# HubNet Position Paper Series

## Smart Grids and Communications Systems

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About HubNet

HubNet is a consortium of researchers from eight universities (Imperial College and the universities of Bristol, Cardiff, Manchester, Nottingham, Southampton, Strathclyde and Warwick) tasked with coordinating research in energy networks in the UK. HubNet is funded by the Energy Programme of Research Councils UK under grant number EP/I013636/1.

This hub will provide research leadership in the field through the publication of in-depth position papers written by leaders in the field and the organisation of workshops and other mechanisms for the exchange of ideas between researchers and between researchers, industry and the public sector.

HubNet also aims to spur the development of innovative solutions by sponsoring speculative research. The activities of the members of the hub will focus on seven areas that have been identified as key to the development of future energy networks:

- Design of smart grids, in particular the application of communication technologies to the operation of electricity networks and the harnessing of the demand-side for the control and optimisation of the power system.
- Development of a mega-grid that would link the UK’s energy network to renewable energy sources off shore, across Europe and beyond.
- Research on how new materials (such as nano-composites, ceramic composites and graphene-based materials) can be used to design power equipment that are more efficient and more compact.
- Progress the use of power electronics in electricity systems through fundamental work on semiconductor materials and power converter design.
- Development of new techniques to study the interaction between multiple energy vectors and optimally coordinate the planning and operation of energy networks under uncertainty.
- Management of transition assets: while a significant amount of new network equipment will need to be installed in the coming decades, this new construction is dwarfed by the existing asset base.
- Energy storage: determining how and where storage brings value to operation of an electricity grid and determining technology-neutral specification targets for the development of grid scale energy storage.

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Abstract

This paper presents an overview of the research and applications of communication technology applications for smart grid development, and identifies challenges relevant specifically in this area. This paper draws on discussions and positions presented at three cross-disciplinary colloquia/seminars organised under the Smart Grid theme of the HubNet project at Imperial College (2011) and University of Bristol (March and September 2012), and the EPSRC COMNET Smart Grid Communications Workshop (Loughborough, September 2012), as well as published research work.

A comprehensive bibliography of related works can be found at the end of the paper, in addition to the works referenced here.
1 Introduction

The initial drivers for Smart Grid system development that require a step-increase in ICT-enabled grid operations in an end-to-end system are still there. The societal, environmental and business drivers and incentives towards a low-carbon economy have not changed in the past decade, since the Smart Grid conceptual work started [1]. However, it has also become clearer that the level of integration and co-operation between different stakeholders (generation, retail, regulators and consumers) and technology domains (power systems, sensors, communications, and information technology), operating typically in the context of different industries, is quite significant. This is exacerbated if we also consider the fact that even within existing power networking systems the number of functions (and corresponding entities) is very large, and that the interconnection between these functions typically includes human-in-the-loop when the functions interface with one-another.

The underpinning technology that interconnects all these different stakeholders is communications. As an enabling technology, the design and operation of communications networks and systems is driven by demand; meeting demand at a particular quality of service level corresponds to a certain cost. From this point of view, the recurring question in workshops, discussions and academic and industry papers related to Smart Grid communications challenges is the identification of the expected service demand: what data rates are required, what is the quality of service in terms of delay, jitter, loss and throughput, and what are these in different parts of the system when required to support different functions (e.g. a system protection system requires different delays than a meter reading).

One can answer this question in two ways. The business-as-usual approach is to design a system based on existing known functional architectures and reflect, as much as possible, the functional and non-functional requirements that both existing and new functions of power grids pose. The second approach reflects on the fact that the introduction of end-to-end large scale ICT solutions in the Smart Grids requires rethinking of the power system as an autonomic, self-organised, platform whose operation should be deterministically guaranteed within known/accepted bounds. In this approach, the communications plane of the Smart Grid is not an off-the-shelf technology solution, but becomes part of the overall system in order to address, with existing technologies or new solutions, the challenges arising in such a system in terms of robustness, resilience, interoperability of equipment, auto-configuration and self-management, etc.

This paper presents an initial take/snapshot of the current state-of-the-art in understanding of communication network challenges and requirements to support Smart Grid functionality, within the constraints identified above. This work is ongoing, both within the HubNet project and elsewhere, aiming to define a Smart Grid blueprint that can evolve and provide reference points for the work to be done at different layers of the Smart Grid conceptual model shown in Figure 1.
Although the conceptual model for Smart Grid is often presented as a significant step-change in power systems management and operations, the realisation of this conceptual model is an evolutionary process. Signposting the roadmap to the realisation of Smart Grids for the communications plane is one of the aims of the work initiated with this paper, understanding very well that Smart Grids systems are but one of the components of a smarter cyber-physical infrastructure often referred to in other contexts as Smart Cities, Smart Energy and more generally, the concept best presented by IBM’s Smarter Planet initiative.  

2 Smart Grid Communications Challenges

As the power grid evolves from relying mainly on centralised generation, to one that can support diverse and distributed sources of energy (with many ingress and egress points for variable energy), there will be a large increase in the number of points to monitor and control. Communications and information technologies will make up a considerable part of the future power grid—interconnecting stakeholders and systems, and enabling new approaches for designing, operating, and managing the power infrastructure. However, this step change will have major consequences for existing communications networks and present significant challenges for future communications networks.

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1 http://www.ibm.com/smarterplanet/uk/en
2.1 Integration and Interoperability

Many different technologies are involved, with different levels of investment and at different levels of maturity and readiness. Furthermore, the development of technologies from conception to reality happens at different speeds—application layer (fastest), ICT (fast), power (slowest?). This happens naturally – architectures and requirements being are defined for systems, but often with little regard for how they will operate or have an impact in a larger system-of-systems context (integration problem). The larger the system, the larger the variable space that needs to be tested. However, the power grid is a highly critical infrastructure, and near impossible to trial on a large scale.

2.2 Scale and Complexity

The closer integration of systems in the power, communications, and IT industries (e.g., home and building automation systems are a combination of these) across different domains will create a larger and ever more complex system of inter-dependent systems. The resulting data explosion and inter-dependencies could have a significant impact on the stability and integrity of the system as a whole—a system could be behaving normally, but could cause another to become unstable. In particular, there is a critical need to understand the demands for communication resources due to distributed system interactions, but this can be extremely difficult to analyse due to the wider extent and impact of distributed system interactions across different systems and domains end-to-end (the result of closer integration).

2.3 Distributed Intelligence

One of the drivers for Smart Grid deployment is the expected fluctuation of the demand at the edges of the power network, combined with potential variations in generations using distributed renewable sources. Whilst load balancing is a well-known functional requirement for power systems, the slow-changing nature of the energy demand and its known diversity has focused the solutions in attempting to balance the load in the medium- and high-voltage parts of the power network. Energy demand is expected to change more frequently, and in ways that, at the moment, are not predictable, due to introduction of both energy demand management interventions in the end-user premises (one of the main objectives for the deployment of Smart Meters), and the unpredictability of the availability of distributed generation sources. This requires a significant amount of intelligence to be shifted from the core of the power network, which is already highly automated and reasonably monitored, towards the edges of the power network, which at the moment, to quote a colleague from Power Systems research, “… is only a lump of iron and copper”.

This is the main paradigm shift that the Smart Grid presents – the shift of the intelligence from the “core” power network towards its edges, expecting the devices and terminals to become more proactive in behaving in ways that affect the core of the system. This description has a very strong analogy – it is the same situation – with the telecommunication industry at the end of 1980’s and early 1990’s, and its shift from (virtual) circuit-switched telecommunication services networks towards IP networking solutions; the rise of the IP network was driven as much from the rise in “edge intelligence” as justified by the relatively low cost of the IP-based networking solutions relative to ATM-based ones. This was associated with specific architecture changes in ways that functionality was distributed in the network, and accompanied with new services introduced both in
the core network functions to support this edge-intelligence shift. Lessons learnt from the work done, both at design and structuring the work there, are directly applicable in the evolution of the power grids towards the Smart Grid.

Furthermore, the power network’s main goal – supplying a particular service over a shared infrastructure subject to specific physical, administrative and regulatory aspects – is the same as that of a communication system. In this context, the advances on resource sharing algorithms and protocols, network access management, quality of service and managing this for networks under varying load conditions through using diversity of service demand rather than increasing capacity, are directly applicable to the power systems network. It is in this space that most of the communications network community papers are targeted at (see attached bibliography, filter for IEEE Transactions on Smart Grid, IEEE Smart Grid Communications, and IEEE Communications Magazine articles since 2010).

Finally, whilst the core power network (transmission and medium-voltage distribution networks) are well specified and well managed, the step-change will be at the edge of the network. The tussle at the moment is to identify ways the functions currently performed in the core of the power network can be shifted, or at least supported, by functions provided by a proactively interacting edge of the power network. It is interesting, but the “rise of the stupid network” discourse [20] could be applied directly in the Smart Grid case, together with the additional lessons learnt since 1997.

2.4 Security and Privacy

New capabilities for power grid systems and networks such as distributed intelligence and broadband capabilities can greatly enhance efficiency and reliability, but they may also create many new vulnerabilities if not deployed with the appropriate security controls[2]. NISTIR 7628, which provides guidelines for Smart Grid cyber security, states that “it is important to assume devices will become penetrated and there must be a method for their containment and secure recovery using remote means. This is of great importance to maintain the reliability and overall survivability of the Smart Grid”.

Smart meters are the most common components on the demand-side and they represent the distribution endpoint for communication. Providing communications to a system increases accessibility and therefore security risks and vulnerabilities (familiar to networked and distributed systems – a host that is not properly secured could allow hackers to gain access to the entire network). Risks and classic attacks on hardware and software systems also apply to Smart Grid systems. Business and engineering constraints (e.g., budget, time to market, hardware limitations, poor software practices, inadequate testing, etc.) on the design, implementation, and deployment often result in vulnerabilities being introduced.

The issue of privacy is of particular importance to consumers, and technology acceptance is crucial if we expect to close the loop with demand – will consumers follow or influence? Crucially, consumers may view usage monitoring as an intrusion into their privacy. Privacy concerns that the Smart Grid must address include identity theft, real-time surveillance, identification of personal behaviour patterns and appliances used, and revelation of activities through residual data.
2.5 Bridging the Gap

The knowledge gap between industry and research, and between the power and ICT domains is not an unknown problem and is not unexpected in such a large interdisciplinary field. It represents the early stage struggle between communities when novel technologies are being introduced and/or adapted.

- **Terminology**: there is still work that needs to be done in fomenting and encouraging the establishment of a common language and terminology for the system. This should be one of the activities of any architecture documentation activity. Difference between data and information; interpretation required, data analytics and management, etc. Multidisciplinary discussions are a start, but we need to establish mechanisms, methods and processes to get a common terminology.

- **Understanding**: There is a need to define problems at the same scale and level of abstraction. For example, there is a dichotomy in understanding of the performance requirements towards communication link vs. communication networks. End-to-end communications service is provided by the communication network, and it is this that will largely affect the end-to-end behaviour of the system.

- **Research vs. industry**: There is a concern that there is a disparity in assumptions between the research community and what is actually happening in industry. There is significant pressure from industry to move from conceptual and reference models into practical single-domain and cross-domain models that work or can be shown to work in the future. There is a perception that, currently, industry is moving faster with the Smart Grid than the academic research, or even industrial R&D. In particular, the experience, knowledge and understanding collected in the existing Smart Grid projects in the UK, and in the world, is typically open\(^2\) and it is being disseminated widely – but there is no specific, focused, concentrated activity to generalise and distil these learnings in ways that can facilitate knowledge exchange between the different projects, cross research disciplines, and between industry and academia.

3 Managing Smart Grid Complexity

The Smart Grid vision is built on two fundamental realisations. Firstly, that there exists untapped potential for using advances in information and communication technologies to dramatically improve (or even change) the management and operation of every aspect of the power system. Secondly, that it is not only desirable but necessary to close the generation-transmission-distribution-loop with direct and potentially quasi real-time interaction with consumers (e.g., real-time pricing) by leveraging mature and new information and communication technologies.

Large-scale systems are incredibly complex and as such models are needed to understand them. Models give structure to complex systems and scenarios, allowing us to isolate variables in order to better understand their roles, and understand which elements are truly important and which are only seemingly important.

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\(^2\) Not the least because the majority of these projects have benefited from public funding or subsidies, often with conditions attached requiring open dissemination of learning and results.
• Models help us to see the full dimensionality of the problem, and figure out what works and what doesn’t.
• Models help us identify the relevant parts and how they are related, so we can work through the problem logically, identify boundaries, explore and understand outcomes, and communicate ideas.

Models help us structure data into information, and turn information into knowledge: identify patterns and bounds, estimate parameters, predict likely outcomes, and inform decision-making.

The requirements of the Smart Grid can be divided into functional and non-functional aspects:

• Functional requirements describe the intended behaviour in terms of services, tasks, or functions the system is required to perform.
• Non-functional requirements describe the system properties. That is, how well some behavioural or structural aspect of the system should be accomplished. These include those properties that are observable at runtime (e.g., performance, security, reliability, availability, and usability), as well as those that are not observable at runtime (e.g., extensibility, portability, and re-usability).

3.1 Smart Grid Conceptual Models

The primary conceptual models that represent the different stakeholders and the interconnection between them as an end-to-end system are the NIST Smart Grid Interaction of Smart Grid Domain Actors (p.33 in [3]), and the corresponding EU Energy Taskforce Smart Grid Architecture Model [4], which is shown here in Figure 2. The NIST conceptual model (shown in Figure 3) divides the smart grid into seven domains, with each domain comprising of a group of actors (devices, systems, or programs that make decisions and exchange information) and applications (tasks performed by actors within a particular domain).

Figure 2 – EE CEN-CENELEC-ETSI Smart Grid Architecture Reference Model [4]
These two models are the starting point for all papers related to functional requirements analysis and discussions related to architectures for the Smart Grid, and are important in representing both the scale of the system being considered as well as conveying, clearly, the main characteristics and challenges to realise the vision of a grid whose subsystems are fully interconnected to intelligently provide cost-effective and reliable energy supply.

3.2 Smart Grid Interfaces

Power systems (like most other industrial systems) have been highly automated—with reasonably well-defined information models and communication protocols—since before the concept of a Smart Grid was formulated (circa 2001). Typically, these focused on the high value (high voltage and medium voltage) parts of the network. Advances in this domain are reflected in the very mature IEC 61850 series of standards [5], managed by the IEC TC 57, which cover substation information models and communication protocols, and which are already implemented by industry and academia (open source). These standards also present a reference model for substation automation processes, providing further specification for the sensor interfaces, information exchange interfaces and communication protocols supporting these processes. Although traditionally the focus has been in communication networks and systems in substations, it is interesting to note that specific working groups within IEC TC57 have started work to extend the definitions of the interfaces towards distributed energy resource management and interfacing with the consumer, including smart metering, in areas where this may interact or support grid operations.

The main issue, reflecting the relatively slow maturation of the Smart Grid vision at present, is that it is still relatively difficult to find specifications and definitions of smart grid subsystems that show true cross-connectivity across different classical functional areas in ways that would map or exemplify the models presented in these conceptual and architecture documents, and in all the other works following them. The challenge now is to bring out the details of these conceptual architecture models and start to develop the smart grid blueprint, and in the process, identify the necessary interfaces to really cross the different domains. Scoping this challenge and addressing it is the objective of the Smart Grid Blueprint activity in HubNet [6].

3.3 Smart Grid Functions

A functional overview of the Smart Grid operations and its domains is presented in Figure 3. One can note two things: first, all new functions identified even at this very high conceptual level are located in the Customer domain, and second, the subsystems are highly interconnected. Taken together, they point towards an expectation of enhancements to existing functions and applications, such as Energy Management Systems or state estimation, by leveraging the new stream of measurement data that a fully sensor-enabled grid would provide; the expectation of new functions is implicitly expressed, and mostly through the data from the customer.
The need to derive the functional interdependencies, and using these to ultimately derive requirements for design, has been clearly identified in the EU Energy Taskforce Smart Grid Architecture Model [4], as shown in Figure 4. The working group also realised at that time that a full formalised process needed to be described and put in place to derive requirements for the different layers (or functional planes) of the Smart Grid across the different domains. The process, described in the document, starts with submitted use cases (typically from domain experts and industry), which are then used to drive, consecutively, the specification of requirements and the development of the Component, Business and Function layers, which in turn drive further the requirement specification and development of the information and communication layers. This is a very important observation addressing a recurring discussion theme between power system domain and communication technology experts: how can the design of the system be initiated and progressed, is it by starting with the ability of the communication technology to provide a data transport service to which the power system functions and applications adapt as best they can, or do power systems functions (old or new) specify their expectations for communication networks to be designed accordingly. The question in itself is not a new one when using enabling technologies, and it does not have an either-or answer. Both approaches will need to be followed; it is a reflection of the (not unexpected) gap in terminology, domain knowledge and design approaches between the two communities [7]. One can surmise (even after a quick review of published works) that the functions, and therefore requirements for communication networks, in the Smart Grid system context are not yet well defined.
3.4 Smart Grid Standards

It is important to standardise protocols, architecture models and interactions. Standardisation can help to maximize compatibility, interoperability, safety, repeatability, or quality. Standards by their very nature are considered to be a reliable specification of how the system should be and behave. However, it can be very difficult to pin down specifics for such a large and complex system – there remain many unknowns. Smart Grid standards will require experts, from across different domains and disciplines, working together. Lessons learnt from demonstration projects, and research, will form input to standards working groups.

Standardise too early, we restrict innovation; standardise too late and we get a confection of ad-hoc solutions that will ultimately gravitate towards a common solution (most feature/functionally-complete, extensible) that will become the de-facto standard anyway. Most large-scale systems are designed and developed in this manner, and evolve as needs arise. There is a need to allow the Smart Grid system to evolve and mature, and standards must evolve as the Smart Grid evolves.

Key principles for a SG architecture framework: open, interoperable, modular, secure, extensible, scalable, and reliable. SG communications must also be standards-based (interoperable), manageable, modular, scalable, and secure.

Instead of a single and all-encompassing standard that “is all and does all”, Smart Grid standardisation will likely follow a layered and progressive approach (c.f., the development of Internet RFCs, where system implementations go hand-in-hand with standardisation). The architecture needs to provide the “big picture/generic approach” and at the same time it needs to break down the larger system into smaller interoperable and modular components with clear inter-domain/segment demarcation points. For example, the core IEC Standards relevant to Smart Grid include:

- IEC/TR 62357: Service Oriented Architecture (SOA) – Power system control and associated communications – Reference architecture for object models, services and protocols
- IEC 61970: Common Information Model (CIM) / Energy Management – EMS-API
Smart Grid Communications Landscape

From a communication networking system research point of view, the Smart Grid is a very interesting system, as recognised in all review and tutorial papers [6-8, 10], and it was looked at with marked interest from the networking and communications research community even before 2008, with a new IEEE Conference on Smart Grid Communications established in 2010. It is clear that the Smart Grid system exhibits a combination of characteristics amongst which the scale and penetration of required embedded sensing and actuation poses the main difficulty. However, it is to be noted that the domain of embedded networking systems has been very well researched since the end of 1999, which presents a clear analysis of the challenges for systems composed of networked embedded real-time sensors and actuators that would provide interfacing between software controls and the physical world [16]. In the 15 years since then we have seen a substantial amount of work done in wireless and wired sensor networks, middleware for embedded networked devices and systems, and the algorithms to process, understand and make decisions from the data provided in such systems in an adaptive way. It is important that these advances, which underpin the newly-coined cyber-physical systems, are utilised and exploited in the design and development of the Smart Grid [7]. However, herein lies one of the key challenges of the Smart Grid (and any system similar to it): the scale of the end-to-end system is unparalleled until now, and most of the solutions, be those academic research or industrial development, have not been trialled, tested or designed for such large systems. At the same time, piece-wise solutions to support specific areas of work have already been demonstrated and trialled, from distributed energy management systems, micro-grid environments, and researched – the papers listed in the bibliography capture this well.
Figure 5 – UML Model of Energy Management System in Smart Grid
### Table 1 – Smart Grid Functions and communication technology options

<table>
<thead>
<tr>
<th>Functions or Applications</th>
<th>Generation</th>
<th>Transmission</th>
<th>Distribution</th>
<th>Consumption</th>
<th>Distributed Generation/Storage</th>
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<td>• Advanced forecasting</td>
<td>o Weather forecasts</td>
<td>o Financial and Energy markets</td>
<td>o Load, resource, and grid conditions/status</td>
<td>o Day-ahead, hour-ahead, intra-hour</td>
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<td>• Grid operations: EMS/SCADA, DMS/DA, MDMS, OMS, DR</td>
<td>o Transmission grid monitoring and control</td>
<td>o Scheduling and optimisation</td>
<td>o Asset monitoring (e.g., stress and utilisation), optimisation, management and conditioning</td>
<td>o Automatic generation control</td>
<td>o Automation and maintenance of transmission control</td>
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<td>o Automated/Active distribution operation (matching local distribution system with high-voltage transmission system)</td>
<td>o Load control and dispatch</td>
<td>o Power quality maintenance</td>
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<td>• Energy trading and commercial applications</td>
<td>• Customer engagement</td>
<td>• Smart metering</td>
<td>• Demand-side management: Demand response, direct load control</td>
<td>• HEMS, BEMS</td>
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<td>• Communication operations: Integrated Digital Services, Network Management Systems</td>
<td>• Planned and emergency switching</td>
<td>• EV / smart charging</td>
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<td>• Customer management: CIS, Call Centres, Billing Systems</td>
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<th>Connectivity</th>
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<th>New (access and home-area) networks</th>
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<td>• LAN / Core network</td>
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<td>• WAN / Backhaul</td>
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<td>• Corporate networks</td>
<td>o Ethernet</td>
<td>o To grid assets (typically dedicated links)</td>
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<td>o Private circuits</td>
<td>o Wireless 2G/3G/4G</td>
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<td>o Leased line</td>
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<td>• Access WAN (FAN and NAN)</td>
<td>o Wireless / Mobile / GRPS</td>
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<td>o Long-range radio</td>
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<td>o WiMAX / LTE</td>
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<td>• Within the home (HAN)</td>
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4.1 Communications Requirements

The scale and complexity of the system is illustrated by the UML (Unified Modelling Language) model in Figure 5, which provides only a partial view of the relationships and interdependencies between entities that exist in the first interaction domain. The envisioned smart grid will be a more complex power delivery system; it will depend on more information flows, events and require more autonomous operation as a self-organised system, even if initially only in parts. The fundamental drive is the need for greater visibility of performance and status of any part and component of the system in order to support faster decision making, and maintain the service availability of the grid as a critical system to the current levels. However, as no new functions have yet been specified in any great detail and the learning around possible interactions between functions and applications across classical operation areas is still ongoing, there is uncertainty around what specific requirements Smart Grid pose for communication systems and networks that are not already addressed other elements of work. It is for this reason that several review, tutorial and position papers around Smart Grid communications [8-12] have tried to identify and address the potential challenges at a relatively high level and, with few notable exceptions, put forward very few quantitative performance requirements for the Smart Grid. What is certain is that the Smart Grid will employ a mix of different communications technologies. Table 1 provides an overview of the possible connectivity solutions that may be used to enable functions and applications in each of the interaction domains.

Establishing boundary requirements for different existing applications in an interconnected end-to-end intelligent real-time system that uses, potentially, a very large number of heterogeneous devices, from data capture (e.g. PMU) to decision making control centre applications, remain a significant challenge. Monitoring systems to provide control centres with real-time data to enhance the decision making process already exist, but they are not used to provide a direct (automated) action on controllable elements. Furthermore, study tools, methodologies and simulation platforms are not fully integrated together in a form that would reflect the Smart Grid architecture models. Several simulation tools and platforms have been developed and/or adapted in order to allow modelling and simulation of integrated ICT and power systems applications together (i.e., co-simulation), rather than separately. Note that the latter approach is perfectly valid, subject to knowing the boundary conditions and interactions between different interaction domains (e.g. knowing the traffic characteristics of a Distributed Energy Management application and its reaction, traffic-wise, to expected events). At the moment work is still going on in this area (e.g., the IEEE P2030 Smart Grid Communications Reference Architecture, a.k.a., SG-CRA, has use case mapping examples showing priority/criticality level for different application); an extensive review of the simulation and modelling work is presented in [7], and an example of an integrated simulation package for Smart Grid applications is presented in [13].

Earlier HubNet work related to scenario identification for Smart Grid simulations [7] has identified three (partially overlapping) interaction domains in the Smart Grid:

1. Power grid operations and interactions:
   a. Balancing of the power system, and congestion management.
   b. Management of large-scale installations of renewable generation.
c. Wide-area Measurement, Protection and Control (WAMPAC). This function depends on high accuracy data from phasor measurement units (PMUs); the number of these at the moment is relatively small (the GB transmission system has an installed base of 40 PMUs) [14, 15], but is expected to increase as the need for improved system monitoring and control grows.

d. Distribution automation for voltage regulation and control, and to improve fault and outage conditions.

e. Management of distributed generation and storage.

f. Power quality monitoring and control across the entire grid, typically using SCADA systems.

2. Interactions with end users and their premises (both industrial and domestic)

a. Smart Metering Infrastructure (SMI), including automatic meter reading, time-of-use pricing, remote (dis)connecting, etc.

b. Using the SMI to specifically support grid operations, e.g., through demand-side management (DSM), home renewables and micro generation

c. Home energy management systems (HEMS) and building energy management systems (BEMS)

d. Electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs)

3. Interactions with markets

a. Energy trading and brokering.

A review of the current state of published research and relevant R&D activities in this space shows that there is very little quantitative specification of requirements (e.g., delay) for the communication subsystem of the Smart Grid. Even where these requirements are specified, they are either very specific in a narrow domain (e.g. protection system applications), or very general, as in specifying overall data rates and latency expected on almost a back-of-the-envelope calculation. Overall, it either shows the lack of interaction between the communications and power systems domain, or the fact that the communications requirements are understood only after the implementation aspects of a particular solution are well understood (i.e., what needs to be achieved) and we are still in the process of defining this.

As discussed earlier, there is quite a substantial and mature set of requirements for communication systems in high- and medium-voltage grid substations, and these are a good starting point. Wang et al. [8] refer to the IEEE 1646 standards, which specify timing requirements for electric substation automation functions (shown in Table 1), and the IEC 61850 standard, which specify communication requirements for functions and device models. They experimented, in very simple scenarios, with measuring delay in a realistic low-load network for various communication technologies (Ethernet, 100Mbps, IEEE 802.11b/g, IEEE 802.15.4) in both single-hop and multi-hop topologies. Their conclusion is that, specifically under low communication network load conditions, Ethernet solutions will be suitable for substation automation, providing delays of 3 milliseconds or less. On the other hand, none of the wireless communication solutions, especially in multi-hop topologies, could be used for real-time critical messaging. Note that their analysis did not take into account other aspects of the operating environment that can influence performance, such as the interference conditions for wireless communications in substation environments.
**Table 2 – IEEE 1646 standard: Communication timing requirements for electric substation automation [8]**

<table>
<thead>
<tr>
<th>Information Types</th>
<th>Internal to substation</th>
<th>External to substation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection information</td>
<td>4 ms (1/4 cycle of electrical wave)</td>
<td>8-12 ms</td>
</tr>
<tr>
<td>Monitoring and control information</td>
<td>16 ms</td>
<td>1 sec</td>
</tr>
<tr>
<td>Operations and maintenance information</td>
<td>1 sec</td>
<td>10 sec</td>
</tr>
<tr>
<td>Text strings</td>
<td>2 sec</td>
<td>10 sec</td>
</tr>
<tr>
<td>Processed data files</td>
<td>10 ms</td>
<td>30 sec</td>
</tr>
<tr>
<td>Program files</td>
<td>1 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Image files</td>
<td>10 sec</td>
<td>1 min</td>
</tr>
<tr>
<td>Audio and video streams</td>
<td>1 sec</td>
<td>1 sec</td>
</tr>
</tbody>
</table>

**Table 3 – IEC 61850: communication requirements for functions and device models [8]**

<table>
<thead>
<tr>
<th>Message Types</th>
<th>Definitions</th>
<th>Delay requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Messages requiring immediate actions at receiving IEDs</td>
<td>1A: 3ms or 10ms; 1B 20ms or 100ms</td>
</tr>
<tr>
<td>Type 2</td>
<td>Messages requiring medium transmission speed</td>
<td>100ms</td>
</tr>
<tr>
<td>Type 3</td>
<td>Messages for slow speed auto-control functions</td>
<td>500ms</td>
</tr>
<tr>
<td>Type 4</td>
<td>Continuous data streams from IEDs</td>
<td>3ms or 10ms</td>
</tr>
<tr>
<td>Type 5</td>
<td>Large file transfers</td>
<td>1000ms (not strict)</td>
</tr>
<tr>
<td>Type 6</td>
<td>Time synchronisation messages</td>
<td>No requirement</td>
</tr>
<tr>
<td>Type 7</td>
<td>Command messages with access control</td>
<td>Equivalent to Type 1 or Type 3</td>
</tr>
</tbody>
</table>

Another attempt to estimate, through communication network simulations, the deliverable bandwidth and delay for various realistic grid scenarios is shown by Kansal and Bose [16]. There are few other attempts at estimating quantitatively the data rate requirement (bandwidth) to support Smart Grid functions. Some of these were discussed in the EPSRC COMMNET Smart Grid Communications Workshop (Loughborough University, September 2012). Taking an example following an analysis given by Bose in [17] to estimate the communication requirements for Wide-area Protection and Control, we consider each function in turn:

- Frequency Control and Regional Voltage Control requires data samples at 2-4 second intervals, with very low data rate;
- Small Signal Stability Control (i.e. involves offline tuning of power system stabilisers) depends on PMU data, but the calculation is done, currently, every few minutes;
- Voltage Stability Control depends on continuous modelling of system operating conditions, and does not pose any particular requirements for the communication system.
- Transient Stability Control: the requirements here will depend on the algorithm adopted and on the local vs. remote computation choice (soft-wired SPS, which requires large PMU data volumes delivered remotely, vs. adaptive SPS, which still depends on large volume PMU data but performs more computation locally)
- State estimation (real-time): the paper lists possibilities in terms of being able to run more frequent state estimation, based on a larger amount of data, with fewer erroneous data, and with exchanges of state estimation results between control regions/balancing authorities.
This analysis shows that, for existing applications and current algorithms, the communication requirements do not appear to be too onerous; where new applications/possibilities are mentioned (as in the case of state estimation above) the requirements are not specified. Taking the example of the applications requiring PMU data, and using a quick calculation on the raw data delivered by a PMU for every single variable, at a sampling rate of 900 samples/sec, gives a requirement of 10-14kbps raw data rate, or an aggregate of between 1.5-5Mbps per PMU. This is not a problem to be transported over a 100Mbps Ethernet segment at 40% utilisation, but it is a different problem if it is to be processed outside the substation. Another example given in the paper refers to the IEEE 1547-2003 standard, which has a requirement of a 2sec reaction time to detection of an island creation in the power system, but different algorithms meet this requirement differently, with different requirements for data volumes and latency for different algorithms.

Table 4 – Latency and data rate requirements for different Smart Grid Applications [16]

<table>
<thead>
<tr>
<th>Main Application</th>
<th>Applications based on it</th>
<th>Origin of Data/Place where we need the data</th>
<th>Data</th>
<th>Latency requirement</th>
<th>Number of PMUs we may need to optimally run the application</th>
<th>Data time window</th>
</tr>
</thead>
<tbody>
<tr>
<td>State Estimation</td>
<td>Contingency analysis, Power flow, AGC, AVC, Energy markets, Dynamic/ Voltage security assessment</td>
<td>All substations/ Control center</td>
<td>P,Q, V, theta, i</td>
<td>1 second</td>
<td>Number of buses in the system</td>
<td>Instant</td>
</tr>
<tr>
<td>Transient Stability</td>
<td>Load trip, Generation trip, Islanding</td>
<td>Generating substations/ Application servers</td>
<td>Generator internal angle, df/dt, f</td>
<td>100 milliseconds</td>
<td>Number of generation buses (1/20 buses)</td>
<td>10-50 cycles</td>
</tr>
<tr>
<td>Small Signal Stability</td>
<td>Modes, Modes shape, Damping, Online update of PSS, Decreasing tie-line flows</td>
<td>Some key locations/ Application server</td>
<td>V phasor</td>
<td>1 second</td>
<td>1/10 buses</td>
<td>Minutes</td>
</tr>
<tr>
<td>Voltage Stability</td>
<td>Capacitor switching, Load shedding, Islanding</td>
<td>Some key locations/ Application server</td>
<td>V phasor</td>
<td>1-5 seconds</td>
<td>1/10 buses</td>
<td>Minutes</td>
</tr>
<tr>
<td>Postmortem analysis</td>
<td>Model validation, Engineering settings for future</td>
<td>All PMU and DFR data/ Historian. This data base can be distributed to avoid network congestion</td>
<td>All measurements</td>
<td>NA</td>
<td>Number of buses in the system</td>
<td>Instant and Event files from DFRs</td>
</tr>
</tbody>
</table>

The rough calculation work given above is a common occurrence [17, 18], as it is a first, engineering, approach to trying to establish some indication of volume of data, data rate and latency requirements. Most of the other requirement specifications works, referenced here or found in the attached bibliography, are usually qualitative high-level indications of challenges projected for a system with Smart Grid characteristics: very large geographical area distribution, very large number of devices, large variation in latency requirements and some very low latency requirements, very tight time synchronisation, large heterogeneity of devices and functions operating concurrently over the same system, uncertainty of administrative ownership/operation of the communication infrastructure.

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3 By raw data we mean pre-packaged data, or the effective application protocol data unit (A-PDU); depending on the networking technology deployed, the actual on-the-wire packet size will be bigger as it will include technology-specific communication protocol overheads.
4.2 Communications Networks and Technologies

A good introduction for power systems engineers to available communications technologies and their possible application to power grid operations can be found in [19]. In particular, and similarly to [4, 8], it depicts the possible communication systems deployment necessary to support the Smart Grid, divided into wide area networks (WAN), field area networks (FAN), Neighbourhood Area Networks (NAN), and Home Area Networks (HAN), reflecting both separate regions of geographical coverage and possibly operation/administration (illustrated in Figure 1 and summarised in Table 1).

- The WAN refers to the high-speed, dedicated backbone connection to the local area networks that will cover a specific location, e.g. a neighbourhood in the case of Smart Metering or a substation network.
- The FAN refers to the communication and networking technologies typically used within a substation – the term is often used for industrial communication networks solution. In the context of the Smart Grids FAN refer to the communication networks used for power distribution automation and control devices, such as the networks that connect PMUs, Remote Terminal Units (RTU) and other Intelligent Electronic Devices (IED), typically running SCADA protocol over industrial Ethernet solutions.
- The NAN is an evolution of the local area network term to refer to networking systems that are geographically close but are not necessarily under the same administrative management in terms of physical access network end-points; it can be seen as a bridge between FAN solutions and the connectivity to end-user premises (domestic or industrial).
- The HAN refers to the single-location/home networking system that connects end-user premises equipment, such as in-home displays, smart meters and appliance control devices when a demand response/demand control system is in place.

Although this separation is didactically correct, the actual deployment will depend on the specific technologies [4, 7, 13]; for example, the above will not map directly onto a deployment that uses cellular communication technologies. Therefore it should be treated purely as guidance for separating the concerns and identifying the different requirements in each area, leading to particular solutions. The key elements that need to be considered are the ability of different communication technology solutions to support low-latency real-time applications (which is easier to do in a non-shared network), the amount of traffic to traverse the particular network, and the necessary support for prioritisation in that technology.

The communications technologies available for each area of the grid is well known/surveyed. It is important to remember that communications and information technologies (like security) are not domain-specific. Technology most appropriate for the environment is chosen to meet objectives and maximise cost-performance ratio (in terms of scalability, coverage/access, reliability, etc.). The main driving requirement in this space is to provide reliable, robust and cost-effective solutions that provide connectivity/coverage over a large geographical area. The two main contending technologies in this space are cellular technologies (3/4/5G) and multi-hop mesh networks that deploy existing (IEEE 802.11 and IEEE 802.15.4) link-layer technologies, or newly developed solutions
in the TV White Space\textsuperscript{4}, which are interesting as they have better propagation characteristics than the higher-frequency technologies (IEEE 802.11 and IEEE 802.15.4). The difficulty with a cellular communication solution is the potential higher cost of the end device, as well as the uncertainty in terms of packet latency; concerns that LTE-based cellular system for sensor networks will not be able to support a large number of devices due to Radio Access Network protocols and configuration are shown to be unfounded, under specific traffic generation mostly associated with Smart Metering devices [20]. Establishing the expected performance (successful access rate) for such networks under lower-density networks but with higher event sampling rates is still an open question. The main challenge with short-range radio solutions is the low data rate and high latency of such links, and the susceptibility to interference, which provides best-effort type of service without the reliability and reliance expected for control applications in the low voltage part of the grid; however, for non-critical elastic applications (non-deterministic domestic demand side management) these technologies are quite suitable.

4.3 Communications Protocols

The current view of the networking community is that embedded networks will support \textit{largely} IP protocols either fully end-to-end, or in a two-tier system where non-IP nodes at the periphery of the network (so-called \textit{capillary network}) will be connected through IP gateways that will, effectively, proxy the IP service end-to-end. There are two main challenges in this space: routing in low power and lossy networks at the edge of the Smart Grid, and providing guaranteed quality of service for different types of traffic classes in the core of the grid. The provision of QoS over shared wireless environment remains still a challenge, but this is not specific to the Smart Grid. Routing at the edge of the network, and in short-range multi-hop low-power and lossy networks remains the main challenge, as it is building a large, reliable multi-hop network in the NAN/HAN area [21]. Another research area, again not specific to the Smart Grid but highly relevant to it, is the work on heterogeneous networks – networks where the combination of embedded networked devices, link technologies and protocols connecting them is highly heterogeneous.

The Smart Grid communications plane is assumed to use TCP/UDP as transport protocols, depending on real-time, reliability of delivery and delay requirements. There have been several works that have considered other transport protocol options, specifically to provide secure connection-oriented transport services for core smart grid data collection [22], addressing the complexity and size of IP-based security solutions (IPsec and TLS) for embedded systems.

Much work has also gone into identifying protocols suitable for the Smart Grid. For example, Saputro \textit{et al.} [23] provides a detailed analysis of suitable routing protocols for Smart Grid communications, covering the HAN, NAN, and WAN. Gungor \textit{et al.} [24] go further to cover communications protocols for building automation, substation automation, powerline networking, HAN device communication measurement and control, application-level energy management systems, cybersecurity, and electric vehicles. The IETF has also worked to identify key infrastructure protocols of the Internet

\textsuperscript{4} TV White Space refers to frequencies allocated to a broadcasting service but are not in use locally, or are released from broadcasting service due to the switch to digital broadcasting.
Protocol Suite for use in the Smart Grid (see RFC 6272), and the European Telecommunications Standards Institute (ETSI) has published the Open Smart Grid Protocol (OSGP)—a family of specifications used in conjunction with the ISO/IEC 14908 control networking standard for smart grid applications. OSGP is optimized to provide reliable and efficient delivery of command and control information for smart meters, direct load control modules, solar panels, gateways, and other smart grid devices.

4.4 Network Control and Management

The least addressed area of the communication network is network configuration and management. This is somewhat surprising—we can try to match communications technologies to expected applications/functions, architectures, and traffic, but will the chosen technologies be able to scale to support new applications? The SG system spans across large geographical areas across different technologies and networks, and one of the key problems for smart grid communication network solutions is that the traffic characteristics are unknown. Furthermore, the Smart Grid will evolve continually towards its vision and the traffic dynamics will evolve with it. Therefore network management and configuration solutions that provide the capabilityflexibility to create new circuits and network configurations are absolutely necessary. Solutions such as Software Defined Networks (SDNs) and Network Function Virtualisation (NFV) would be able to provide for network resilience and adaptation outside the substation domains that, currently, are provided only within substations through high redundancy (and cost) solutions in the form of the Parallel Redundancy Protocol (PRP) and the High-availability Seamless Redundancy topologies (HSR) defined in the IEC 62439: High Availability Automation Network standard. Additionally, the Smart Grid could be seen as one of the first examples of large systems where information-centric networking can effectively take hold. Albeit proposed as a protocol to provide security on information-centric IP-network overlays for the Smart Grid [25], information-centric networking is a highly interesting area for research into potentially new architectures and solutions that would be more flexible and targeted at such large embedded networked system as the Smart Grid, rather than continuing with piece-wise incremental applications of existing networking solutions designed for a different purpose (human-human or human-machine communications), which have typically elastic latency and bandwidth requirements, and with reasonable large computational resources per node.

4.5 Security

Security of communications for the Smart Grid is currently a critical/hot area of research. Security, like quality of service and interoperability, traverses the Smart Grid architecture model layers. However, whilst there are numerous mentions of security (and privacy) concerns related to Smart Grid, there are few new directions of work or possible solutions that go beyond existing state-of-the-art in research on security of embedded networked systems, similarly to the discussion above on information-centric networking. Both Smart Grid and, adjunct to it, Smart Metering systems, are continuously reviewed as being underspecified in terms of security support, but on the other hand it appears that there is not enough certainty and evidence of suitability of existing security solutions in this space to be adopted by industry. In itself, the security, just like communications, appears to be an all-encompassing concern that needs to be broken down in individually addressed problems.
5 Future Work and Ongoing Research

The current power grid (a very large and complex, albeit mostly centralised, system) has taken decades to develop and mature. So, we need to ask the question: Where are we in terms of achieving the SG vision? What is the status quo? The discussion below is a reflection on the review of the literature and projects being undertaken in the Smart Grid area, and it is based on views expressed and discussed in the various workshops organised or attended by HubNet partners. The challenges and possible directions discussed here do not present a comprehensive list of communication challenges in the Smart Grid, but the aim is to provide some indication of how the research in communication networks can contribute to address Smart Grid challenges.

5.1 Mapping Smart Grid Requirement onto Communication Services and Architectures

This still remains the biggest challenge for the Smart Grid in both the conceptual architecture documents and review papers. We know (mostly) where we want to be (i.e., what the Smart Grid should be); now we need a roadmap to get us there. It is indeed the case that Smart Grids is a large complex system, with multiple interacting sub-systems, some of which already use an appropriate communication system to fulfil the existing functional requirements. However, as the work on Smart Grid architectures, new functions and applications is still going on, there is little quantitative specification of requirements. This gap was clearly identified in all workshops organised or attended by the HubNet partners related to this area (see Figure 6, taken from HubNet partner presentations in the 1st Smart Grid Communications workshop).

The main issues concerning Smart Grid communications requirements and applications remain:

- What requirements should come first: communications or Smart Grid applications? Which part of the grid should drive, initially, the requirements? Examples and lessons learnt can be drawn from the EPSRC AuRA-NMS project; other EU and UK based projects should also be consulted.
- There is huge variability in requirements between the different areas of the Smart Grid, and for different applications – how do we define/refine the requirements there?
- What are the applications in the Smart Grid? What do we need to do in the Smart Grid that is different from what we do today? We need to differentiate between data-flows and control-flows, and analyse what exactly needs to be communicated.
This challenge requires a clear architecture of the Smart Grid ICT plane with enough detail to allow at least initial requirement specifications that can be tested in large scale trials, Smart Grid testbeds and/or simulation platforms. This work is already being undertaken, but it is still in the early stages, and it necessarily – probably more than any other aspect of the Smart Grids – requires very close collaboration between power system Smart Grid architects, IT system architects and communication networks researchers.

5.2 Integrated Modelling and Simulation Tools for Smart Grid Systems

The development of Smart Grids has progressed quickly from high-level conceptual models, to identifying the necessary underlying technologies as well as areas requiring further research and development. However, the problems are not yet entirely clear and many of these problems will undoubtedly arise during implementation—the need to maintain normal service of such a large and critical infrastructure makes the integration of new and existing functions across different domains much more difficult. Furthermore, application and information models are often accepted as-is, and they are great for helping implementers understand the relationships and interactions between applications/functions, and for building and integrating applications and systems. However, they cannot provide insight about how a communications network will perform. The distributed nature of Smart Grids (of both energy and ICT systems) and the closer integration of (and inter-dependencies between) systems and critical infrastructures, makes it more difficult to predict system behaviour. A system may be behaving normally, but could cause another to become unstable. As such, modelling and simulation tools for analysing different aspects of the system (especially runtime behaviour and dynamic interactions) will be critical to the development and operation of the Smart Grid.

Whilst there is a strong interest from both power systems and communication networks to look at the Smart Grid system end-to-end, it is clear that there is a lack of proper tools for modelling and simulation of these systems. The two communities have their own approaches and tools and models for studying their respective systems, but there is still a need for either rigorous methodologies for modelling and simulating power system and communication networks system interdependencies as a dynamic interactive system. There have been several projects addressing co-simulation tools, each reflecting specific constraints derived from the fact that few have been designed and developed from scratch with a Smart Grid-like system in mind, and therefore their uptake is limited. This challenge, again, requires a concerted interdisciplinary effort between power system,
communication network and intelligent agents communities to deliver one (or a set of) tools and platforms that can be used to study, in real scale, the Smart Grid interactions. HubNet has undertaken several early activities in this space, and an extensive critical and comparative review of Smart Grid simulation platforms will be published as a white paper.

The architecture of the Smart Grid actually reflects both technical considerations and the regulatory and market framework (UK and EU). The Smart Grid until now is seen as a complete, end-to-end, system architecture design. In practice constraints will apply (technical and regulatory). To address this any architecture proposals for the Smart Grid should consider breaking down what the areas of control/functions (Smart Grid) are likely to be, and start establishing/considering realistic performance requirements for these areas so that there is some belief that the system will function end-to-end. Requirements should be derived from realistic use cases/examples (e.g. from DECC/Ofgem work on SG). Design flexibility at this early stage of the specification of Smart Grid architecture is absolutely necessary.

5.3 Digitalisation of Low-Voltage Distribution Network

There is a very significant body of work focused on either systems and algorithms for distributed energy management (i.e. shifting demand response/management intelligence to the power network edges), or the communication network solutions (systems and protocols) that support these; both have a higher participation from the computer science and communications network research communities than functions, architectures and models in the core of the power network. One reason appears to be that the low-voltage part of the network presents characteristics that clearly require new solutions (such as wireless sensor networks with reliable communications over multi-hop to provide large geographical coverage; the opportunity to use TV White Space spectrum or even cognitive radio for the same reasons, etc.). This region of the power network is also of strong commercial interest precisely due to low penetration of monitoring and control technology, and also where most of the interaction with distributed generation and demand management is expected. Therefore, for communication networks and computer science community this is an area of particular interest – this interest is not, as of today, matched by similar interest outside of Smart Metering systems by the power systems research community, a point clearly made by the HubNet “Smart Metering for the UK” position paper [26].

In this part of the network the main challenges remain in:

- Architecture and solutions for reliable communications over heterogeneous networks for smart grid functionality.
- Quality of Service management, and in particular, scheduling for large scale real-time sensor/actuator systems with overlaying applications, including evaluating (if not guaranteeing) stability of system under congestion or fault conditions. Most of internet-based applications are designed to be flexible towards the communication network service fluctuations; the energy supply regulatory requirements do not allow, at the moment, such flexibility.
- New communication network management solutions to cater for self-configuration and management of large number of embedded devices in the field. The applicability and scalability of existing IP-based solutions for auto-configuration and, especially, network management tools and protocols has not been studied in depth for systems expected in
the low-voltage distribution network. Note that this challenge is not unique to Smart Grid – the Internet of Things (or embedded-networks) domain faces the same challenge, but not necessarily with the same level of criticality that is envisaged for supporting some of the power networks functions in a Smart Grid context.

- Considering the cost of deploying this infrastructure and the uncertainty of future requirements that it faces, the ability to reconfigure the network service by controlling network nodes (using, for example, programmable concepts found in Software Defined Networks) and/or the networked terminals (e.g. using capability for end-terminals to dynamically select and switch, at runtime, the transport protocol that best suits the application and the network conditions) remains a research challenge.

6 References


Appendix I – HubNet Smart Grid Communications Workshop

HubNet SMART GRID COMMUNICATIONS WORKSHOP

SMART GRID COMMUNICATION REQUIREMENTS

Imperial College, London, 13th September 2011

2. The 1st HubNet Smart Grid Communications scoping workshop was held on 13th September 2011.

3. The workshop objectives were:
   - To explore with a community of people with different relevant expertise the landscape of Smart Grids and, specifically, their requirements on communication solutions, and

4. To identify key challenges and priorities to be explored in future workshops and through HubNet activities.

5. The workshop was attended by about 35 people, from different domains: multi-agent control and multi-agent systems, system stability analysis, integration of cloud-computing in power grids, algorithms for smart grid (SG) control, how to use smart metering to support SG functionality, agent based coordination & control for ancillary systems, overload management, (mathematics) large data set processing, testing effects of communications for smart metering, distributed control of power systems, smart grid applications, IEC 61850 digital subsystems, substation communication controls.

During the discussions, the following topics and areas were discussed. Key comments and the challenges identified are noted below.

6. The following perceived issues with communications were identified:
   - There is a perception that the communications requirements for smart grids are not known/understood.
   - Under assumptions of “business as usual”, the predictability of the communication network performance (i.e. in terms of guarantee of bounds for latency and loss) is a big issue.
   - It is unclear if the Smart Grid presents special issues and challenges for communications? If yes, in what way? Is it due to the scale, or the heterogeneity of devices, or the relatively large scope of the first definitions of the Smart Grid?
• Is the sharing of the Smart Metering data necessary for the functioning of the Smart Grid? If yes, what are the technological barriers to accomplish this? Is the problem only technical or more widely data sharing in such a large system with multiple, often competing, stakeholders?

• What is the role of standards in communications for the Smart Grid? There will be different communication technologies – how can we define a path for interoperability within a Smart Grid?

• Building security and trust support mechanisms for the Smart Grid.

• Smart Grids will be a long-term evolving large scale system. Flexibility/autonomy should be built into the system. There are open questions such as: how easy would it be to introduce/attach new devices, agents, applications – how does trust/security come into this? What is required, as a system, to allow this to happen?

7. The specification of the communications requirements within smart grid applications is difficult because:

• communication networks can be designed once one knows the application requirements;

• the application requirements are somewhat flexible and applications can be designed to meet communication network constraints.

In the ensuing discussion an agreed position emerged about the need to break the closed-loop between communications and power systems research. The following topics were identified during the discussions:

• Requirements and applications:

  i. What requirements should come first: communications or smart grid applications? Which part of the grid should drive, initially, the requirements? Examples and lessons learnt can be drawn from the EPSRC AuRA-NMS project; other EU and UK based projects should also be consulted.

  ii. There is huge variability in requirements within the Smart Grid in different areas of it, and for different applications - how to define/refine the requirements there?

  iii. What are the applications in the Smart Grid? What do we need to do in the Smart Grid that is different from what we do today? We need to differentiate between data-flow and control-flows, and analyse what exactly needs to be communicated.

• Concrete examples of control algorithms at different scales for grid management are necessary:

  i. We need concrete examples of control algorithms and the needs of those applications, and their requirements on the communications architecture. Are the applications/algorithms well known? Can we be confident?
ii. What does DSM brings into the communication requirements? Does it lead to additional challenges, due to the diversity of applications and user types? For example, differences in supply/demand in urban vs. rural areas may have/require different requirements/constraints.

- **Technology choices and implementation strategies:**
  i. The communication layer is an enabler. The choice of communication technology is driven by the data requirements, the control architecture choices, and the information flows. It is necessary to explore any flexibility at the design stage in deciding what information is necessary where.
  ii. The choice of control architecture (centralised vs. de-centralised) was discussed; the emerging view was that this is not an issue, and it will be driven by whatever is required/necessary. A better description is centralised and distributed control. This means that the control algorithms are designed such that they can be physically spread throughout the power network and still operate effectively. The decision on where to physically place them is made on a case by case basis depending on data access, telecommunications issues, etc. GB Smart Metering programme rollout has produced a functional specification for the Smart Meters - what would be enough to support Smart Grid applications? Is data aggregation for Smart Metering being considered?

- **Research vs. Industry:**
  i. There is a concern that there is a disparity in assumptions between the research community and what is actually happening in industry – this needs to be resolved.

- **Interdependency, reliance, redundancy:**
  i. The Smart Grid will result in an increased reliance on communications – therefore the reliability of communications becomes a key issue (collapse of network/system). How does the recovery process happen? What is the impact of depending on communications during power system transients and faults? What is the required communications network restoration time? What is the impact of the interdependency between the communications and power systems layer? How will we manage the transition path between what is a largely deterministically-behaving system today into one that will depend strongly on systems with statistically-governed behaviour, such as communication systems? One example given was that the recovery of the power network in case of significant nature disruptive event. For example, the impact of such an event in Scotland was 4 months.

- **Cost-benefit analysis for Smart Grid developments:**
  i. Are the necessary functions/requirements too expensive to achieve?
  ii. For a system that will evolve over time, and which may break current working practices, one way to design will be to, initially, ignore the cost. What is possible if we ignore the cost, and is ignoring the cost practicable?

- **Security - this was indicated as a key issue:**
i. Should be included from the start, because it is a system issue.

ii. Should be given top priority, since it will likely determine/constrain strategies for data aggregation, processing, communications, etc.

- The architecture of the Smart Grid actually reflects both technical considerations and the regulatory and market framework (UK and EU). The Smart Grid until now is seen as a complete, end-to-end, system architecture design. In practice constraints will apply (technical and regulatory). To address this any architecture proposals for the SG should consider breaking down what the areas of control/functions (Smart Grid) are likely to be, and start establishing/considering realistic performance requirements for these areas so that there is some belief that the system will function end-to-end.

Requirements should be derived from realistic use cases/examples (e.g. from DECC/Ofgem work on SG). Design flexibility at this early stage of the specification of Smart Grid architecture is absolutely necessary.

- The Smart Grid community needs a common language/terminology/understanding:

  i. Difference between data and information; interpretation required, data analytics and management, etc.

  ii. Multidisciplinary discussions are a start, but we need to establish mechanisms, methods and processes to get to a common terminology and definition of problems at some scale.

  iii. There is a dichotomy in understanding of the performance requirements towards communication link vs. communication networks. End-to-end communication service is provided by the communication network, and it is this that will largely affect the end-to-end behaviour of the system.

- The power networks and existing market structure itself has implications for the way data is collected, processed, communicated, stored, etc.

  i. Data and information sharing - who does it, how do you share the data?

  ii. Communications is not necessarily direct; data can take different paths through different stakeholder networks and systems.

  iii. There is a broken value chain.

- Other communities (e.g. Internet of Things) are looking at similar issues/having the same discussions: how do we bring the two communities together?

As a result of the wide ranging technical discussion, and the challenges identified, the following activities were identified as the way forward.

8. The way forward
• **Define, if necessary, and catalogue use cases and system functions.** These can be used as drivers for communications requirements analysis. Building and analysing use cases and functions will lead to the identification of communications requirements.

• **State-of-the-art and literature review.** What resources are available? (e.g., IEEE Smart Grid register, LCNF projects, etc.) How can these resources be brought together/bridged for the benefit of the SG community?

• **Multi-disciplinary teams to focus on and analyse use cases,** from the following list, to determine what are the new challenges:
  
  i. Future scenarios - what needs to be done, e.g., ENA
  
  ii. Projects in progress.
  
  iii. Transferable technologies, standards and research that can be re-used.
  
  iv. Current scenarios are simple; consider more complex scenarios (e.g., involving coordination functions). Look from simple to more future-related use cases (mixed level of functions/simplicity).
  
  v. Build some strawman use cases together, work on them and present them to the community.

• **Smart Grid Blueprint:** As a community we should work towards detailed requirements specifications and functional specifications. These documents will become the blueprint for the smart grid. They should consider together the following interactions: Physical communications → Networking system and data flows → Information flows → Control.

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Appendix II – Smart Grid Communications Bibliography


