A Control Framework to Develop Smart Grid Communications

Possible Pointers from Multiservice Network Research

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ABSTRACT

This paper addresses the challenge of developing an architecture for the Smart Grid with the particular focus to support Smart Grid communication. It considers the Smart Grid system in general to identify the relationship between the power distribution and communication networks, and then focuses mainly on Smart Grid communication requirements. It observes the similarity between the Quality of Service (QoS) requirements for Smart Grid communications and those identified in multiservice networking. It reviews the principles of open communication and introduces architectures for open communication that have been enhanced to meet the requirements of multiservice. It discusses previous research into multiservice with a review into recent work focused on meeting the multiservice requirements of Smart Grid communications. Based on these, the paper presents key specific pointers toward defining a contextual control framework for the data transport system of the Smart Grid.

Keywords: Smart Grid communications; Open Communication ; QoS; Multiservice Networking; middleware; software defined networking; cross-layer; class based queuing; active queue management; weighted fair queuing

1. INTRODUCTION

The concept of the Smart Grid presents a new and challenging direction for communications research. This challenge is in many ways similar to that presented by the concept of Multiservice Networking some twenty, or more, years ago in that it requires both the adaptation of existing concepts and the development of new paradigms (Bouhafs 2012, Fan 2010).

Bringing the Smart Grid into existence involves the amalgamation of two complex individual systems, both of which are systems of bidirectional flow: flow of power in one case; and flow of information in the other. This amalgamation will produce one single system of even greater complexity (Budka 2010, Fan 2010). A successful realization of the Smart Grid will depend on the support of an appropriate, clearly defined and widely accepted architecture (Budka 2010, Fan 2010, Jeon 2011). In general, any such architecture will need to address problems of building the Smart Grid at multiple levels of abstraction, and to consider numerous different perspectives, e.g. scientific, technical, commercial, economic, political and social etc.

Given the complexity of the Smart Grid system and the wide diversity of stakeholder interests, defining architecture for the Smart Grid will be a main responsibility. It seems doubtful that developing a widely accepted architecture could be done by separated groups of researchers and it is almost certainly a task that requires wide ranging multidisciplinary collaboration.

For any Smart Grad architecture there is a need for an effective Smart Grid communication architecture. Although there will be degree of separation between communications network system and the power distribution system at the physical level, and possibly other lower levels of abstraction, they both need to be considered within the context of the overall Smart Gird system. However, a degree of decomposition may be possible for the development of the Smart Grid communications architecture, although the need to maintain a focus on the wider context will still remain.

This paper focuses mainly on issues relating to Smart Grid communication that could inform the development of Smart Grid communications architecture. For the reasons we have stated above, its aim is to make a contribution to the opening discussions on the development of this new architecture. It does this by offering pointers from the experience we have gained while researching into multiservice networking which we do believe will be relevant to Smart Grid communication.

The remainder of this paper is structured as follows: it first presents a background to recent Smart Grid research and highlights the need for an open communications architecture. Next, it discusses the main principles that define architectures for open communications and identifies their strengths and introduces advances on the basic architectural approach that accommodate support for multiservice, management, control and QoS. It then presents a summary and brief history of previous research into multiservice networking, discusses the current state of multiservice research and the deployment of its results within IP networks, and then reviews recent work into multiservice that focuses directly on smart Grid communications. Following this, the paper then relates the finding of the previous sections to the potential development of a Smart Grid architecture with particular focus on its communications architecture; finally the paper concludes and outlines future work.

2. BACKGROUND

Over the past few years researchers have been considering the problem of evolving and extending grid communications into a greater and more heterogeneous system that will support the requirements of the Smart Grid. This body of work has focused largely on the overall physical systems architecture of the smart grid, considering general infrastructure, the interoperation and integration of heterogeneous technologies and the relationship between different participants in the Smart Grid (Budka 2010, Fan 2010). It has resulted in the generalization of a Smart Grid system, a simple example of which is shown in Fig. 1. It has also addressed the challenge of Smart Grid communications and the Quality of Service (QoS) requirements of Smart Grid applications and services, including management, control and security (Budka 2010, Fan 2010, Yin 2011).

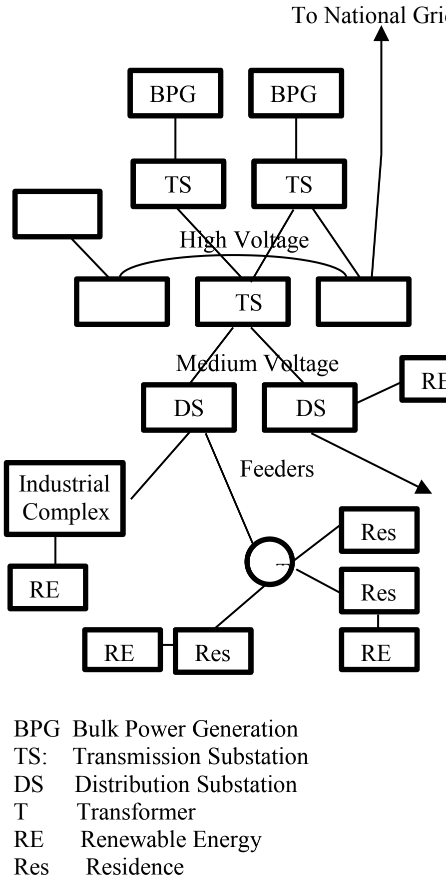

Fig. 1. A simple example of a Smart Grid System

Collectively, this body of work presents a general picture of the Smart Grid system and its basic requirements that, for the purpose of this discussion, can be summarized by the following points.

- The Smart Grid will have a hierarchical structure
- It will comprise multiple domains of ownership that do not necessarily have a one-to-one correspondence with the hierarchical structure.
- It will involve bi-directional flow of both power and information.
- The Smart Grid will be built using heterogeneous technology.

- Its communication infrastructure will need to provide appropriate QoS for a number of different classes of communications traffic
- Both power distribution and communications will need to be secure and robust.
- It is generally expected that IP networks will provide the basic transport mechanism for Smart Grid communications.

This body of work also shows a general consensus regarding the need for a Smart Grid communications architecture. In particular, Bouhafs et al (2012) make explicit the case for a new architecture that will accommodate the introduction of new technologies and protocols, provide scalability and be extendable for future application and services. Furthermore, the case is made for an open architectural approach.

Clearly, A Smart Grid communication architecture will be influenced by the points listed above. However, these points are not exhaustive and given that research into the Smart Grid is still in its relatively early stages, results from future work may identify further considerations.

The remainder of this section reviews ideas and concepts that take a more generalized view of the Smart Grid and its communication system that could impact on the development of a Smart Grid communications architecture. Including non-technical issues that support the case for an open communications architecture, and higher level systems approaches.

Hierarchical structure and general topologies have been considered by many researchers, generally with particular focus on the physical structure and interoperation of various technologies. However, more recently Rech and Harth (Rech 2012) have proposed a generalized hierarchical abstraction. The levels of hierarchy in this model are based on voltage levels and the topology of a sub-grid is represented by an atomic tree motif. Any number of atomic tree motifs can then be used to build a self-similar network topology model for the entire grid. Each sub-grid manages its own resource allocation and data and provides aggregated data to the sub-grid above it. Some interesting properties of this model could be worth taking into consideration in the development of a Smart Grid Architecture. Specially, the fact that the grid is partitioned based on the voltage level. This allows computing nodes to be deployed at existing interconnection points in the power network and supports the partitioning of the computational work needed for communication and resource allocation.

Data transport is vital for Smart Grid communications and there is general consensus that IP networks will play a major role in providing this service (Cupp 2008, NIST 2009, Lobo 2008). The Internet offers global interconnectivity and is an obvious candidate for providing data transport for Smart Grid communications. Furthermore, for organizations with their own private IP networks interworking over the Internet is relatively straightforward. However, vulnerabilities of the current Internet and the need for greater resilience have been recognized, particularly if it to be considered as a critical resource for Smart Grid communications (DHS 2009). Sterbenz et al (2010) identify three principles of resilience and present an architectural framework and set of design strategies for achieving resilience. They identify the principles that encompass the properties and behaviors of a resilient system: these being; self-organization and autonomic behavior; adaptability; and evolvability.

Following an investigation into the requirements and practicalities of Smart Grid communications Fan et al (2010) consider the use of self-organizing overlay networks over the wide range of existing infrastructure to be the best way forward in the development of Smart Grid communications. However, they also recognize that Smart Grid applications may have significantly different user expectations, security problems and QoS requirements to those of the applications that are currently being served by existing infrastructures.

Middleware solutions are seen by many as a critical component in a Smart Grid communications systems. Martinez et al (2013) provide an extensive survey of middleware architectures and identify the general role of middleware as being to abstract the diversity of communication and power transmission devices thereby providing the application layer with a homogeneous interface involving power production and consumption management data. The survey recognizes a few drawbacks to employing current middleware approaches in a wider architectural context. Firstly, there are many middleware architectures often with very different characteristics; secondly, in cases where the middleware is strongly defined in terms of scope and objectives extra effort may be needed to adapt to other architectural components; and thirdly, it may be difficult to develop an ultimate standard in the area of middleware.

A further consideration with middleware deployment is the problem of interoperability between heterogeneous middleware architectures. Bromberg et al (2011) recognize that currently, there are numerous middleware solutions in use that cannot directly interact with one other without interoperability solutions such as software bridges and Enterprise Service Buses. In more dynamic environments these interoperability solutions are not practical unless all possible combinations of middleware protocols are known in advance. As a solution to this problem Bromberg et al (2011) have developed the Starlink framework that provides dynamic protocol interoperability by raising the level of abstraction and introducing high-level models to describe protocol messages, protocol behaviour, and protocol interoperability.

Both self-organizing overlay networks and middleware solutions are seen as being significant components of the Smart Grid communications system. Furthermore, self-organizing middleware solutions have been considered (Awad 2012) in which the middleware component handles service provisioning and the self-organizing component carries out decisions based on information provided by the middleware component. These approaches place most of the activity, control and interaction within the smart grid at the higher layers in the network above the data transport layers. Together they can enhance the basic services available from the underlying data transport layers, providing additional security, greater resilience and in certain cases improve levels of QoS (Alkhawaja 2011). However, for high quality real time communication in the case of interactive continuous media applications (voice and video) and time critical control the underlying data transport system will also need to capable of providing the necessary delay characteristics and throughput requirements for this type of traffic. For this type of traffic, middleware and self organizing mechanisms will need to ensure that the underlying data transport network complies with necessary requirements before offering service for this type of communication.

Non-technological and operational issues may also need to be considered when developing a communications architecture for the Smart Grid. The Smart Grid concept brings about a change in the relationship between supplier and consumer. With existing grids, for the majority of cases the consumer's role is generally passive. In contrast, the consumers in the Smart Grid can play a more active role in the control of their consumption (Bouhafs 2012, Budka 2010, Jeon 2011). The Smart Grid also introduces the concepts of the Consumer-Supplier and Communities of Consumer-Suppliers, thereby increasing the potential range in domains of ownership. This particular paradigm shift further strengthens the case for an open communications architecture to allow all participants some degree of control and choice. Given that a significant objective of the Smart Grid is to encourage a greater use of renewable energy sources, e.g. solar power, wind power etc, an area in which consumer-suppliers are most likely to be involved, it is important for them to have a reasonable degree of control over their participation in the Smart Grid. Closed architectural approaches could lead to unfair domination by the major participants and lock users into vendor specific solutions.

Finally, the development and evolution of the Smart Grid is also being considered from a higher level systems perspective by members of the control community. The Smart Grid can be categorized as a system of systems (SoS), i.e. it comprises components that are themselves systems (Samad 2011). The same can be said for its power distribution and communications networks. In addition to its composition a System of Systems must possess two properties: Operational independence of components; and managerial independence of components. System of systems architectures are applicable to complex dynamic systems in general and are considered to be appropriate for the evolutionary development of the Smart Grid system (Chandy 2011).

In summary, the research reviewed in this section has identified the scale and complexity of the Smart Grid and the heterogeneous nature of its technological constituents. A number of architectural models have been developed that capture the physical interconnectivity and topology of the Smart Grid together with the interactive and interdependence of its heterogeneous components. Collectively, the more recent examples of this research imply the need for a new generalized open architectural approach for the development and evolution of the Smart Grid, an important component of which should be an open architecture for Smart Grid communications. High level system perspectives such as SoS that have the potential to simultaneously model both the system as a whole and its constituents may well have a role to play in the development of the Smart Grid architecture. However, for lower levels of abstraction in the communication process, adaptations of the existing architectural approaches may be more appropriate. This section has also reviewed examples of work that addresses the problems of heterogeneity, resilience and QoS in the communications process. Although workable solutions are offered in the form of middleware architectures, communication between different middleware architectures generally requires protocol translation. For their effective operation they also rely on information from the underlying layers in the network. Furthermore, for certain classes of traffic they can only offer an appropriate QoS if this is also supported in the underlying network infrastructure.

3. ARCHITECTURES FOR OPEN COMMUNICATION

Architectures for open communication, also called reference models, differ somewhat from physical architectures of network systems. Rather than specifying such matters as topology, types of devices, interaction between devices etc. they represent an abstraction of the communications process that is independent of platform, device and implementation. They provide a control framework within which to develop and specify communication protocols and their interfaces (Campbell 1997, Tanenbaum 2013). The general principle being that the communications process is divided into different levels of abstraction (layers) and for each layer the problem of communication is solved at that particular level of abstraction (the solution being formalized in a protocol). Each layer also provides services to the layer above via a clearly defined interface and in turn makes use of the services of the layer below it (leading to protocol stacks). Their strength lies in the principles of clearly distinguishing between the concepts of service, interface, and protocol and strongly differentiating between specification and implementation (Tanenbaum 2013). The first, widely known architecture of this type is the Open System Interconnection (OSI) reference model. Other popular architectures that follow the same general principle include the IEEE 802 series and the TCP/IP model. However, the TCP/IP reference model does not strictly adhere to the general principles given above. The concepts of services, interfaces and protocols are less clearly distinguished and the model does not clearly differentiate between specification and implementation. Furthermore, it comprises only two layers, considers the link layer as an interface rather that a layer and does not distinguish between the data link and physical layers (Tanenbaum 2013).

This layered approach has been applied almost universally to the transport of data for many years and has proved to be successful. However, with the advent of multiservice and the consequential need for differing Quality of Service (QoS) the one-dimensional layered approach becomes less effective. The basic layered model does not directly support the exchange of control and management information between the layers for functions such as security, QoS establishment and QoS maintenance. Layer breaching may be the only option when such information needs to be exchanged between layers, and examples of this practice can be seen in IP networks, e.g. Network level processes using information present in Transport level packets. Although this limitation does not prevent the implementation of control and QoS mechanisms it leads to untidy solutions that can limit generality and openness.

To overcome the limitations of the basic layered model, two-dimensional communications architectures have been developed. These models follow the same horizontal layering but add a number of vertical control, or management, planes. A general example of this type of architecture is the Lancaster University QoS Architecture (QoS-A) (Campbell 1997). The layers represent the same levels of abstraction as in one-dimensional model and in the case of QoS-A there are three planes: the Protocol Plane; the QoS Maintenance Plane; and the QoS Establishment Plane. This approach allows a clear separation between basic protocol operation and the QoS mechanisms and allows for additional set-up and control interfaces between the layers. The planes also represent the different time scales involved in a QoS enabled communications process. For example, the Protocol Plane represents the time scale at which the protocol handles its data units i.e.

microseconds to a few milliseconds, the time scale of the QoS Maintenance Plane can range from a few milliseconds to a few seconds, and the QoS Establishment Plane covers a range from several seconds to hours or even days, depending on the dynamic nature of the establishment process.

In general, a major advantage of open communications architectures lies in the separation between specification and implementation, thereby allowing any appropriate technology or platform to be used when implementing protocols and interfaces.
Furthermore, two dimension architectures also provide further strength though a clear separation between protocol operation and control activities.

The one dimensional layered model has been used successfully for many years and still forms the basic framework for the current Internet. However, in addition to being inadequate for meeting the requirements of multiservice traffic, in particular for real time applications, they are now also being seen as inadequate for coping with the dynamics of TCP/IP based wireless communication and the requirements of autonomic communication (Razzaque 2007). The cross-layer approach has been proposed as a solution to the interaction and exchange of information between non-adjacent layers and is seen by some as an implementation optimization that leads away from the strictly layered approach. However, others (Kliazvich 2011 Razzaque 2007) have shown that cross-layered architectures can preserve the strict layering of the basic protocol functions whilst meeting the requirement for non-adjacent layer communication. In fact, from the perspective of a control frame work the cross-layer approach closely follows the same principles as QoS-A.

In Summary, it is expected that the Smart Grid will need to rely on a wide range of heterogeneous technologies to provide its communication infrastructure. In turn, the communications infrastructure will be required to support both data and control services and provide varying levels of QoS to Smart Grid applications. The two dimensional open architectural models discussed in this section offer a control framework that not only provides a clear distinction between the concepts of service, interface, and protocol but also makes a clear differentiation between protocol functions and the functions of management and control, e.g. monitoring, QoS establishment, Qos maintenance etc. Conceptually, they provide multiple interlayer interfaces, one for protocol operations and one, or more, for the operation of management and control. They also provide a separate path, or paths, for the exchange of management, control and information between the layers, thereby avoiding the need for layer breaching within the basic protocol operation. Furthermore, as with the original one dimensional models they strongly differentiate between specification and implementation.

4. POINTERS FROM MULTISERVICE NETWORK RESEARCH

The concept of multiservice networks originally came into being though the desire to integrate data and voice services within one telecommunication network. This ultimately lead to the definition of ATM (Asynchronous Transport Mode) networks and the proposal for their use in future broadband multimedia communication. This in turn inspired a significant amount of research into multiservice networking including the development of QoS architectures and QoS support mechanisms initially focused on ATM networks.

In general, this work has shown that in order to meet QoS requirements of both data traffic and continuous media (real-time audio and video).the following three basic functions must be provided within the network (Campbell 1997, Ball 1995) .

- Bandwidth Partitioning: to provide bandwidth sharing and isolation between individual classes of traffic.
- Admission Control: to control the acceptance of traffic flows into a given class.
- Access Control: to control access to the resources allocated to each individual classes.

Later research, including the work of the authors, has shown that it is also possible to meet the same QoS requirements in IP networks provided that these three basic functions are present within the IP layer.

Both WFQ (Weighted Fair Queuing) (Parekh 1993) and CBQ (Class Based Queuing) (Floyd 1995) can provide bandwidth partitioning in IP networks . A comparative evaluation of these two approaches has shown that WFQ is best suited to the needs of data traffic whereas CBQ offers better service to continuous media traffic (Ball 1999). However, the evaluation also has shown that a hybrid CBQ-WFQ approach (Ball 1998) can meet the requirement of both types of traffic without compromise .

Admission control mechanisms for IP networks that operate in conjunction with the hybrid CBQ-WFQ approach have also been shown to be feasible (Ball 1998, Maqousi 2002, Maqousi 2003). These mechanisms fully support the QoS requirements of continuous media traffic and service differentiation for data traffic but at the cost of increased complexity. Generally, they require additional instrumentation to be provided within the routing devices and require individual queues for each class of traffic. They can be used with either static bandwidth allocation or more dynamically in conjunction with a resource reservation protocol such as RSVP, although dynamic resource allocation can result in a significant amount of signaling traffic.

The development of mechanisms for the classification of IPv4 packets and the inclusion of an explicit class field in IPv6 helps to support access control in IP networks. Leaky Bucket and Token Bucket mechanisms have been used for some form of access control for many years. However, perhaps the most significant development for access control in IP networks are Active Queue Management (AQM) mechanisms, e.g. RED WRED etc (Floyd 1993). In general these mechanisms vary the packet dropping probability for incoming packets according the current state of the queue they are managing. They have been shown to increase average throughput by improving the overall behavior of congestion reactive protocols, in particular TCP. Since the basic approach to AQM was introduced over twenty years ago (Floyd 1993) research has led to significant improvements in AQM mechanisms that are responsive to correlation in the traffic arrival process (Fares 2010). Service differentiation with respect to throughput can be achieved by providing separate queues for each traffic class and differing the settings of their respective AQM mechanisms. However, AQM mechanisms are best suited for providing service differentiation for data traffic and are not generally beneficial for continuous media traffic unless they are combined with some form of priority scheduling mechanisms such as CBQ.

In addition to the three basic functions as outlined above, multiservice networking research and work relating to the development of QoS-A (Campbell 1997) has indentified the need for QoS mapping between different levels of abstraction in the communication process. In the case of traffic flows, QoS mapping will need to consider any change in the temporal structure of the traffic, e.g. as is the case where IP packets are to be transferred over an ATM network. This leads to the concept of QoS and Temporal Mapping (Ball 1995) and mechanisms for the process have been developed (Basu 2002) to work in conjunction with the admission control and bandwidth partitioning mechanisms introduced above (Ball 1998, 1999).

The work presented above was focused on providing multiservice within the network. It was carried out in parallel to, and in collaboration with, the work of other groups of researchers who were focusing on providing multiservice within the transport and application layers (Campbell 1997). However, at some point around c. 2002 there began a change in the general direction of multiservice and QoS research with the emphasis moving away from the network level and more toward meeting QoS in the higher layers, e.g. adaptive applications, middleware (Martenez 2013, Yin 2011, Xiao 2010) and self organizing overlay networks (Sterbenz 2010). However, despite this change in emphasis, research into network level QoS support mechanisms has continued to some extent, focusing on QoS routing (Li 2010), the development of MPLS and the improvement of AQM mechanisms (Fares 2010).

In 1998 the IETF (Internet Engineering Taskforce) standardized an architecture, namely differentiated services or Diffserv (IETF 1998), as a framework for class based, as opposed to per flow based, QoS. Since then research has continued with the development of variations of the network level QoS support mechanisms discussed above for deployment within the Diffserv framework (Dini 2010). A number of these developments have been deployed within IP networks and propriety solutions for Diffserv are on offer. However, in cases where service differentiation is available in IP networks it is often limited to a small number of classes with differing throughput assurances plus the standard best effort service, as presented in (Dini 2010).

Although research has shown that IP networks can provide both an appropriate QoS to real-time continuous media and offer different levels of service for data traffic, in general this potential has not yet been fully realized. In particular, the Global Internet does not currently provide an appropriate QoS for real-time traffic. The additional cost and complexity needed to provide high quality real-time services within IP networks is undoubtedly the reason that they are rarely available. To date there has been no commercial imperative to provide such a service within the Global Internet to justify the higher costs of implementing the complete range of QoS support mechanisms that are available. Whilst video and audio communication does take place over the Internet users seem to be willing to accept a much lower quality as long as the service remains virtually free. However, the advent of Smart Grid changes the situation and a greater importance may need to be placed on real-time communications. For example, if someone is watching a video over the Internet, or using an Internet voice service, and the service degrades or fails, they may be annoyed, but it will not result in a disaster. Conversely, loss or degradation of time critical communication within the Smart Grid could lead to very serious consequences. Therefore, there will be operational, economic, and possibly regulatory, imperatives for providing an appropriate level of service to real-time traffic within IP networks if they are going to become the back bone of Smart Grid communications.

Recently, researchers have begun to revisit the problem of multiservice at the network level in line with the requirements of Smart Grid communications (Alishahi 2013, Sadeghi 2012). This work follows a very similar approach to that of earlier research, recognizing the importance of delay bounds as well as throughput requirements, and proposing the combination of priority based schedulers, CBQ/WFQ and AQM mechanisms within the network layer. However, it does differ in that it addresses the problem from the perspective of the DiffServ paradigm and is explicitly focused on meeting the QoS requirements of Smart Grid communications traffic. The delay requirements of Smart Grid applications with regard to maximum allowable/desirable latency are estimated showing a range of 8 to 1200 ms for all applications. However, for the time sensitive applications the range is considered to be between 8 to 200 ms, 200ms being the value ascribed to VoIP (Voice Over IP). This work shows that the timing constraints of certain Smart Grid applications are much tighter than those of the time sensitive applications considered in previous research into multiservice networking.

Although it is important to address the needs of time critical and time sensitive traffic within the network layer, it is also necessary to address the problem in the lower layers, i.e. the Link and MAC layers (Maaser 2010). This is also a point at which technology convergence may need to be considered. Certain MAC protocols e.g. IEEE 802.11 (IEEE 2008) support option extensions to support QoS, including measurement and link monitoring. However, in practice these are rarely implemented, probably due to inadequacies in current LLC (Logical Link Control) interfaces. Maaser et al (2010) propose an Inter-MAC adaption layer that sits between the network layer and LLC. Conceptually, the model presented makes a significant contribution to the problems of technology convergence and making the QoS capabilities of the MAC layer available to the network level However, from an architectural perspective it is questionable as to whether a new layer should be defined or the functionality be addressed at the link level. Practically, the Inter-MAC concept offers an immediate solution, but the question of where this type of functionality should ultimately be placed needs to reconsidered in line with future architectural developments.

In Summary, the research discussed in this section relates mainly to the data transport level of the Smart Grid communication system. An historical perspective of this research has been provided to highlight the fundamental principles for multiservice as recognized in early work and to draw attention to ideas that may have renewed relevance for the new direction of Smart Grid communications. The work surveyed in this section has shown that IP networks can fully meet the QoS requirements of both data and continuous media traffic given that appropriate mechanisms for bandwidth partitioning, admission control and access control are deployed appropriately within the network. However, it has identified that for current IP networks in general and the Internet in particular service differentiation is often limited to a few classes of service best suited to the requirements of date traffic. Recent research into the QoS requirements of Smart Grid communications traffic has proposed models for service differentiation that are very similar to those developed in earlier work into multiservice. However, they have shown that the traffic characteristics of time sensitive Smart Grid applications will be significantly different from those of continuous media traffic. In particular, certain applications will have very stringent timing requirements, but significantly less demand on throughput. The problem of meeting the QoS requirements of Smart Grid communications traffic has also been addressed at the Link and MAC layers with particular focus on problems of technology convergence and accessibility of QoS capabilities with the MAC layer. This has led to the proposal for an Inter-MAC layer that solves the problem but also highlights a potential inadequacy in the current architectural framework. The points raised in this section together with those highlighted in the previous section will be considered further during the discussion presented in the following section.

5. TOWARDS AN ARCHITECTURE FOR OPEN COMMUNICATIONS FOR THE SMART GRID

Given that the Smart Grid can be considered as a System of Systems, and the same can be said for both its power distribution and communication systems, it follows that an all encompassing Smart Grid Architecture may need to be considered as an Architecture of Architectures. The Smart Grid system will involve a wide diversity of stakeholders who may view the Smart Grid from different perspectives, including scientific, technical, commercial, economic, political and social. These various perspectives together with stakeholder interests will need to be reflected in the Smart Grid Architecture. Therefore, it will need to capture multiple viewpoints, hierarchical structures and different levels of abstraction and very possibly other factors as yet not identified. It will also need to support appropriate levels of decomposition whilst maintaining a clear picture of inter-relationships, dependencies and interactivity.

To date, Smart Grid research has investigated many diverse issues that are vital to the development of the Smart Grid system and the implementation of Smart Grid services. Collectively, this body of work has addressed many specific problems, and in most cases identified potential solutions. A number of architectures focusing on specific problem domains have been proposed, the principles of which could make a useful contribution within the framework of a wider architectural context. Previous and ongoing research into other areas, including work into multiservice networking as discussed in the previous two sections, can also contribute. Although not surveyed in the this paper, a vital contribution will be needed from research into systems security.

The outcomes from Smart Grid research has produced a significant diverse knowledge base that needs to be coordinated, merged and channeled toward a Smart Grid system, hence the need for a Smart Grid Architecture. As stated in the introduction defining an architecture for the Smart Grid will be a very major undertaking that will require wide ranging multidisciplinary collaboration.

Therefore, a vital step in the overall process toward a Smart Grid architecture will be to build and strengthen collaboration through relevant established bodies, special interest groups, themed conferences and journals etc. Further research into individual areas will need to continue simultaneously to the effort of establishing collaboration. However, this research still needs to be carried out with an awareness of the wider context.

A Smart Grid architecture for open communications will need to be developed within the framework of the Smart Grid Architecture as it cannot be considered in total isolation due to interaction and interdependence between the communications network and the Power Distribution system. As to what extent the communications architecture can be decoupled from, or how it will be integrated in, the overall architecture needs further investigation. However, it is possible to start addressing the architectural requirements of the lower levels of abstraction in data transport process, i.e. transport, network link and physical layers, in relative isolation since the communication pathway they represent will generally be encapsulated between two middleware entities and hence may be partially decoupled from the rest of the system.

Given that IP networks are expected to form the backbone of Smart Grid Communications, then from an architectural perspective, the first step could be to consider the adequacy of the current TCP/IP reference model with respect to the requirements of Smart Grid communications. The current model would seem to be inadequate for four reasons: firstly, in common with all one dimensional reference models it cannot explicitly capture the requirements of multiservice and QoS.; secondly, it does not strictly adhere to the general principles of open communication as discussed in a previous section; thirdly, it does not view the link layer as a true layer but simply as an interface, thereby failing to distinguish between the link and physical layer; and finally, and very importantly, it does not strongly differentiate between specification and implementation.

The TCP/IP reference model has also been shown to be inadequate for supporting TCP/IP based wireless communication and autonomic communication, and this has motivated the development of cross-layer architectures. Although some instances of cross-layer architectures are depicted as the implementation of a solution, conceptually, a cross-layer approach can be made compliant with the general principles for open multiservice communication. However, whether compliance can be assured when cross-layering is implemented within the current TCP/IP framework has not yet been demonstrated.

The cross-layer concept is based on inter-layer communication throughout the full protocol stack, from application layer down to physical layer, following a general framework for layer interaction. Therefore a generic cross-layer architecture compliant with the general principles for open multiservice communication could provide an appropriate control framework in which to develop the data transport component of the Smart Grid communications system. However, this brings into question the future role of the TCP/IP reference model: should the model (not the protocols) be abandoned in favor of a new and more suitable framework, or should the model be modified so it can be incorporated into a new framework?

Research into the future Internet is addressing similar points and raising the same basic concerns to those discussed above, leading to the increasing popularity of the cross-layer approach. Discussions into the way forward for the future Internet are addressing the merits of both the "clean slate" approach and continued evolutionary development. Although there could be benefits in combining both approaches, opinion is divided between the two and appears to be somewhat polarized (Dovrolis 2011, Rexford 2010). The cross-layer approach can be considered as being either evolutionary or "clean slate" depending on perspective. In cases where the approach is thought of as being simply a means to optimize implementation, it could be considered evolutionary. However, when it is viewed as being an architectural framework that can encapsulate inter-layer communication and inter-action whist preserving the fundamental principles of open communication, it potentially becomes a "clean slate" solution.

In view of the Smart Grid's expected dependence on IP networks and its potential relationship with the global Internet, the issues raised in the preceding paragraphs lead to another question: Should the Smart Grid communications systems architecture have its own framework for IP networks or fit into the framework of the global internet? In many ways the Smart Grid represents a step change both socially and technologically, and brings with it new communications requirements, therefore it would seem to be a suitable candidate for the deployment of some "clean slate" solutions. The current global Internet cannot fully meet the needs of Smart Grid communication, particularly for many of its real-time applications, and is unlikely to be able to do so in the foreseeable future, unless some step change takes place. Major participants in the Smart Grid will very likely have their own IP network infrastructure, as may some less major participants, therefore the option to take a new approach independent of the global Internet community is possible. However, it is obvious that preserving the ability to interwork with the global Internet is essential.

A cross-layer architectural framework could also help to redefine the problems that have led to proposals for an Inter-MAC adaption layer that sits between the network layer and LLC. The cross-layer approach may allow solutions to be developed that avoid the need to have this addition layer. However, further research is needed to verify that this is the case.

Finally, as the cross-layer approach also extends up into the application layer its architectural relationship to middleware and self-organizing mechanisms needs to be considered. Although the functional relationship is generally known, given the plethora of middleware architectures, many with very different characteristics, recognizing a generalized framework would not be straight forward. Therefore, this is also an area for further research and analysis.

In Summary, the Smart Grid, is a system-of-systems that is based on heterogeneous technology and will have a wide diversity of stakeholders who view the Smart Grid from different perspectives. It comprises two major interdependent components, the power distribution network and the communications system, each of which is also a system-of-systems. The Smart Grid system will have a complex hierarchical structure due to the need for inter-communication and interaction between components that may be in different levels of the hierarchy. Defining a Smart Grid architecture that will serve as a control framework to guide the open development and evolution of the Smart Grid system will be a daunting task requiring multidisciplinary collaboration, the establishment of which is probably the most important first step in the path toward a Smart Grid architecture. Fortunately, research into the Smart Grid and other related areas has produced a significant body of knowledge to guide the debate toward a Smart Grid architecture. However, further research is still required, with a particular focus on the future architecture. Although defining a Smart Grid architecture for open communications cannot be done in complete isolation from the overall Smart Grid architecture, some decoupling is possible for the data transport system allowing specific problems to be addressed in relative isolation. Given the importance of IP networks to the Smart Grid and the more stringent real time requirements of certain smart grid applications it is important to address the inadequacies that have been identified with the current TCP/IP and to consider the possibility of defining a new control framework for Smart Grid IP networks. A generalization of the cross-layer architectural approach following the principles for open multiservice communication as possible new framework may be something worth investing. A cross-layer control framework may also allow the problems that have been identified at the link and MAC layers to be addressed without the need to consider additional layering. In general the points raised in this section are not intended to be specific proposals but rather pointers to the issues and idea we believe need to be considered. However, we firmly believe that the Smart Grid architecture should follow the principles of open system and open communications, and the only way of successfully defining this architecture will be through wide ranging collaboration and inclusive and open minded debate.

6. Conclusion and Future Work

This paper has surveyed current research into the Smart Grid and has identified a common generalization of its form, general requirements and the communications requirements of Smart Grid applications. The survey has also recognized a consensus for the need of a Smart Grid architecture, a major component of which should be an architecture for open communications. It then continued with a review and discussion of research into a number of areas of relevance to Smart Grid communications including network resilience, self organizing networks, middleware architectures and relevant non-technological issues

This was followed by a discussion on architectures for open communications that identified the fundamental principles of open communication and outlined the development of these architectures, from the basic layered one dimensional models to enhanced two dimensional versions that can also provide a framework multiservice and QoS.

A review of research into multiservice networking was then presented, that identified the fundamental principles that must be followed in order to meet the QoS requirements of multiservice traffic, and discussed the mechanisms needed to implement these principles. This was followed by discussions on: the general change of emphasis some years ago away from research into the network level QoS to a greater focus on adaptive applications, etc.; the current state of QoS implementation in IP networks; and the revived interest in network level QoS research recently stimulated by the Smart Grid. Recent work that explicitly addresses the network level requirements of Smart Grid applications was reviewed and a significant difference in the delay requirement of Smart Grid real-time applications to those of previous real-time traffic was observed.

Based on the findings of the previous sections the paper then presented a discussion that generalizes the Smart Grid as a system-of-systems and outlines the complexity that will be faced when trying to define its architecture and re-iterates the importance of multidisciplinary collaboration. The discussion recognizes that the Smart Grid's architecture for open communications will need to be defined with reference to the overall context of the Smart Grid architecture but indentifies a possible degree of decoupling that could allow a control framework for the data transport component of the communications system to be defined in relative isolation

The paper then addresses issues relating to the role of IP networks and indentifies the inadequacies of the current TCP/IP reference model for supporting the communications requirements of the Smart Grid. It then presents the concept of cross-layer architectures and considers how a generalized form of this type of architecture could form the basis of a more suitable framework. The implications of introducing a new framework for IP networks were then addressed in line with discussion of the future Internet that are taking place within the Internet community, and the possibility of the Smart Grid having its own control framework for IP networks was considered. As a future work we plan to further investigate the role of multiservice in Smart Grid communications and the enhancement of network level QoS mechanisms to address the real time requirements of the Smart Grid.

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