart grids. For example, the work in [75] uses convex optimization techniques for the power consumption scheduling of appliances to minimize peak-to-average load ratio. The concept of congestion pricing in Internet traffic control has been applied to smart grid demand response in [76]. The work in [76] has demonstrated that the burden of load leveling can be shifted from the grid (or supplier) to the end users via this pricing mechanism. This idea has been further extended to distributed electric vehicle charging in [77]. A least-cost dispatch of available generation resources to meet the electrical load has been proposed using a unit commitment mode that relates the demand side and supply side management through a hidden Markov model and a Markov-modulated Poisson process in [78]. Most recent work in this area can also be found in, e.g., [79][80][81].

We finish this section by briefly discussing some of the challenges of demand side management (DSM). Having surveyed various optimization techniques for DSM, it should be highlighted that regardless of the potential economic benefits, not all consumers will be willing to participate in demand side management due to reasons for example the consumption discomfort introduced by load scheduling. Therefore, more work in terms of incentive design is required for the successful deployment of coordinated scheduling algorithms. Further, various distributed energy generation and sell back technologies can help further reduce the dependency on central supply. Therefore, optimization of energy dispatch at residential level is also a significant challenge for future DSM.

V. Smart Metering Standardization Activities in Europe

To realize the vision of smart grid enabled by technologies mentioned above, it is essential that we have a whole set of industrial standards in place to ensure interoperability and reliability. A key component of smart grid is the smart meter, which is capable of performing detailed measurements at customer premises and reporting them back to the utilities. Smart meters and the information they generate will provide the glue that allows the components of a smart grid to work together effectively and efficiently. A major paradigm shift in the operation, management and behavior of the energy industry could be achieved through smart metering. With the target of near-real-time response to potential grid problems, the communication flow between millions of residential customer premises will also be bi-directional and at many levels. Examples include user load controls, smart meters, user distributed energy source control (i.e., micro-generation at the home), home network and energy control, power distribution equipment, supply and demand control software, large-scale power source control (i.e. power stations), and of course, billing and service provisioning infrastructure at the utilities themselves. For instance, having access to real-time information on the flow of energy in the grid enables utilities and consumers to make smarter and more responsible choices. Also, the ability to monitor demand and supply allows remote sensing of damages, fault detection and tampering (electricity theft). At the same time, significant opportunities are presented to technology solution providers to develop enablers and techniques to deal with complex supply, demand and controls and to facilitate sustainable energy production and security.

While the benefits of smart meters will be common across the world, their functionality, the adopted communications technologies, standardization and regulation will be different due to geographical, economical, political and social factors. The envisaged systems are highly complex, not only due to the high level of distribution but also due to the large number of stakeholders with direct interests in the process. Therefore, a key enabling role to ensure successful integration is to be played by standards, as clearly recognized in [82] and [25].

Following the third Energy Package, Directive 2009/72/EC of 13 July 2009, the European Commission has decided to set up a Task Force on smart grids aiming to develop a common EU smart grid vision and identify key issues that need to be resolved[2]. The Task Force consists of a steering committee and three Expert Groups. The high level steering committee includes regulatory bodies, Transmission Systems Operators (TSOs), Distribution System Operators (DSOs), Distribution Network Operators (DNOs), and consumer and technology suppliers working jointly to facilitate the smart grid and smart metering development, and supporting the achievement of the 2020 targets. The three EGs are the following:

- EG1. Functionalities of smart grids and smart meters (current state of the art, services, smart grid components, functions, strategy for standards);
- EG2. Regulatory recommendations for data safety, data handling and data protection (need for standardized data model, cyber security);
- EG3. Roles and responsibilities of actors involved in the deployment of smart grids, such as DSOs/DNOs and the role of standards.

It is clear that there is a conscious effort within Europe to harmonize smart metering/grid standards, and to create a single set of European standards that will be widely used. A significant part of this endeavor targets communications architectures and solutions. This section summarizes the European perspective on smart metering.

[2]http://ec.europa.eu/energy/gas_electricity/smartgrids/taskforce_en.htm

A. Smart metering communication standardization in Europe

Metering standardization, including automatic/remote meter reading, is a well-established activity both at international and European standardization levels (CEN/CENELEC and ETSI). However, the functionality envisaged for smart meters (e.g. support for multiple dynamic tariffs/time of use tariffs, energy export functions, variable scheduled meter reading, demand control, etc.) requires interfacing to and either adopting existing or establishing new data formats and standards in areas not considered by the metering community so far. This has required bringing together and streamlining activities from multiple technical committees and standardization organizations for smart metering.

In response to the identified need for comprehensive standards for all aspects of smart grids, the European Commission issued Mandate M/441 EN [25] in March 2009. This mandate was targeted to the standardization bodies of CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization) and ETSI (European Telecommunications Standards Institute), with the prime objective being "...to create European standards that will enable interoperability of utility meters (water, gas, electricity, heat), which can then improve the means by which customers' awareness of actual consumption can be raised in order to allow timely adaptation to their demands (commonly referred to as smart metering)". The current target for the European standard for smart meter communication solution is August 2010, with the harmonized solution for additional functionalities being completed by December 2011.

Table II and Table III[3] present the various communication and data exchange standards applicable in different segments of the end-to-end smart metering distributed system. More specifically, we have grouped together standards, either agreed or proposed in the relevant technical committees (TCs) in European standardization organizations (CEN/CENELEC and ETSI), covering the HAN and WAN elements of the communication system supporting the smart metering applications, and layered according to the application, network and transport, and communication link technologies.

Currently the HAN area is populated strongly by IEEE 802.15.4-based communication technologies, and in particular ZigBee-based solutions, with the forthcoming ZigBee v2.0 with native support for 6LoWPAN [30] aiming to provide seamless IP networking connectivity between the smart meters, the metering gateway and the home appliances. The other candidate technologies are Bluetooth, but with no specific provisioning for application support for energy management (which ZigBee currently provides through the ZigBee

[3]Please note that the connections we show in Figure 1 are physical connections, whereas Table II, Table III and Figure 4 refer to standardization efforts and are more to do with the logical connections between entities in the smart metering infrastructure.

TABLE II
HAN COMMUNICATION AND DATA EXCHANGE STANDARDS FOR SMART METERING IN EUROPE

	Connection between smart meters, devices, and displays	SM to SM-GW	HBES (home automation network device, control, server, external server)	HBES to SM or SM-GW interface
Application	ZigBee Smart Energy 1.0/2.0, proprietary data model	**CEN TC 294**: EN 13757-3 M-Bus, **CLC TC 13**: IEC 62056 COSEM	**CLC TC 205**: EN 50090-3	**CLC TC 205**: EN 50090-3, **CLC TC 13**: IEC 62056 COSEM
Network and transport	ZigBee 2.0, 6LoWPAN	ZigBee 2.0, 6LoWPAN	**CLC TC 205**: EN 50090-4	**CLC TC 205**: EN 50090-4
Link and physical media	ZigBee, PLC, 802.15.4, Bluetooth, Proprietary protocols	**CEN TC 294**: EN 13757-2 M-Bus wired, **CEN TC 294**: EN 13757-4 M-Bus wireless, **CLC TC 13**: IEC 62056-31, Euridis 2	**CLC TC 205**: EN 50090-4	**CLC TC 205**: EN 50090-4

TABLE III
WAN COMMUNICATION AND DATA EXCHANGE STANDARDS FOR SMART METERING IN EUROPE

	SM-GW to Data Concentrator	Concentrator to DCS	SM-GW to DCS
Application	**CLC TC 13**: IEC 62056 COSEM	SMTP, SFTP, Web Service, COSEM	**CLC TC 13**: IEC 62056 COSEM
Network and transport	TCP/IP	TCP/IP	TCP/IP
Link and physical media	**CLC TC 13 / IEC TC 57**: IEC 62056 COSEM, DLMS/COSEM over IEC 61334/S-FSK, PLC, GPRS and/or Ethernet/ADSL	GPRS/GSM, PLC G3, Fibre VLAN, Point to multi-point radio	**CLC TC 13 / IEC TC 57**: IEC 62056 COSEM, DLMS/COSEM over GPRS

Smart Energy Profile [83]), and various narrow-band power-line communication solutions. However, it is to be noted that the currently existing standards for full-protocol stack communication in a HAN for home automation applications (Home and Building Electronic Systems - HBES) are already proposed as the way forward, and are currently covered by the CEN/CENELEC TC 205 technical committee in the EN 50090-x series.

The WAN solution is largely populated in the data exchange format (application) layer through the standards output from CEN/CENELEC TC 13 and the IEC TC 57 committees. Analyzing the proposed solutions and the existing standards, it is obvious that an IP-based solution at the network layer will have lower integration and interoperability costs than any non-IP based solution.

While Table II and Table III mainly focus on communication network standards for smart metering, there are other important standards that cover different aspects of smart metering. For example, IEC 61968-9 specifies interfaces for meter reading and control. It specifies the information content of a set of message types that can be used to support many of the business functions related to meter reading and control, e.g. meter reading, meter control, meter events, customer data synchronization and customer switching. It also defines a list of functionalities such as metrology, load control, demand response and relays, as well as a related set of XML-based control messages [84].

B. Standardization technical committees

1) Smart Meters Coordination Group (SM-CG): The SM-CG was set up as a Joint Advisory Group between CEN, CENELEC and ETSI to manage the standardization work in support of European Commission Mandate M/441 for the creation of European standards for an open architecture for utility meters enabling interoperability and to improve customer awareness of consumption. The SM-CG is not empowered to develop standards, but to propose allocation of the work to existing CEN, CENELEC and ETSI technical committees.

As can be seen in Figure 4, the European perspective on smart metering (especially within the home area) has been split into three distinct standardization targets: electricity meters, non-electricity meters (gas, water and heat) and home automation [26]. The M/441 standardization area also includes an M2M remote gateway which will send the collected metering data to the wider network (to be used by utilities and other interested parties). Beyond basic smart metering and communications functionality, a number of additional functionalities (F1 to F6) have been identified as optional (but strongly desirable) features of smart meters:

- F1 - Remote reading of metrological register(s) and provision of these values to designated market organizations,
- F2 - Two-way communication between the metering system and designated market organizations,
- F3 - Meter supporting advanced tariffing and payment systems,
- F4 - Meter allowing remote disablement and enablement of supply,
- F5 - Communicating with (and where appropriate directly controlling) individual devices within the home/building,
- F6 - Meter providing information via portal/gateway to an in-home/building display or to auxiliary equipment.

2) CENELEC TC 13 - Equipment for electrical energy measurement and load control: The scope of CENELEC TC 13 is to prepare European Standards (using whenever possible IEC standards) for electrical energy measuring and electrical load control equipment (such as watt-hour meters,

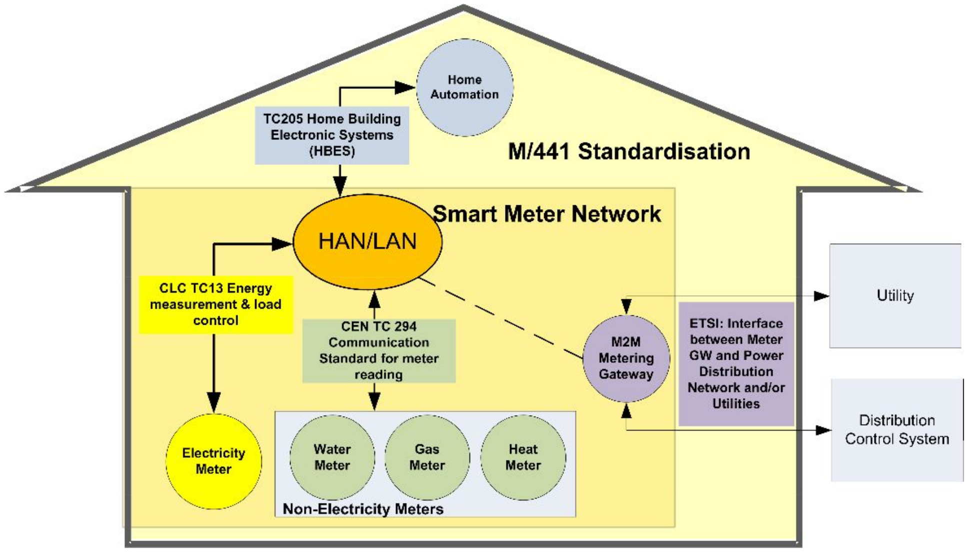

Fig. 4. TC responsibilities in European smart metering standardization

var-hour meters, maximum demand indicators, telemetering for consumption and demand, equipment for remote meter reading, time switches, equipment for the control of loads and tariffs and consumer services) including the equivalent electronic forms of these devices and their accessories. The activities of TC 13 encompass the development of the IEC 62056 DLMS/COSEM.

3) CEN TC 294 - Communications systems for meters and remote reading of meters: The work of CEN TC 294 encompasses the standardization of communication systems for meters and remote reading of meters for all kind of fluids and energies distributed by network and not necessarily limited to household meters. The activities of TC 294 encompass the development of the EN 13757 suite of standards on Meter-Bus (M-Bus) and wireless M-Bus.

4) CENELEC TC 205 - Home and Building Electronic Systems: The scope of CENELEC TC 205 is to prepare standards for all aspects of home and building electronic systems in relation to the Information Society. In more detail: to prepare standards to ensure integration of a wide spectrum of control applications and the control and management aspects of other applications in and around homes and buildings, including the gateways to different transmission media and public networks taking into account all matters of EMC (electromagnetic compatibility) and electrical and functional safety. TC 205 will not prepare device standards but the necessary performance requirements and necessary hardware and software interfaces. The standards should specify conformity tests. TC 205 will perform the work in close cooperation with relevant CENELEC TCs and those in CEN and ETSI. The activities of TC 205 encompass the development of the EN 50090 and EN 50491 suites of standards on Home and Building Electronic Systems (HBES) and Building Automation and Control Systems (BACS).

5) ETSI M2M: As mentioned previously, a new ETSI Technical Committee is developing standards for machine to machine communications. The group aims to provide an end-to-end view of machine to machine standardization, and will cooperate closely with ETSI's activities on Next Generation Networks, and also with the work of the 3GPP standards initiative for mobile communication technologies. According to the Terms of Reference for ETSI TC M2M [85], the responsibilities of the ETSI TC M2M are the following:

- "to collect and specify M2M requirements from relevant stakeholders;
- to develop and maintain an end-to-end overall high level architecture for M2M;
- to identify gaps where existing standards do not fulfil the requirements and provide specifications and standards to fill these gaps, without duplication of work in other ETSI committees and partnership projects;
- to provide the ETSI main center of expertise in the area of M2M;
- to coordinate ETSI's M2M activity with that of other standardization groups and fora."

As part of their activities in smart metering, ETSI M2M has recently approved a smart metering use cases document [34] which discusses various detailed use cases in relation to a typical smart metering configuration, as shown in Figure 1. Examples of these use cases include: obtain meter reading data, install, configure and maintain the smart metering information system, support prepayment functionality, monitor power quality data, manage outage data, etc. All these use cases are discussed in terms of general description, stakeholders, scenario, information exchanges, and potential new requirements.

The use case of "obtain meter reading data", as an example, is aligned to the additional functionalities F1 and F2 as described previously. It describes how the Smart Metering Information System provides this meter reading data to the Read Data Recipient, either periodically or on request. The stakeholder for this use case is Read Data Recipient. The information exchanges involve both Basic Flow and Alternative Flow. For instance, the basic flow for automatically scheduled readings is: Smart Metering Information System registers meter reading along with time/date stamp, and Smart

Metering Information System sends meter reading data to Read Data Recipient. The potential new requirements (from an M2M perspective) for this use case are mainly regarding reliability and security: minimal latency for on-demand readings of distribution network management applications such as overload or outage detection; accurate and secure time synchronization; support of various information exchanges from M2M Devices and M2M Gateways; authentication of the M2M Device or M2M Gateway; a security solution in place to prevent eavesdropping at any point in the network; verification of the integrity of the data exchanged [34].

A number of liaisons have also been established with other standardization bodies, e.g. CEN, CENELEC, DLMS UA, ZigBee Alliance and other ETSI TCs. The TC M2M domain of coordination to answer M/441 includes: providing access to the meter databases through the best network infrastructure (cellular or fixed); providing end-to-end services capabilities, with three targets: the end device (smart meter), the concentrator/gateway and the service platform. Further, smart metering application profiles will be specified including service functionalities.

C. Worldwide standardization

The outcome of any deployment of smart grid/metering systems will depend on successful, quick and future-proof standardization of the major, long-lived components of the system, including the communications. In this section we have given an overview of smart metering standardization activities in Europe. However, it has to be mentioned that there are other major smart grid standards worldwide, for example, in US notably IEEE P2030 [86], ANSI [87], US NIST [48] and future IP for smart grids in the IETF [88]. For instance, it is important to note the development of the ANSI C12 suite of standards in the USA, that have been developed for electricity meters, in a similar capacity to the standards under the aegis of CLC/TC 13 in Europe. These standards are now being updated to reflect advances in smart metering, e.g. with the introduction of, among others, the C12.19 standard for Utility Industry End Device Data Tables (data models and formats for metering data) and the C12.22 standard for Protocol Specification for Interfacing to Data Communication Networks (communicating smart metering data across a network) [89].

The IEEE P2030 [86] project addresses smart grid interoperability and is composed of three task force groups looking at different aspects of interoperability in power systems (Task Force 1), information systems (Task Force 2) and communication systems (Task Force 3). The aim of this project is to provide guidelines for enabling integration of energy technology and information and communications technology (ICT) to achieve seamless operation of the grid components and a more reliable and flexible electric power system.

The IEEE 1547 standard was approved in October 2003 and outlines the collection of requirements and specifications for interconnecting distributed energy resources to the distribution segment of the electric power system [90]. The outlined requirements are relevant to the performance, operation, testing, safety, and maintenance of the interconnection. They are globally needed for interconnection of distributed energy resources including both distributed generators and energy storage infrastructure, which is essential to realize the goals of smart grid.

In China, smart grid standardization is led by the State Grid Corporation of China (SGCC). SGCC has recently signed a strategic cooperation agreement with General Electric (GE) and the Chinese Academy of Science to jointly develop smart grid standards. Standardization activities are expected in the following technical areas: electric vehicle charging, grid-scale energy storage integration, distributed resources, and microgrids [91]. In India, the IEEE Standards Association (IEEE-SA) has introduced two new standards, IEEE 1701 and IEEE 1702, to create a multi-source plug and play communications environment for diverse smart metering devices. Both standards provide lower layer communication protocols for LAN/WAN ports and telephone ports, respectively, used in conjunction with utility metering [92]. In Japan, standardization activities have been focused on the vision of "Smart Community" which involves the integration of smart grid, energy storage, electric vehicles, and intelligent transport systems. The newly established Japan Smart Community Alliance is coordinating industrial efforts in this area [93].

VI. Conclusion

In this paper we have presented an overview of the unique challenges and opportunities posed by smart grid communications, e.g. interoperability, new infrastructure requirements, scalability, demand response, security and privacy. The success of future smart grid depends heavily on the communication infrastructure, devices, and enabling services and software. Results from much existing communications research can be potentially applied to the extremely large-scale and complex smart grid, which will become a killer application. In parallel to technical issues of smart grids, we have also discussed the current status of standardization on smart metering in Europe. It is very desirable to have a single set of standards defining the interfaces, communications and data exchange formats for smart metering and smart grids in Europe. However, due to the current pressure on deploying smart metering solutions at different timescales in different countries, and for different energy supply companies, the timely harmonization of the many existing standards with the new additional functionality requirements will be very difficult. It is very important that the European standardization activities are aligned and take into account these requirements, and reflect them well at international standardization activities.

Although the roadmap of worldwide smart grid deployment is still not clear, it is almost certain that the future intelligent energy network empowered by advanced ICT technology will not only be as big as the current Internet, but also change people's lives in a fundamental way similar to the Internet. As communication is an underpinning technology for this huge development, we envisage that smart grids will be an exciting research area for communication engineers for many years to come.

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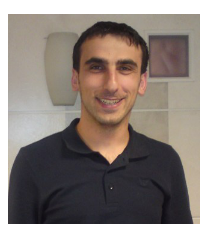
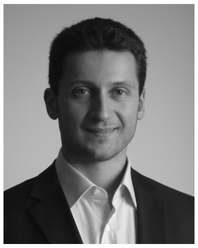
Zhong Fan is a Chief Research Fellow with Toshiba Research Europe in Bristol, UK. Prior to joining Toshiba, he worked as a Research Fellow at Cambridge University, a Lecturer at Birmingham University and a Researcher at Marconi Labs Cambridge. He was also awarded a BT Short-Term Fellowship to work at BT Labs. He received his BS and MS degrees in Electronic Engineering from Tsinghua University, China and his PhD degree in Telecommunication Networks from Durham University, UK. His research interests are wireless networks, IP networks, M2M, and smart grid communications.

Parag Kulkarni is a Principal Research Engineer at the Telecommunications Research Laboratory of Toshiba Research Europe Limited, Bristol, UK. His work focuses on systems aspects related to wired/wireless communication networks and their management, communication/networking aspects related to energy management and intelligent context aware adaptation algorithms. He holds a Bachelors degree in Computer Science and Engineering from the National Institute of Technology Calicut, India and a PhD degree from the University of Ulster, Northern Ireland.



Sedat Gormus received a B.Sc. degree in Computer Science from Karadeniz Technical University, Trabzon, Turkey in 1999. He then worked as research and development engineer in several Turkish and British technology companies. In 2004, He was awarded a PhD scholarship as part of OSIRIS project at the University of Bristol, UK. He finished his PhD studies in Cooperative Relaying Networks in 2008 and joined the Telecommunications Research Laboratory of Toshiba Research Europe Ltd. in March 2009 as a Senior Research Engineer in wireless communications field. He has been involved in a number of EU and UK Technology Strategy Board projects such as ViewNet. His current research activities include smart grid communications and wireless sensor networks.

Costas Efthymiou photograph and biography not available at the time of publication.



Georgios Kalogridis is a Senior Research Engineer at Toshiba Telecommunications Research Laboratory in Bristol, UK. His current research focuses on energy management, smart grid control, and smart metering privacy protection. More generally, his research interests lie in the areas of information security and privacy, combinatorial designs, network reliability, wireless mesh networks and mobile agents. He is the inventor of numerous patents granted in the UK and worldwide, he has published papers at major journals and conferences, and he has been actively involved in collaborative projects and ETSI standardization activities. Georgios has received an MSc in Advanced Computing from University of Bristol (UK) and a Diploma in Electrical and Computer Engineering from University of Patras (Greece). He is also due to his final examination for a PhD in Mathematics from Royal Holloway, University of London.

Mahesh Sooriyabandara photograph and biography not available at the time of publication.

Ziming Zhu received the MSc degree in Communication Networks and Signal Processing with Distinction from Bristol University, U.K., in October 2010. He is currently a Ph.D. student within the Advanced Signal Processing Group (ASPG) at Loughborough University, U.K. His research interests include resource management and optimization for wireless networks and smart grids.

Sangarapillai Lambotharan received the Ph.D. degree in signal processing from Imperial College London, U.K., in 1997. He was with Imperial College until 1999 as a Postdoctoral Research Associate. In 1996, he was a Visiting Scientist with the Engineering and Theory Center, Cornell University, Ithaca, NY. From 1999 to 2002, he was with the Motorola Applied Research Group, U.K., as a Research Engineer, and investigated various projects, including physical-link layer modeling and performance characterization of GPRS, EGPRS, and UTRAN. From 2002 to 2007, he was with the King's College London, London, U.K., and Cardiff University, Wales, U.K., as a Lecturer and Senior Lecturer, respectively. In September 2007, he joined the Advanced Signal Processing Group, Loughborough University, Leicestershire, U.K., as a Reader, and was promoted to Professor of digital communications in September 2011. He has published more than 100 conference and journal articles in these areas. He serves as an Associate Editor for the EURASIP Journal on Wireless Communications and Networking. His current research interests include multiple-input-multiple-output, wireless relay networks, cognitive radio networks, and smart grids.

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