ADVANTAGE

Advanced Communications and Information processing in smart grid systems

MARIE CURIE ACTIONS -7th FRAMEWORK PROGRAMME

ADVanced communicAtions and iNformaTion processing in smArt Grid systems

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WP1 D.1.1

State of the Art in Smart Homes and Definition of Application Scenarios and Research Problems

Abstract:	This deliverable will explore the initial literature study and research directions for WP1 of the ADVANTAGE project. This WP will consider how communications within the home can enable future smart grid systems. The first topic to be studied relates to how wireless technology can support communication between electronic devices within the home and to the power supplier – so called machine-to-machine communications. The second topic relates to modelling and control of heating systems within the home, so they can be integrated effectively into the smart grid network.
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1 INTRODUCTION TO WORK PACKAGE ONE: SMART HOMES

This workpackage will address two fundamental problems of Smart home integration into the Smart grid system:

1) Communication Technologies (Alexsandar Mastilovic, ESR1):

This part will address the problem of connecting massive amount of devices such as smart meters as well as communication enabled home appliances to available wireless communication infrastructure such as 4G/5G mobile celullar systems. The emphasis will be on upcoming Machine-to-Machine (M2M) communication service to be delivered by mobile celullar operators.

2) Modelling, Monitoring and Control of significant low-voltage grid users (Pierre Vogler-Finck, ESR2):

This part will address the problem of modelling and controling specific individual low-voltage grid users. The emphasis will be on individual home and building heating systems and their modeling and control compatible with upcoming Smart grid concepts and interfaces towards distribution network.

The structure of the document is as follows. We provide a background on both above mentioned research fields by providing focused overview of the current state of the art, listing important literature findings and indicating major research trends and identifying relevant research problems. Then, we provide an overview of selected research questions to be addressed by the workpackage participants throughout the course of the ADVANTAGE project.

2. SMART HOME ENVIRONMENT ADAPTATION

This part of the workpackage activities is aimed at developing novel solutions across the 4G/5G protocol stack addressing massive connectivity of small devices such as sensors that occasionally send short packets towards the infrastructure such as mobile cellular systems. The research in this part will be hosted by University of Novi Sad (Serbia) as part of the ADVANTAGE ITN project.

The proposed research will focus on communications technologies which are possible solutions for Smart Grid applications in the home environment or so-called Home Area Networks (HANs). In the initial phase, the focus will be on wireless communications and protocols where we will provide an overview of existing and upcoming technologies such as: ZigBee, XBee, 6LoWPAN, Bluetooth, WiFi but also cellular mobile network technologies as 3G (UMTS, WCDMA), 4G (LTE, LTE Advanced) and future 5G networks, which will be designed to support applications for Internet of Things and its subsystems as Smart Grid, respecting all future functions defined in IPv6 protocol stack for higher network layer and practical implementations. [5G2014]

2.1 COMMUNICATION TECHNOLOGIES OVERVIEW

For implementation of communication networks for the Smart Home and to support Smart Grid systems in general, there are few dominant concepts and communication technologies to reach this target.

All possible solutions for communications system could be organized into two groups:

- wired communications systems,
- wireless communications systems.

Wired communication technologies are divided into two groups depending on the form of the transmission media:

- copper-based infrastructure communications systems;
- fiber-optics-based infrastructure communications systems.

Wireless communication technologies are divided into two groups depending on the system architecture:

- non-cellular wireless communication systems,
- cellular wireless communication systems.

Wired communications have some advantages comparing to wireless communications, but this type of systems are infrastructure dependent and they could be used only on the locations with existing communication lines. This type of the system does not allow mobility and it is not a practical system for operation over short periods of time. On other side, this type of system have the advantage in security and operation is much more reliable compared to wireless systems. Implementation of wired communication systems are possible in locations where the required infrastructure is available. Consequently, it is more applicable for some part of Smart Grid systems as Distribution Network and Production Network, where some type of cable infrastructure and additional mechanical parts for installation are already available. Some competitive solutions for supporting Smart Grid functionalities are fiber-optics communication lines (very often already co-existing with Distribution Power Line for monitoring and management) and Power Line Communications (PLC) with some technical constraints: noise, interference and attenuation performance are very critical for long-distance lines and there is a major limitation to data transfer crossing transformer equipment.

Wireless communication systems are better options for more dynamic services and to support mobility. This type of communication system is infrastructure independent and they could be implemented in any location, where it is necessary and where wireless service is available. Wireless communications has some critical issues and challenges for the future use. One of these is to ensure required Quality-of -Service (QoS) for application and also security and privacy issues. Introducing the Internet-of-Things concept and some others concepts as Big Data, Smart Grid, Smart Cities, will utilice the TCP/IP stack and protocols based on IP version 6. There is a popular trend in telecommunications world to converge all technologies and protocols into one super-system for serving very different type of service and users using one common communications infrastructure with the same protocols. Examples include using the same addressing scheme as IPv6 on the Network Layer of the ISO/OSI model and advanced Multiple Access concepts and modulation formats on lower Layers of the ISO/OSI model. The development of communications technologies has given an advantage to wireless communications trying to reach QoS performance and security level of wired communication, but at the same time improving target to avoid the disadvantages of non-deterministic processes in communication channel (interference, noise, antenna design, etc.) and user locations (fixed and mobile users/devices, including human and machine users/devices). This trend and the defined challenges will be the focus of this research study, and some wireless solutions will be developed. Existing wireless non-cellular solutions in LAN and HAN and also the wireless cellular solutions 2G, 3G, LTE and LTE-A (Release 12) will be presented and compared, as the beginning for future work. [LTEA2013]

One perspective for future needs is the idea to take key existing Wireless technologies and to make them part of new wide area 5G Wireless cellular system. The 5G cellular wireless network is envisioned to overcome the challenges of existing cellular networks with higher data rates, low latency, less energy consumption and improved cumulative end-to-end performance for users and services. 5G networks will adopt multi-tier environments consisting of macro-cells, small-cells, different types of relays and gateways, but also pico-cells and femto-cells for Home Area Network systems to support Smart Home services.

The following challenges should be tackled by future research to reach 5G expectations [5G2014]:

- at least 1000 times higher mobile data volume per unit area, compared to existing 3G traffic,
- at least 100 times higher numbers of connecting devices (human-centric and machine devices), compared to existing 3G devices;
- at least 10 times longer battery life to ensure independent and autonomous sensors and other non-human-centric devices, comparing to battery life of existing human-centric devices as smartphones
- at least 10 Gbps maximum throughput, for the most resource-hungry devices and applications.

Future research work will be focused into following topics to reach defined targets written upper:

- Channel Allocation
- Power Control
- Cell Association
- Load Balancing and Data Routing
- Security and Privacy

Following the defined targets, it would be necessary to analyze some of topics together because their correlation, for example Power Control and Cell Association, where a joint solution would be called the Cell Association and power Control Joint approach (CAPC). The major challenge for 5G system development and standardization would be interference management because heterogeneous and multi-tier and planned multi radio access technologies (Multi RAT) coexistence will be crucial. All these wireless technologies and carriers will be placed in the same spectrum intervals, organized in frequency bands with the option of carrier aggregation and some other advanced techniques. [5G2014]

2.2 Smart Home Communications: State-of-the-Art and Beyond

Regarding to the expected 5G technical specification, the Smart Home environment should ensure services such as Smart Metering, Video Surveillance, multimedia services and Internet access for the home, but also to ensure collection of anonymised statistical data about consumers habits and behavior without security and privacy issues. For these target services, it is possible to use some of existing technologies for traffic/data aggregation, or directly sending collected data to servers using 5G access to the Internet.

With respect to the recommended 5G architecture of the system, the Home Area Network will be organized as part of 5G networks with local signal coverage using traditional macro-cells, but also small-cell, pico-cell and femto-cells, and also using Multi RAT which will allow existence of traditional wireless solutions such as the IEEE 802.11 WiFi family of standards (in version a, b, g, n, ac, ...), Bluetooth (all versions including version 4 and future enhancements), IEEE 802.15.x Wireless Personal Area Network (WPAN) family (IEEE 802.15.4. based protocols: 6LoWPAN, ZigBee, XBee, Z-Wave; IEEE 802.15.1. based: Bluetooth, etc.).

In this environment, it is very critical to avoid interference issues between different types of device in very heterogeneous system. Especially, it is very important to develop power management algorithms to efficiently avoid interference between different tiers of devices, such as for example are HeNB (Home eNode B) and MeNB (Macro eNode B) devices. The huge number of devices expected in the system in future motivates us to try to develop decentralized and distributed algorithm to control and manage transmitting power. This problem can be defined as a convex optimization problem, with the goal to minimize interference power to the device with expected constraints to ensure proper level of QoS for each application in the system. [CONX2004]

The target types of links in multi-tier networks are:

- MeNB-to-UE
- MeNB-to-HeNB/MTCG
- MeNB-to-MTCD
- HeNB/MTCG-to-MTCD
- MTCD-to-MTCD (D2D communications)

where first four links are infrastructure and architecture dependent, and the last one is a peer-to-peer direct link between local devices. The UE is the general User Equipment, usually human-centric device, the MTCG is a Machine Type Communications Gateway, usually some type of aggregation access point, sometimes called small-cell or other types of lower level cells, and the MTCD is the Machine Type Communications Device, associated as HeNB or MeNB, but usually a non-human-centric device in the system. [LTEAM2M2012]

Simulations and analytical formal calculations will be developed for different architectures of the system, as following:

- Direct Transmission (without MTCG, mixing of H2H and M2M devices)
- Multi-Hop Transmission (with MTCG, in multi-tier environment)
- Peer-to-Peer Transmission (D2D direct communications, with supervising of the system)

The focus of research will address Distributed Uplink Power Control for Small-Cells trying to minimize interference situations to ensure a high level of QoS for all devices depending on the application. Propagation conditions in the radio channel will be analyzed respecting all conditions and constraints such as path-loss, shadowing and multipath fading issues, which are well-known radio channel limitations and very dependent on the carrier frequency.

Also, the huge number of existing devices in future systems motivates us to check all possibilities to improve Multiple Access schemes, improving existing efficient algorithms based on the ALOHA protocol [CRDSA2007] and its variants [OPTCRDSA2011]. To reach the performance target, new signal processing techniques such as Multi-Packet Reception (MPR) and Packet Capture (PC) will be evaluated to improve the efficiency level of existing ALOHA protocols, respecting new environments and requirements.

3. Modelling Energy Consumption and Designing Optimal Control for Low-Voltage Grid

This part of workpackage activities is aimed at developing a smart-grid controller for heat pumps in buildings. The research in this part will be hosted by Neogrid Technologies ApS in Aalborg (Denmark) as part of the ADVANTAGE ITN project.

The research will proceed in several steps. To start with, the modelling of thermal dynamics of a building will be studied. This step will consist in finding relevant models and associated identification methodology to allow fitting a consistent model to a building using past measurement data. At this level, another aim is to extract user disturbance based upon past data and propose a model for it.

In a second part, a stochastic model predictive controller will be developed for the individual heat-pump. This controller will act according to various strategies such as minimising energy consumption, cost of heating or maximising flexibility based upon comfort requirements and system model.

Then, a virtual power plant controller will be investigated. The aim of this controller will be to coordinate heat pumps in a common pool in order to enhance the value of the portfolio and benefits to the power system.

Lastly, the above-mentioned control algorithms will be implemented and tested on a set of real households to ensure practicability of the solution.

3.1 Modelling Building Heat Dynamics

Model of building heat dynamics with different structures and complexities were developed in the literature. Most of the developments found in the literature are made using a grey-box model approach. Starting at fundamental level, the building thermal dynamics are described mathematically using differential equations, with an example to be found in [MHDB00]. These 'low level' models require a deep knowledge of the building structure and are more appropriate for building simulation tools than for application to control. This is why 'high level' models that model the building using less prior knowledge are needed.

Higher level models were developed by Peder Bacher who conveyed extensive research on the modelling of building heat dynamics as part of his PhD work [PBPT12]. This includes a methodology for maximum likelihood estimation of different grey-box models for describing the heat dynamics of a building which was described in [ISMH11]. However, the identification made using those methods was not affected by user behaviour as the building was empty, so that this methodology must be extended to occupied buildings with active users.

In many case, building thermal models rely upon detailed computer simulation of a building to generate the model. Examples with application to real buildings may be found in the OptiControl project at ETHZ (http://www.opticontrol.ethz.ch/) which used EnergyPlus software [EPCN01] to simulate the building. Its results are summarized in reports [UWOF10] for the preliminary results part and [UWOF13] for the more applied part. Another example from the literature may be found in [BTMR02] where the authors used a high order model assumed to be realistic to generate the data that they tried model reduction so as to fit data with lower order models that were more appropriate for control. Those results provide a good basis for building models from simulations to identify the most relevant model structures. However, the challenge to be then faced is to make the transition from simulation-based modelling to “historical data”–based modelling.

Other approaches such as lumped models are found in the literature, for example in [LTHM13]. In this case, a model reduction is operated so that a single house model represents the aggregated state of a set of houses. This approach has the benefit to be very simple but does quite limit the potential for optimisation at individual level.

3.2 Stochastic Model Predictive Control of Individual Heating

The application of model predictive control (MPC) to the problem of building heating has been studied rather intensively over the last five years. As this relies rather heavily on optimisation methods, it is important to make use of existing robust tools such as the YALMIP interface [YALM04] from MATLAB [MATL14] to different solvers which is one of the references in the field.

Rasmus Halvgaard has been working on the topic as part of his PhD research at DTU [RHPT14] and has developed a variety of models for individual components to be controlled, including heat-pumps in individual buildings. However, this work has been rather theoretical and basics-oriented so that they are to be used as an introduction to MPC in the field of smart-grids.

Another team at EPFL has been conveying extensive research on optimisation of heating in buildings through MPC, with different strategies. For example, [RPED10] studies how to modulate heating loads so as to reduce peak load electricity demand in a building with MPC and real-time pricing.

The OptiControl project (already mentioned above, [UWOF10], [UWOF13]) has also come up with an MPC control scheme in that was applied to a real world office building in north-west Switzerland.

Stochastic model predictive control (SMPC) is starting to be investigated, such as in [EEBC10] where the stochastic aspect lies in the weather data. Frauke Oldenwurtel who was part of this work has then written her PhD thesis on stochastic MPC for building heating [FOPT11] in 2011. The disturbances studied in this work are weather fluctuations compared to prediction and internal gains due to user behaviour. This seems to be the most advanced work in the field of SMPC-based heating to our current knowledge, and will be used as a basis for building the individual control scheme.

3.3 Virtual Power Plant Control

Management of flexible power loads is being investigated in the TotalFLEX project (http://www.totalflex.dk/) to which Neogrid is participating. This project is building around the central theoretical framework of Flex-Objects which aggregation and dispatch is described in [ADFO12].

The virtual power plant approach relies on coordination of the control implemented over a set of distributed assets. Such coordination has been studied rather intensively in recent years, as it is one of the basics of the smart-grid.

The automation and control department at Aalborg University has been one of the research institutes where particular focus was made on this topic. In particular, Morten Juelsgaard has been working on portfolio optimisation for providing services to the power grid as part of his PhD research at Aalborg University [MJPT14]. Benjamin Biegel [BBPT14] has also been working upon the management of distributed energy resources in distribution grids. Both works provide a theoretical framework that I will use to support my future work.

Another methodology for control of smart-grid assets was developed by Vincent Bakker as part of his PhD research at the University of Twente [VBPT11] is expected to provide a good structured starting point in designing the practical control scheme, while diversifying from a pure 'Aalborg University approach'.

Work by Navarro-Espinosa and Mancarella on the effect of heat-pumps operation upon low voltage grids in [PMAI14] suggest that there is interest in understanding how the control scheme might affect the distribution grid. Then, the study of the power system dynamics may help to optimise the setup by extending the control strategies built.

Services from smart-grid control of heat pumps to the local grid are presented in [IHPD12] where benefits in terms of grid extension savings are demonstrated, showing that a good coordination may help decreasing distribution costs by up to 10% whereas a bad coordination could increase those costs by up to 70%.

4. Key Research Objectives for Work Package

The research objectives of WP1 in the ADVANTAGE project will be organized into two directions.

The first research direction will be focused on developing and/or improving algorithms to increase communications systems efficiency and throughput to be able to ensure efficient and scalable M2M services. The second research direction will develop novel solutions for practical implementation of smart home enabled system of heat pumps and their integration into Smart Grid system.

Main research objectives for algorithms and/or protocols development:

- multiple access protocol solutions for M2M services over LTE small cell networks in multi-tier environment;
- the role of small cell in supporting identified M2M services;
- uplink communications models in 5G multi-tier heterogeneous access networks focusing on uplink power control, cell association, resource allocation and scheduling and multiple access control as enablers for establishing low-delay and ultra-reliable service reliability.

Main research objectives for hardware and practical system development:

- Designing a controller to optimise heating from a heat-pump at the individual building level.
- Designing a control scheme for pools of heat-pumps so as to reach the virtual power plant objectives
- Demonstrating the practicability of the solution on a set of real houses

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