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Communication Architecture for Monitoring and Control of Power Distribution Grids over Heterogeneous ICT Networks

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Abstract*—In order to provide a comprehensive monitoring and controll infrastructure capable of fulfilling the requirements for security, control-ability and reliability of a modern Smart Grid, several factors for the adaptation of ICT technologies and architectures need to be considered. In this context Smart Grid systems operate on two time scales: first requiring delays in the order of μs for reporting events, e.g. short-circuits or component failures, and second data collection of the operational grid state from a huge number of sources, e.g. smart meters, sensors, etc., on the order of seconds to minutes. In this paper we focus on how network technologies can support this communication requirement of Smart Grid operation. Therefore, the focus is on reliability and control-ability of the network by providing the appropriate quality of service. For this purpose an overall heterogeneous communication architecture is presented, mapping the logical components and interfaces of multi-domain use cases to particular physical components and interfaces, which are implemented in testbeds and simulation models for assessment. Hereby, the major objective of the presented reference architecture is an unique definition of technical interfaces, components and information flows. It furthermore provides a framework for the specification of different technological options, information management and data aggregation. This work results in a novel approach for monitoring and controlling of energy distribution grids over heterogeneous communication networks is presented, which is based on two inter-related inner and outer control-loops for energy grid and communication network control. Furthermore, an application scenario is presented based on the integration of advanced meter reading and customer energy management systems into the overall architecture.

***Index Terms*—Smart Grid, Heterogeneous Communication Networks, AMR, CEMS, Control Loop, SmartC2Net.**

I. Introduction

The traditional electric power generation and distribution models face a paradigm shift as the focus moves towards renewable and distributed energy resources. Classically the entities involved in electric power grids fulfill distinct roles like generation, distribution or consumption. With the increasing amount of sustainable power sources like wind and photovoltaics the consumers can also act in the role of producers. Therefore, the new term *prosumers* is derived, who are equipped with devices for measuring power consumption and production and exchange information with the grid operator for billing and grid control. Automated Meter Reading (AMR) enables this capability and provides multi-tariff models, while enabling Customer Energy Management Systems (CEMS).

A CEMS provides advanced techniques like Demand Side Management (DSM) and Distributed Energy Resources (DER) management to the customers' households. Additionally, the generation of electricity in modern grids shifts from large centralized facilities to highly distributed, decentralized and dynamic entities with lower power. Their volatile character makes the balancing of load and generation in order to sustain stable grid operation even more essential than in current grids. Hybrid and electrical vehicles (EV) acting as consumers of energy as well as storage exhibit constantly growing market-shares, thus putting ever more strain on the grid and elevating the need for coordination. Hence advanced control and ICT networks become indispensable. Evidently, a communication architecture needs to be developed which meets the requirements imposed by these novel approaches and is reliable in presence of malicious or accidental failures. Therefore, a communication architecture for smart control of energy distribution grids over heterogeneous communication networks is presented by taking into account different ICT as already deployed in the field or currently under development (cf. Figure 1).

This paper provides an overview of related work in Chapter II. The use cases of the SmartC2Net project and the resulting requirements are presented in Chapter III. A description of the ICT architecture and the corresponding adaptive monitoring and control approaches as well as the adaptive access networks for integration of the AMR/CEMS use case in the overall architecture is provided in Chapter IV. Furthermore, the Low Voltage Grid operation and control concept is presented in Chapter V. Afterwards assessment frameworks for performance evaluation are introduced in Chapter VI and the conclusion is given in Chapter VII.

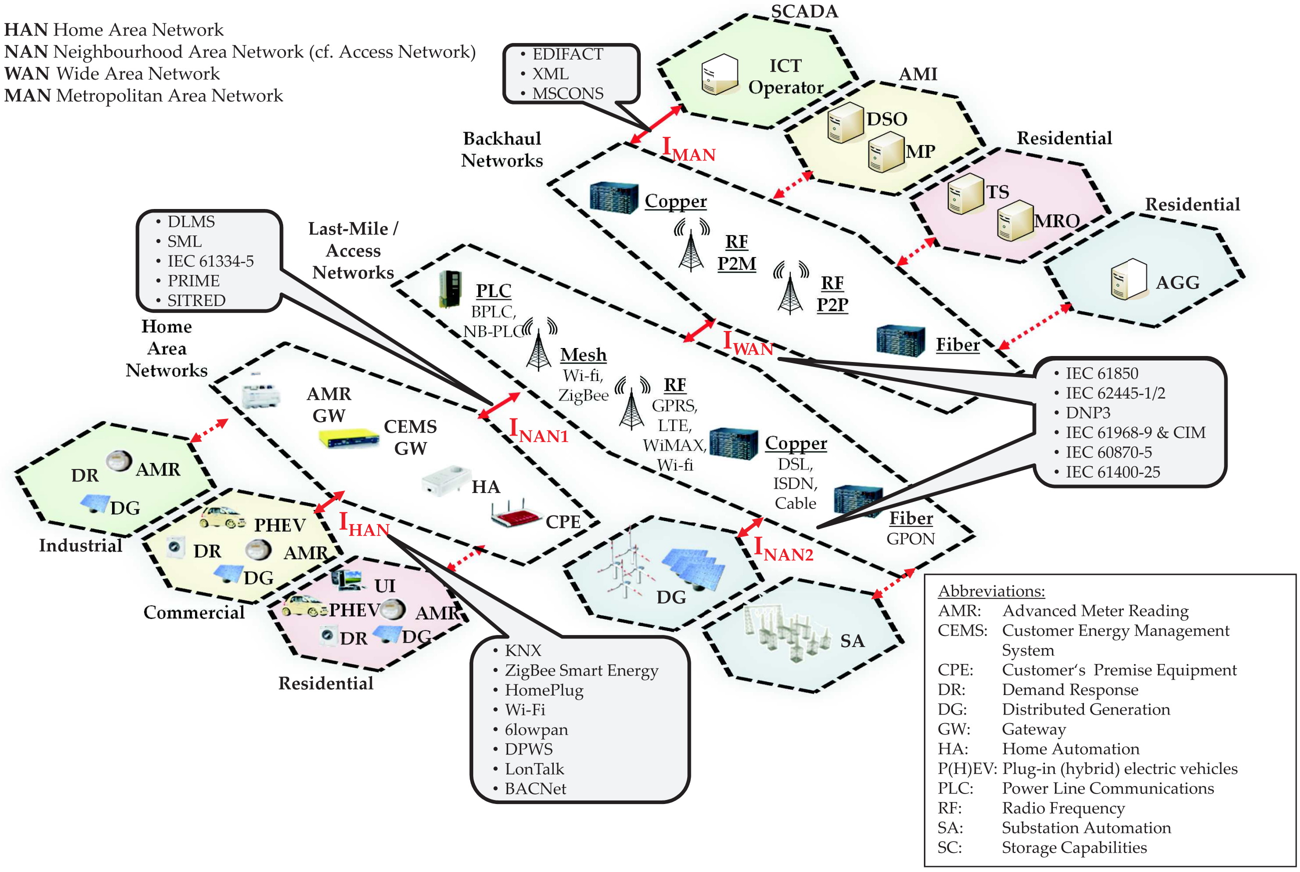

Fig. 1. State-of-the-Art Technologies and Standards for Smart Distribution Grids

II. Related Work

Literature presents a multitude of different approaches for building communication architectures supporting and enabling energy grids of the future. Thus, interoperability becomes an important factor in designing such networks, for which best practices and guidelines are provided by IEEE Std. 2030-2011 [1]. It is the first comprehensive IEEE standard which, amongst other achievements, establishes the Smart Grid interoperability reference model (SGIRM) and sets a roadmap for the development of further information exchange and control communications standards. The activities of the International Organization for Standardization (ISO) regarding the Smart Grid are coordinated by the Technical Committee 57 (TC 57), concentrating on power systems management and associated information exchange, and the TC 13 which includes electrical energy measurements, tariff- and load control activities. Efforts of the International Electrotechnical Commission (IEC) in this direction are, among others, represented by the Joint Working Group 15 which is tasked with the definition of communications for monitoring and control of wind power plants. IEC's Strategic Group 3 created a roadmap [2] in 2010 which contains about 300 standards relevant for Smart Grids. Another, European release on the field of Smart Grid Reference Architectures is available from the Smart Grid Coordination Group of CEN-CENELEC-ETSI [3]. Other relevant architecture and information models in this context are IEC 61850 [4] and IEC 62351 [5]. The former focuses on electrical substation automation in the context of TC 57 reference architecture for power system information exchange [6]. Meanwhile the latter was developed with the intent of handling the security of protocols defied by TC 57. IEC 61970 [7] is a series of standards which describes Application Programming Interfaces (APIs) for Energy Management Systems (EMS), while the IEC 61968 [8] series defines standards for information exchange between electrical distribution systems. The authors of [9] present a reference architecture designed with special focus on the integration of CEMS systems into energy marketplaces of the future [10].

III. Use Cases and Requirements

Resilience in the presence of malicious and accidental faults is a key requirement for every Smart Grid ICT solution, as it is impossible to foresee every potential vector of attack and error in advance. For this reason functionalities essential for reliable grid operation including control, monitoring and communication need to have the means of coping with impaired services. Additionally, as it is prohibitively expensive to build dedicated communication networks for energy grids, it is inevitable to make use of existing ICT infrastructures already deployed in the field. Out of this requirement the properties of heterogeneous communication networks have to be considered in the architecture's overall design. Moreover the full list of requirements depends on the Smart Grid's use cases. Hence four use cases are considered:

- UC1: Medium Voltage Control (MVC)
- UC2: External Generation (ExtGen) (e.g. wind-farms)
- UC3: Automated Meter Reading (AMR) and Customer Energy Management Systems (CEMS)
- UC4: Electric Vehicle (EV) Charging

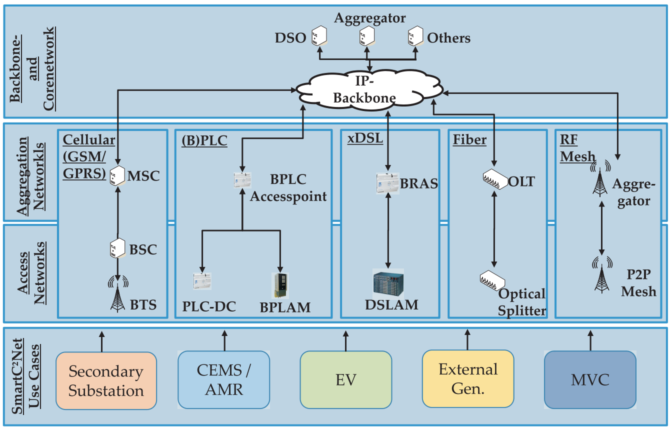

Fig. 2. SmartC2Net Use Cases and Heterogeneous ICT Access Networks

MVC focuses on voltage control in medium voltage grids with focus on enabling and connecting Distributed Energy Resources (DERs). The volatile power production of DERs leads to dynamic power flows in distribution grids, which necessitates reliable means of communication. This is reinforced as the loss or corruption of information, e.g. setpoints, might yield cascading effects endangering the whole grid's stability.

Voltage Control aims at monitoring the distribution grid in order to calculate setpoints for flexible loads, DERs and the high to medium voltage substations' equipment for maximizing grid stability. Load, generation and weather forecasts help in achieving this by providing valuable information for mitigating the negative effects of the stochastic load and generation processes. Architecturally the MVC use case comprises the Transport and Distribution System Operator's (TSO, DSO) control facilities, primary substations, flexible loads and DERs. External generation is a use case focusing on decentralized energy generation and storage, as their importance and deployment steadily rises. It is primarily tasked with the control of entities in the low voltage grid but also includes interfaces to mid and high voltage parts, i.e. secondary and primary substations, as these contain controllers which might benefit from communication with the external generation sites. For example the ability to aggregate flexibility on the low voltage level and pass it on to MVC is of interest, as well as the optimization of energy costs, losses and low voltage profiles. A resilient ICT infrastructure enables these functionalities as they depend on reliable information exchanges for the involved entities. AMR and CEMS are key functionalities of a Smart Distribution Grid. Therefore, the buildings in scope of this paper incorporate Smart Metering devices enabling the collection of electric, gas, water and heating, i.e. consumption data, for customer feedback and transmission to the energy utilities. Billing, accounting and balancing of the grid through DSM are functionalities provided by AMR. Load shifting to time slots with less expensive prices or improved utilization of local energy resources, i.e. DER, are rendered possible by a CEMS, among advanced direct DSM and added-value services. To achieve this diversity in functionalities an architecture that encompasses the devices of households is required, as well as the connection to access networks.

The EV use case is concerned with the handling of highly synchronized charging patterns of EV, mainly due to the circadian rhythm with concurrent working hours, creating high loads. The EVs are connected to the low voltage grid. It is targeted to harness the demand's flexibility to balance the grid's energy flows. Therefore EVs, charging stations as well as the DSO have to be able to exchange information via a reliable and secure communication infrastructure. Each of the outlined use cases presents with its own set of challenges, which are described in detail in [11]. As shown in Figure 2 these use cases are connected to different networks, which exhibit diverging parameters regarding their metrics like data-rate and latency. The overall control of such a Smart Grid is impacted by this in such a way that certain advanced algorithms might exceed the available interface's capabilities.

IV. ICT Reference Architecture Design

Figure 1 gives an overview of a subset of communication technologies fitted into the architectural structure. Starting on the left hand side there are three device groups categorized in industrial, commercial and residential, i.e. the applications in which they are most commonly used. These three groups are on the Home Area Network (HAN) level and are connected to gateways through technologies like KNX, ZigBee Smart Energy, Wi-Fi, HomePlug and others, as listed in the box to their right. The gateways can be of different varieties, depending on their intended uses. Metering GW (henceforth referred to as Automated Meter Reading Gateway - AMRGW), Energy Mgmt. GW (EMG, central device of a CEMS), Home Automation (HA) and Customer Premises Equipment (CPE, i.e. Internet modem/router) are examples for the gateways on this architectural level. They enable access to higher layers, namely the Neighborhood Area Network (NAN). Common technologies include DLMS and PRIME, as shown by the box above the HAN level in Figure 1. Several access networks are discussed in this domain for which wired ICT includes Power Line Communications (PLC), copper-wire based standards like DSL and (Euro-) DOCSIS, as well as fiber optic alternatives like GPON. Concerning wireless standards ZigBee and Wi-Fi represent RF-Mesh ICT networks, while GPRS, LTE and WiMAX are cellular RF technologies. Distributed Generation (DG) sites and Substation Automation (SA) also connect through use of these access networks to higher layers of the overall architecture. The next steps in this hierarchy are the Backhaul Networks, which exist on the WAN scale as they serve to interconnect multiple, physically distinct sites. Due to exacting technological requirements concerning data-rate, latency, reliability, etc., most infrastructure scenarios are based on wired ICT, but can also make use of wireless technologies, mostly comprised of high-grade technology with redundancy and dedicated spectrum in order to provide high reliability. Figure 3 depicts the high-level architecture of SmartC2Net,

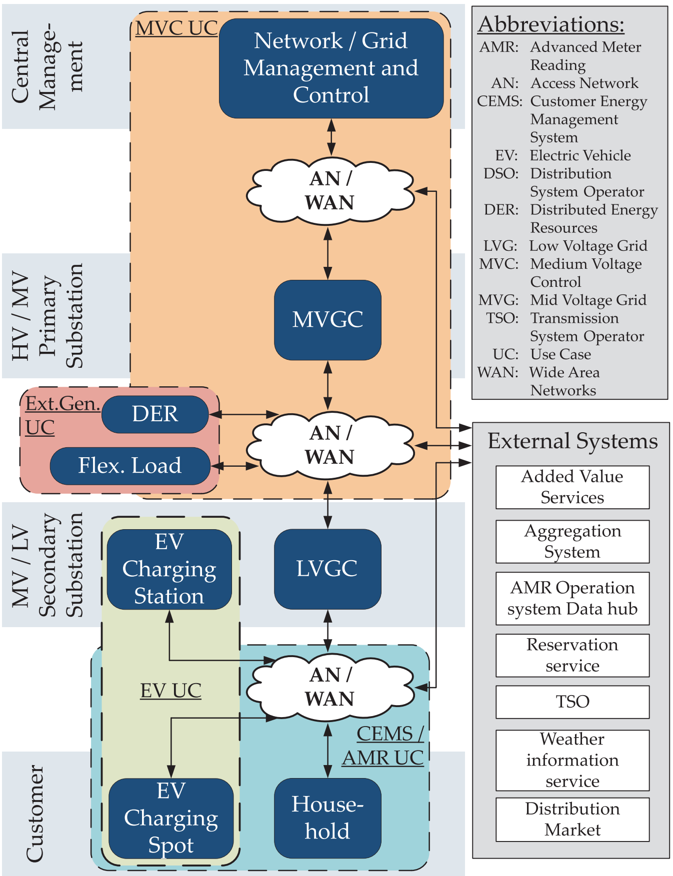

Fig. 3. High-Level System Architectural Overview

incorporating its use cases. It can be observed, that several physically distinct sites connect through Wide Area Networks (WAN) and Access Networks (AN), implemented by different technological options. An extensive state-of-the-art analysis is provided [12] and yields multiple candidates for each link between and inside the use cases, i.e. the physical entities of the grid depended on information exchange. The analysis also provides profiles of the technologies, including their features and properties, as well as lists corresponding standardization bodies/patents, defined OSI layers and an assessment regarding the suitability for the targeted approach to Smart Grids.

A. Security and reliability

Two of the most pressing concerns regarding the use of heterogeneous all-purpose networks, is related to the security and reliability of the system. Security is needed to ensure data cannot be tampered with for malicious purposes (cyber attacks), privacy protection of the end-user and so on. For the SmartC2Net project it is not intended to develop specific solutions for data protection, access control, etc., but rather to evaluate the impact on existing security solutions on the overall system performance. The second aspect relates to the reliability of the data, i.e. that data gets correctly from source to destination, while still being relevant once it arrives. The delays and time intervals of accessing data, have a huge, dynamic impact on the data which therefore must be adapted to the individual situation and for scalability reasons. Caching of data comes at the expense of timeliness and thus relevance. Here we use a model based approach, that links information dynamics, network delay and access mechanisms together to ensure reliable end-to-end data provision. This also includes possible reconfiguration of the network, i.e. if one network interface is completely down, data should still be transported.

B. Monitoring and Control Approach

At the center of this architecture stands a novel method for Smart Grid control, specifically designed to address the inter-dependence of control and ICT networks. Figure 4 depicts this inter-related SmartC2Net control dual-loop. It is constructed

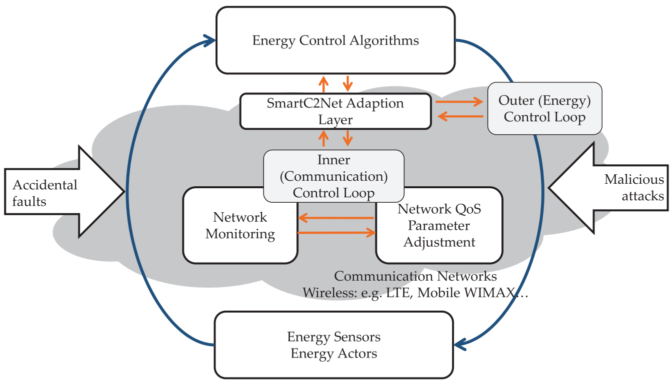

Fig. 4. SmartC2Net Inter-related dual Control Loop for Resilience

out of two interacting loops, the outer energy control loop and the inner communication control loop. Without energy the ICT cannot function while the future grid is more and more dependent on reliable information exchange to balance load and generation along with advanced functionalities like demand side management. Out of this reasoning we developed the presented structure with the communication at its core. Here the network monitoring system and the network QoS parameter adjustment, i.e. network reconfiguration, exchange information. Through this a stable operation and adaption of the ICT to the actual traffic situation is ensured. This enables the detection of failures by the monitoring system, which in turn either triggers the subsequent rerouting of data flows or the prioritization of Smart Grid related information over other information traveling the public networks like video streaming services. The outer energy control loop meanwhile focuses, as its name implies, on stable grid operation. Therefore control algorithms receive information concerning the grids status from energy sensors and alter the state of energy actors as

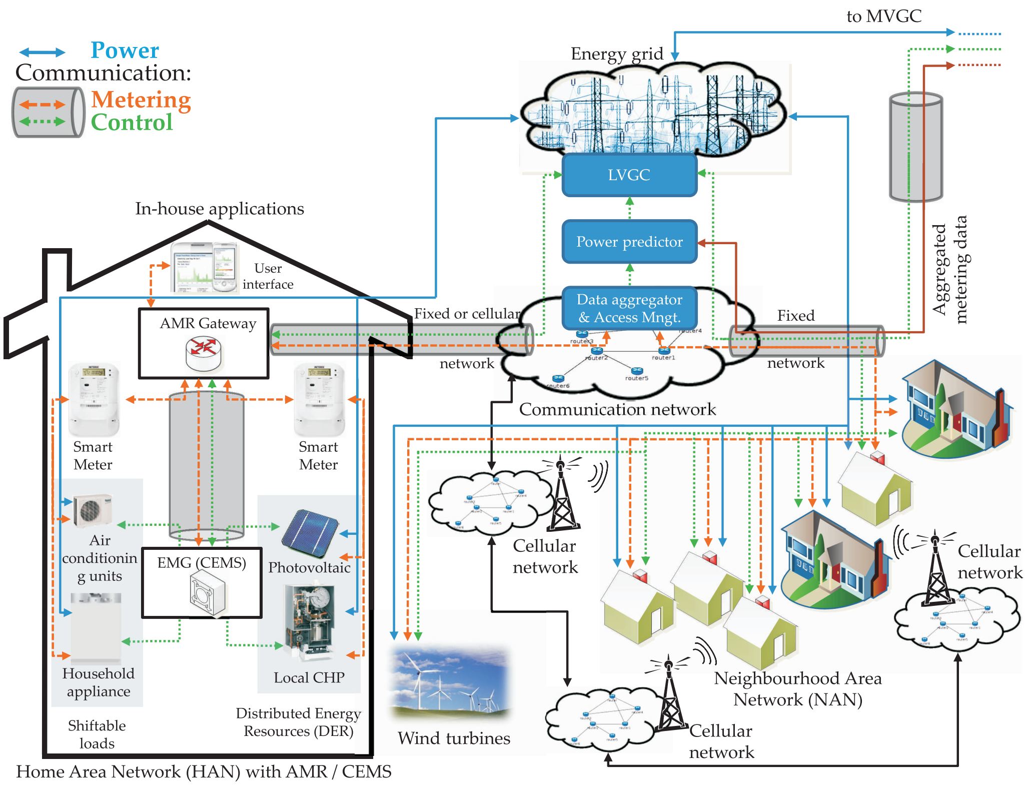

Fig. 5. Advanced Smart Meter Reading and Customer Energy Management System Scenario

necessary. However, as both loops are interdependent, information has to be exchanged between communication and energy control which is to be implemented by taking advantage of the SmartC2Net Adaption Layer. This represents the interface for connecting loops. In cases in which the ICT cannot deliver data with the QoS parameters required by the energy control a feedback is delivered, which signals to revert to another control algorithm, putting less strain on the communication network. The other way round the energy loop notifies the ICT if it is not capable of supplying it with stable power. This way it is possible to only relay information crucial to the grid's stable operation in order to save energy, or to reroute information flows around network elements affected by power failures. The Control Loop also allows for the energy control to request an allocation of networking resources, for example used for complex algorithms in need of detailed grid state information which has to be collected through the ICT. The inner communication control loop will then strive to meet this demand correspondent to its priority, i.e. desired Quality-of-Service. Accidental faults or malicious attacks can occur individually or combined on either of the two loops involved. Facilitated by the intertwined control loop's design such disturbances of normal operation are mitigated as far as possible, thus achieving the goal of a resilient Smart Grid.

C. Network Adaption and Reconfiguration

Figure 5 gives an overview of the AMR and CEMS use case embedded into the context of Smart Grids. On the left hand side several entities of this use case are shown, which exchange information with each other or with devices located off-site, e.g. the DSO's control center. In this case external connectivity is provided through the AMR Gateway, which itself is primarily designed to relay Smart Metering data. Implications of using an AMR Gateway to connect both AMR and CEMS to an access network are discussed in detail in [12], along with several other interfacing options. A graphical user interface provides the residents with detailed information in regards to energy consumption and pricing. Furthermore, advanced functionalities are enabled by the Energy Management Gateway (EMG) which is the integral device of a CEMS. It can, if needed, feature an interface for outbound communication using access networks. In-house an EMG connects to shiftable loads, like household appliances or air conditioning units, collects this flexible demand and can offer it to the DSO or an external Aggregator for balancing load and demand inside the grid. Price optimization, either from customer or grid side is also possible, as discussed in [11]. DERs, including but not limited to Combined Heating and Power (CHP), as well as photovoltaics are also part of a CEMS, i.e. are linked to the EMG. In order to achieve the desired resilience against faults and attacks a mitigation approach, using adaptive access networks, has been introduced into the Smart Grid context and is presented here. A strategy indented for its realization is formulated in Chapter VI. Figure 6 presents the comprehensive network adaption and reconfiguration approaches of SmartC2Net. On the left side

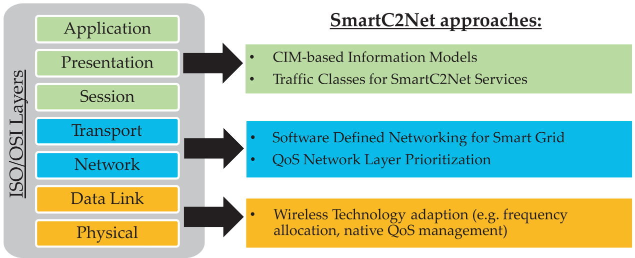

Fig. 6. Network Adaption and Reconfiguration Approaches

of the figure the seven ISO Open Systems Interconnection (OSI) model layers are shown, as the functionality provided by the inter-related control loop involves all of them for maximum effectiveness of the QoS parameter adjustment. The lower layers offer flexibility in terms of QoS like frequency allocation in case of wireless technologies and native adaptions that are part of the respective standards. The middle ISO / OSI layers utilize Software Defined Networking for network reconfiguration, outlined in greater detail in chapter 7, and QoS network layer prioritization. Meanwhile the SmartC2Net approach employs CIM-based information models and traffic classes for SmartC2Net services on the upper layers. Thereby a flexible and powerful method for delivering the required level of network adaptability is provided.

V. Low-Voltage Grid Operation and Control Concept

Assessing the functionalities, developed to address the challenges described in the preceding chapters, requires a multidisciplinary framework. In this work we focus on the AMR/CEMS case and how we will be able to demonstrate the concept of interacting outer energy and inner network control loops. Figure 5 shows one household in detail, outfitted with a HAN and its related gateway functionality, with a large set of other households found within one LV grid domain. Metering and control signals are exchanged between the controller and related system solution, illustrated by the boxes: Low Voltage Grid Controller (LVGC), Data Aggregator, Access Mngt. and QoS control. External to all communication paths, power is flowing through the electrical grid.

From the perspective of the Energy Management Gateway, the Access Management and QoS ensures that data between the Aggregator and the many household are efficiently managed. This entails possible control of QoS parameters, network interface and protocol parameter settings (e.g. changing information update rate) in order to provide reliable data exchange over the access network. Via estimates of the network conditions in combination with the dynamic properties of the information being collected, this device is able to reconfigure network QoS such that the data delivered to the Data Aggregator is reliable.

A. The Grid and Network Control Flow

Figure 7 illustrates the process of households interacting with the LVGC, Data Aggregator as well as with the Access and QoS Mngt. blocks. As illustrated in Figure 4, there are two control loops involved, 1) for the outer energy control loop and 2) to adapt the QoS over the network. The outer loop focuses on collecting and aggregating data for the LVGC (and higher to the MVGC) and distributing calculated individual setpoints to assets in the LV grid (based on a received setpoint from the MVGC). Concurrently to this energy control loop, the Access and QoS Mngt. block monitors the underlying Access Network and evaluates the conditions the energy loop works in. If they change, the blocks will adjust QoS settings and access configuration approaches ([13] presents the concept) (in worst case, shift network interface) to allow a problem free and reliable operation of the outer energy control loop. The Access and QoS Mngt. block also needs to address the different configurations of the households while ensuring that the interaction between the Aggregator/LVGC and the households are as transparent as possible, even in cases of performance degradations in the network.

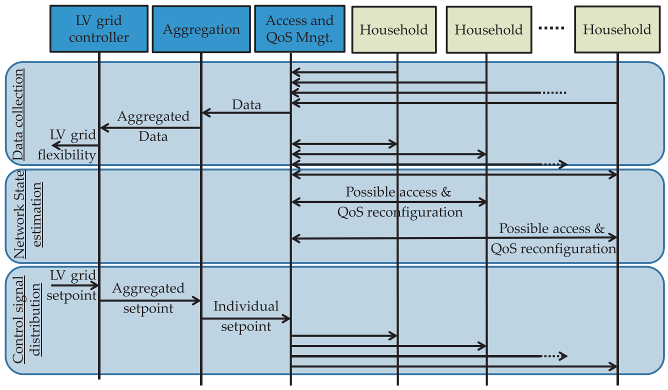

Fig. 7. High-Level Interaction of Functional Blocks and Households

B. Low-Voltage Management and Control Concept

Figure 7 [11] depicts the interaction as well as assumptions of the data aggregation and control framework, focusing on the ExtGen and AMR/CEMS functionality, as follows:

- Each asset (households) is able to receive individual setpoints for active and reactive power production.
- Available flexibilities (difference between nominal and actual power - positive and negative values) are transmitted from the assets (households) to the LVGC.
- Information of the amount of available active and reactive power production is transmitted to the LVGC.
- Trip status of assets (households, e.g. alarms or state changes) is transmitted to the LVGC.
- Smart meters send voltage measurements to the LVGC.
- The LVGC is able to receive setpoints from the MVGC with respect to reactive and active power.
- The LVGC is able to control active/reactive power by calculating setpoints to be dispatched to individual assets.
- The LVGC is able to maintain a certain voltage profile provided to it as reference from the MVGC.

Fulfilling these requirements means that the control structure will work as intended and will be able, via a signal from the Mid Voltage Grid Controller (MVGC), to behave within the desired parameters as needed. However, these requirements spawn additional requirements, concerning the underlying system and network, which are described in the following.

C. Aggregator Capabilities and Requirements

The parts related to the Aggregator are those functionalities which relate to the control aspects of aggregation and dispatching. A single estimate of the LV grid power consumption is constructed by aggregating power consumption from multiple sources, distributed in a LV grid topology. Thus functionality facilitating this is required. Additionally, setpoints from the LVGC are just single values and need to be dispatched logically to the assets in the LV grid domain. Therefore,

1) Data from assets (households) shall be aggregated prior to LVGC input.
2) The setpoints from the LVGC shall be dispatched to the individual assets (households).

This means, that from the surrounding control setup, certain requirements to the interface exist. The next step for the Access Manager is to ensure that the information needed is collected as well as distributed uniformly and reliably, while being transparent to the control process.

D. Access Manager and QoS Control Functionality

The access manager and QoS control ensure that the data elements and setpoints are efficiently collected and distributed over the network. Therefore, the functionality requirements here focus on the ability to:

- Measure and estimate QoS parameters (e.g. delay, packet loss, etc.) between individual households, Access Manager, QoS control box.
- Estimate the reliability of information from households.
- Transparently adapt the information exchange mechanisms used between households and the Aggregator.
- Adapt the communication to the different household gateway scenarios transparently to the Aggregator.
- Be aware of different network interfaces to the individual households while maintaining data's QoS on each of them, and the gateway interface possibilities.

A new aspect has been added to this set of functionalities, namely that which asserts the reliability of the data itself. Research in [14], [13] shows that dynamic data elements transported over a network, hereby imposing a delay, always have some chance of being outdated. The Access Manager and QoS control will be able to assert the reliability (in terms of a probability metric) and use this to 1) adapt its internal access schemes to obtain data, and 2) to provide additional metadata to the controller regarding the correctness of the information element. The controller will thereafter be able to put more or less faith into the data delivery.

E. Household Gateway Functionality

The following bullets list the requirements for the household gateway to be able to interact with the above system.

- Aggregation of household power flexibilities and consumption data.
- Accepting setpoints at household level (for internal dispatching between controllable household devices).
- Detection, filtering and forwarding of events to the LVGC (as a part of requirements to the LV control system to be able to maintain an overview of asset states).
- Accepting changes in subscription conditions from the Access Manager and QoS control.
- Ability to estimate the LVGC's setpoints reliability.
- Optionally, support for time synchronization and related functionalities for active/passive QoS estimations.

Some new features are related to the reliability as metadata, [14], and require additional gateway functionalities. Thus the challenge is how the Access Manager and QoS control, in combination with the many different configuration possibilities of the home gateway, can still maintain its functionality.

VI. Assessment Framework and Performance Evaluation

In order to evaluate the proposed solutions and the impact of the different configurations, different aspects shown by Figure 5 are simulated or emulated. In SmartC2Net the approach of setting up simulators and three testbeds, focusing on the before mentioned use cases, is taken for several reasons. Firstly a controlled, safe environment is needed to perform analysis on, secondly the interruption of end-users in a real environment is unwanted, and thirdly the strength of each of these tools can be used to provide a realistic view of the proposed solutions' performance. Here, as a case study, the AMR/CEMS is evaluated mainly by emulation via dedicated Software Defined Networking (SDN) while having realistic models of households made and evaluated from the experimental testbeds as input. In this way, the evaluation done in this work can focus on the communication aspects and reconfiguration of Quality of Service parameters, adapted to the requirements of the overlayed control system.

A. Emulation and testing framework

Entities of the use case and Smart Grid in need of information exchange are to be represented by their traffic patterns modeled after their behavior observed in the testbeds, i.e. on a data packet level. As different systems of the proposed Smart Grid architecture, i.e. monitoring, grid control and communication, are adaptive to each other as well as the overall system's states and needs, an abstraction layer for linking these sub-systems needs to be devised. We introduce in response to this requirement an approach novel to the realm of Smart Grids, which is based on SDN and aims to deliver higher utilization of networks without exhibiting adverse effects on QoS. Other goals include the lowering of costs due to standardized components while providing increased flexibility, e.g. for resilience to failures, and offering programmability of traffic flows. A separation of control and data plane are the technique's core principles. This facilitates the removal of network control from individual devices to dedicated controllers, typically running on standard computer hardware, which provide a central point for configuration and administration. The data plane remains inside the devices, e.g. switches, deployed in the filed while the forwarding decision is made on the controller level. This enables applications or devices to communicate their demands to the SDN controller which in turn reconfigures the network accordingly. Communication between controller and forwarding hardware, i.e. switches, is handled by the OpenFlow protocol. It is the predominant solution for this task, created by leading ICT vendors organized in the Open Networking Foundation. For example a household equipped with AMR/CEMS may offer multiple interfaces to access networks with different properties. GPRS is commonly used for AMR and a CEMS retrofitted at a later point in time could rely on its own communication technology, for instance Digital Subscriber Line (DSL). Controlled by SDN it is conceivable to automatically reroute Demand Side Management setpoints over GPRS to the CEMS in case DSL fails. Delivering setpoints by rerouting them over the AMR's gateway, if needed also prioritizing them over the AMR's metering data, enables the CEMS to stay operational. It could thus exploit Decentralized Energy Resources in the vicinity and therefore continue to balance demand and generation, which otherwise would be impossible as the original CEMS interface is unavailable. In the SDN testbed effects of other types of traffic, e.g. multimedia streaming services, on Smart Grid behavior with a focus on reliability will be studied. Furthermore an evaluation of the impact of various accidental as well as malicious failures on the overall system architecture is of crucial importance for the project and will thus be a central research target. Testing software is based on emulation setups with simplistic models for LVGC, Aggregator as well as household consumptions. Models of the network behavior are created based on data obtained by physical testbeds implementing important parts of the overall SmartC2Net architecture. The core part relating to the testing of the adaptive access management is implemented.

B. Key Performance Indicators

The system's ability to adapt to different network conditions, is mainly due to the control system's ability to follow given references. Clearly, some delimitations and model simplifications have to be made at this point, but in general the following parameters will be considered:

- Power deviation from reference, $P_{Loss}(t) = |P_{ref}(t) - P_{households}(t)|$
- Energy loss over time, $E_{loss} = \int P_{loss} dt$
- Network load in terms of generated traffic overhead
- Computational load at the Gateway and Access Manger

These performance indicators are hypothesised to be affected by the ability of the network to properly carry data over the network with certain quality attributes. Packet losses and delays are prone to happen during e.g. highly loaded network conditions, or due to poor link quality which will be assessed first, and thereafter the proposed adaptive mechanisms will be added and the efficiency of these mechanisms demonstrated.

VII. Conclusion and Outlook

The control loop and heterogeneous reference communication architecture proposed in this work constitute a novel approach for creating future ICT enabled energy grids. In the next project phases SmartC2Net will setup and validate testbeds physically and trough simulation, which are based on the presented architecture, for implementation of the described use cases. The control loop will be integrated, in an effort to achieve the project's goal of developing a resilient Smart Grid using heterogeneous ICT. Results evaluating the architecture presented in this paper will be presented in further works.

Acknowledgment

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References

[1] IEEE Std 2030-2011, *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*, 2011.

[2] IEC SMB Smart Grid Strategic Group (SG3), *IEC Smart Grid Standardization Roadmap*, Geneva, Switzerland, June 2010.

[3] CEN-CENELEC-ETSI Smart Grid Coordination Group, *Smart Grid Reference Architecture*, CEN/CENELEC/ETSI, November 2012.

[4] IEC 61850, *Communication networks and systems for power utility automation - Part 7-4: Basic communication structure - Compatible logical node classes and data object classes*, Geneva, Switzerland, 2010.

[5] IEC 62351, *Power system control and associated communications - Data and communication security - Part 1: Communication network and system security: Introduction to security issues*, Switzerland, 2007.

[6] IEC TC57/TR62357, *Power system control and associated communications: Reference architecture for object models, services and protocols*, Geneva, Switzerland, July 2003.

[7] IEC 61970, *Energy management system application program interface (EMS-API) - Part 301: Common Information Model (CIM) Ed. 2.0*, Geneva, Switzerland, April 2009.

[8] IEC 61968, *Application integration at electric utilities - System interfaces for distribution management - Part 11: Common information model (CIM) extensions for distribution*, Geneva, Switzerland, July 2010.

[9] C. Wietfeld, C. Müller, J. Schmutzler, S. Fries, A. Heidenreich, and H.-J. Hof, "ICT Reference Architecture Design based on Requirements for Future Energy Marketplaces," in *Proceedings of the* 1^{st} *IEEE International Conference on Smart Grid Communications (SmartGridComm).* Gaithersburg, Maryland, USA: IEEE, October 2010, pp. 315–320.

[10] BMWi - Federal Ministry of Economics and Technology. (2008, January) E-DeMa - Development and Demonstration of Decentralized Integrated Energy Systems on the Way Towards the E-Energy Marketplace of the Future. [Online]. Available: http://www.e-dema.de

[11] G. Dondossola *et al.*, "SmartC2Net Use Cases, Preliminary Architecture and Business Drivers," *Technical Report, FP7 Project SmartC2Net*, September 2013. [Online]. Available: http://smartc2net.eu/

[12] C. Hägerling *et al.*, "SmartC2Net Communication Architecture and Interfaces," *Technical Report, FP7 Project SmartC2Net*, September 2013. [Online]. Available: http://smartc2net.eu/

[13] A. Shawky, R. Olsen, J. Pedersen, and H. Schwefel, "Network aware dynamic context subscription management," *Computer Networks*, 2013.

[14] M. Bøgsted, R. L. Olsen, and H.-P. Schwefel, "Probabilistic Models for Access Strategies to Dynamic Information Elements," *Performance Evaluation*, vol. 67, no. 1, pp. 43–60, 2010.

[15] European Commission. (2012, December) FP7 Project SmartC2Net - Smart Control of Energy Distribution Grids over Heterogeneous Communication Networks. [Online]. Available: http://www.smartc2net.eu