AN INNOVATIVE SOLUTION SUSTAINING SCADA-TO-REMOTE TERMINAL UNIT G3-PLC CONNECTIVITY OVER DYNAMIC GRID TOPOLOGIES

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ABSTRACT

SOGRID is an innovative experimental project, led in Toulouse by Enedis, gathering academia and industry, ranging from silicon manufacturers to system integrators and end-users, active in the smart grid business. Enedis and EDF R&D committed their expertise to solve the technical challenges inherent to the project's aim: develop a full IPv6 G3-PLC telecommunication infrastructure covering both medium voltage (MV) and low voltage (LV) grids to support smart grid and smart metering use cases. One main innovation is presented throughout this paper: sustainability of G3-PLC connectivity over the variable topology of the MV grid using a real-time handover mechanism.

INTRODUCTION

Power line communication (PLC) technologies have been widely deployed for the purpose of in-home multimedia applications or within advanced metering infrastructures (AMI), for example. For smart metering use cases, major utilities favour narrowband PLC technologies operating in the 9-500 kHz frequency range (as opposed to broadband PLC technologies typically operating in the 1,6-30 MHz range), as they enable kilometre-wise coverage at a reasonable cost.

In the SOGRID project, G3-PLC has been used for both LV communications in the Neighbourhood Area Network (NAN) using the CENELEC A frequency bandplan (35-90 kHz according to [1]) and MV communications in the Field Area Network (FAN) using the FCC frequency bandplan (154-487 kHz according to [1]). In the LV grid, G3-PLC is used to establish connectivity between smart meters and a NAN border router also embedding data concentration features for the aggregation of daily meter read-outs, or directly with the head-end system for end-to-end IPv6 communications (instead of using public cellular networks). In the MV grid, G3-PLC is used to backhaul all communications between data concentrators and the Metering Data Management System (MDMS), and to establish connectivity between Remote Terminal Units (RTU) interfaced with field components (sensors or actuators such as MV switch gear) and the Supervisory Control And Data Acquisition (SCADA) system, using a FAN border router which relays the information flow to the head end system over a classical Wide Area Network (WAN) connection. The general architectural concept is depicted in figure 1. Section I presents the application of this concept in the SOGRID project.

In this paper, we will focus on one specific aspect of deploying a G3-PLC FAN over a MV grid, which topology can vary in time. Indeed, as shown in figure 1, the FAN is composed of several adjacent "backbones" which instantaneous logical topology is directly correlated to the grid's physical topology. In section II, we discuss technical constraints being encountered when deploying G3-PLC devices in a dynamic MV grid for applications requiring highly available telecommunication media. Then, section III introduces the technical solution developed and tested in the SOGRID project as well as future works. Finally, conclusions are provided in the last section of the paper.

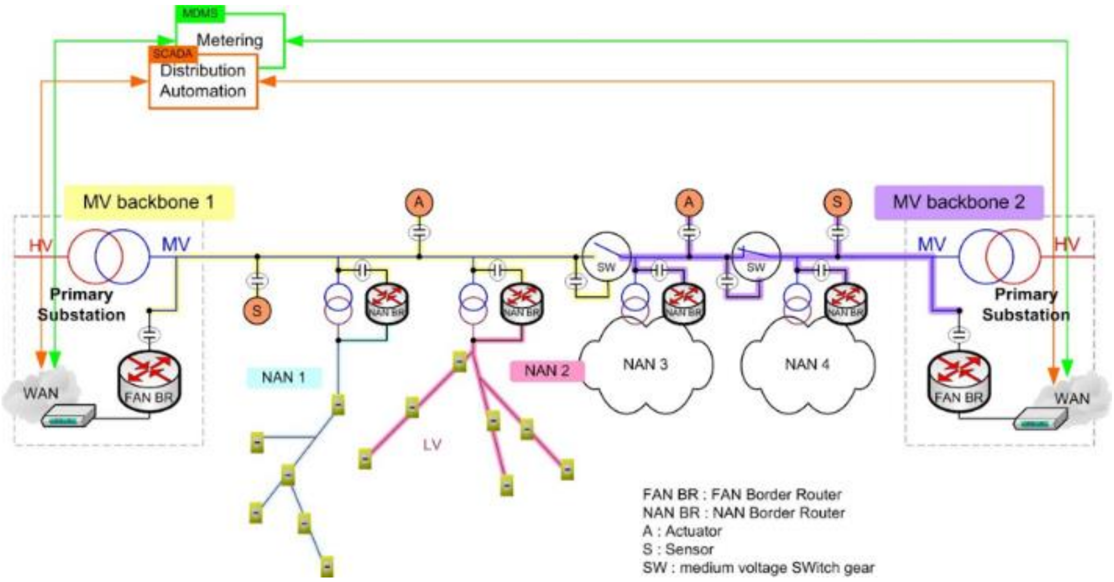

Figure 1: Conceptual architecture of the SOGRID telecommunication infrastructure

I. THE SOGRID PROJECT

Ten partners from academia and industry were involved in the SOGRID project which successfully ended in 2016 and consisted in developing a full IPv6 G3-PLC telecommunication infrastructure covering both MV and LV grids to allow for multiple smart grid and smart metering use cases. SOGRID was deployed in Toulouse and interfaced with Enedis's existing SCADA for grid automation.

Use cases and services

The smart grid and smart metering use cases implemented in the project are the following:

- MV and LV state estimation (using voltage and current sensors in the MV grid and smart meters in the LV grid),
- Ahead optimization and control of the MV grid topology,
- MV fault location,
- LV smart metering services (including backhauling of the metering data using G3-PLC over MV),
- Direct IPv6 communication to LV smart meters,
- Supervision and management of the G3-PLC telecommunication network.

For the first time, different services specific to heterogeneous use cases related to MV and LV smart grid, smart metering and telecommunications management (using different application protocols: IEC 60870-5-104 [2], DLMS/COSEM [3] or CoAP [4]) are carried over a same G3-PLC-based multi-service telecommunication infrastructure.

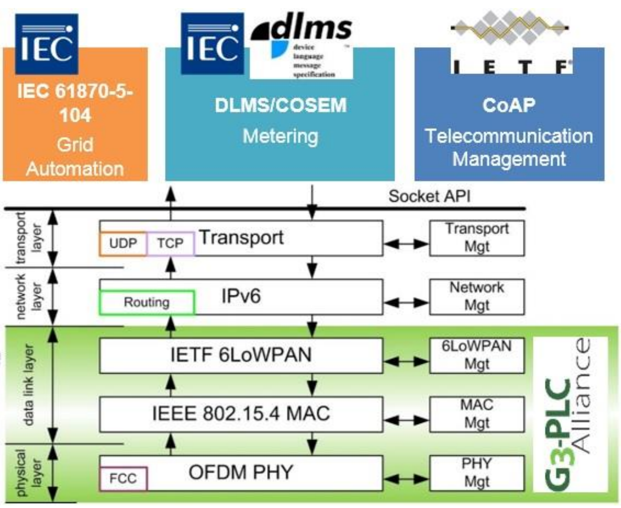

Figure 2: MV G3-PLC communication profile

Main technical developments

In addition to the already well-mastered LV G3-PLC-based AMI, involving data concentrators and smart meters (although specific LV equipment was developed for the SOGRID project), the targeted use cases would not have been achieved without addressing multiple challenges, starting with the design of a secure and resilient MV G3-PLC network. This was accomplished by the design of four main components:

- Dedicated G3-PLC chip (embedded in each G3-PLC device), implementing the MV G3-PLC communication profile (see figure 2),
- MV PLC couplers optimised for the G3-PLC FCC bandplan (154-487 kHz),
- "SA COMUT" RTU, namely enabling connectivity between MV and LV G3-PLC networks (FAN and NAN respectively). In figure 1, it ensures NAN border router functionalities together with the data concentrator installed on LV side.
- MV G3-PLC coordinator for installation in primary substations, allowing for optimised G3-PLC communications over several MV feeders. In figure 1, this piece of equipment corresponds to the FAN border router.

As far as MV and LV state estimation is concerned, new MV voltage and current sensors were developed, and additional computing capabilities were made available in "SA COMUT" RTUs and data concentrators. Furthermore, algorithms relying on these distributed intelligence and embedded processing capabilities can only operate through the implementation of an efficient and accurate equipment time synchronization mechanism, also developed within the project.
Finally, different existing or specifically-developed head end systems enabling MDMS, SCADA or telecommunications management were integrated in the system.
The remainder of this paper is dedicated to one key aspect to allow for the deployment of a secure and resilient MV G3-PLC network: sustain G3-PLC connectivity over a variable grid topology.

II. TECHNICAL CONSTRAINTS

Offering a highly available communication medium is a must for some of the smart grid's most critical use cases, such as grid reconfiguration or fault location. Loss of connectivity could severely entail the operation of the grid and even lead to outages.
Although the highest level of resiliency can only be ensured using redundant telecommunication links, G3-PLC connectivity (here, when operated over MV) can be improved by performing some adaptations to the communication profiles taking into account the technical constraints outlined in this section.

MV grid topology aspects

In France, the MV grid may be subject to frequent topology changes which can be triggered due to unexpected events (fault and fault recovery) or planned occasional events (such as grid reconfiguration for maintenance purposes). When using PLC technologies, opening a switch also interrupts the propagation channel of the PLC signal. This change in the physical topology of the grid will necessarily modify the logical topology of the PLC network. In figure 1, for example, a PLC device coupled to the MV grid may belong to "MV backbone 1" or "MV backbone 2" portions of the G3-PLC FAN when medium voltage switch gear "SW" is operated.

G3-PLC aspects

As already implicitly expressed beforehand, there is a notion of instantaneous affiliation between a G3-PLC device and a G3-PLC network, also called a G3-PLC PAN (Personal Area Network, a term inherited from IEEE 802.15.4 [5]). According to [1], a G3-PLC PAN consists of multiple PAN devices (standard communication nodes) and one PAN coordinator, which manages the network. The PAN coordinator is responsible for starting the G3-PLC PAN and enables PAN devices to join the network it manages. In addition, joining is done in a secured fashion, as an authentication protocol is systematically run between an authentication server and a newly joining PAN device, which ineluctably adds delay.

Once a PAN device successfully joined a G3-PLC PAN (it performs an "association procedure" [1]), this PAN device is "associated" to the PAN. The association procedure is also the opportunity to distribute all PAN-specific parameters needed by the PAN device to communicate within the PAN such as the MAC address of the coordinator or the local ciphering key. Association is also followed by IPv6 information advertisements using Neighbour Discovery (ND) according to RFC 4861 [6] and RFC 6775 [7].

By nature, G3-PLC leads to multi-hop topologies as routing protocols are used to propagate data over long distances (multiple kilometres of MV lines), adding some more latency into the communication between two distant devices.

Finally, G3-PLC belongs to a family of protocols qualified as constrained protocols, i.e. protocols requiring low memory and computing resources but also offering low data rates. For instance, constrained protocols are not to be used as classical high data rate technologies; application layers may implement specific strategies to save network resources.

III. THE G3-PLC HANDOVER MECHANISM

When analysing the issues introduced by MV grid dynamics on G3-PLC communications from a telecommunication architecture point of view, the general problem to solve is very close to a communication node mobility problem. Indeed, each G3-PLC PAN device may not be reachable anymore through the G3-PLC PAN it initially joined ("MV backbone 1" or "MV backbone 2" in figure 1, for example), and therefore, it has to discover its new environment and carry out a new association procedure with the newly available G3-PLC PAN. An example of the goal to achieve is illustrated in figure 3:

- At instant $t = t_0$, the grid operates normally (SW2 is open); PAN device A is associated with "MV backbone 1" through PAN coordinator 1 and PAN device B is associated with "MV backbone 2" through PAN coordinator 2.
- At instant $t = t_1$, an event occurs: SW3 opens. PAN device B instantaneously losses connectivity with PAN coordinator 2.
- At instant $t = t_2$, SW2 closes. PAN device B may be reached through PAN coordinator 1 (possibly using PAN device A as intermediate node thanks to G3-PLC routing capabilities).

Designing such a mechanism while taking into account all other technical constraints listed in section II, and ensuring high availability (recovery duration $t_2 - t_1$ within seconds), is challenging.

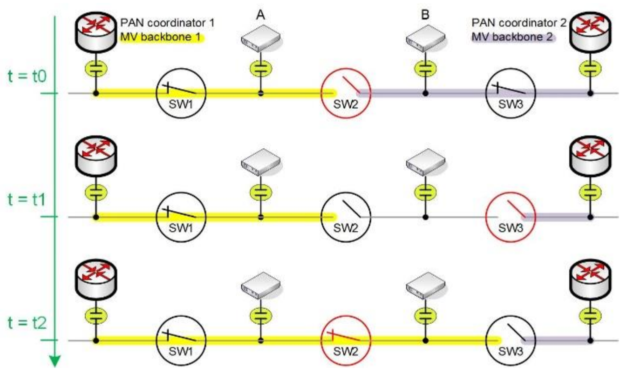

Figure 3: Grid dynamics and G3-PLC network topology

A typical solution used by cellular technologies such as Global System for Mobile communications (GSM) consists in covering an extended geographical area with multiple adjacent base stations covering local areas also known as "cells". A mobile device is always aware of the base stations in its vicinity as they periodically send cell-specific data ("beacons"). Hence, a mobile node is always able to determine the best cell to join based on permanent assessment of performance criteria. When a device decides to leave the cell it is currently attached to for a cell providing better connectivity, the mobile device performs "handover".

Periodic signalling may also be applied to G3-PLC, but due to its constrained nature, this mechanism would be network resource demanding, as two subsequent beacons would be spaced by the desired recovery duration $t_2 - t_1$. Nevertheless different strategies may be implemented to allow G3-PLC PAN devices to perform handover between adjacent PANs. The solution proposed in this paper is based on three steps:

- Early provisioning
- MV grid reconfiguration detection
- Joining a new PAN after MV grid reconfiguration

The rationale and technical details of these three steps are detailed below.

Early provisioning

As reminded in section II, the association procedure and

ND are generating bidirectional data exchanges between a PAN device and a PAN coordinator (possibly using intermediate nodes when multi-hop communication is required) for authentication and local information advertisement purposes, as to establish connectivity. Systematically performing this lengthy procedure for each PAN device having undergone link loss, and involving external components to the G3-PLC PAN such as a remote authentication server, would become too much bandwidth and time-consuming.

Not to affect the overall G3-PLC network performance and allow an acceptable recovery duration, it is proposed to provision all PAN devices with additional data needed to communicate within adjacent G3-PLC PANs from their initial association procedure. As a result, a PAN device joining a G3-PLC PAN for the first time will be provided with appropriate configuration information and credentials related to all alternate PANs it may associate with.

This early provisioning phase also implies that the telecommunications management system must be aware of all possible combinations that may occur, based on the finite number of grid configurations possibly encountered, as depicted in figure 4:

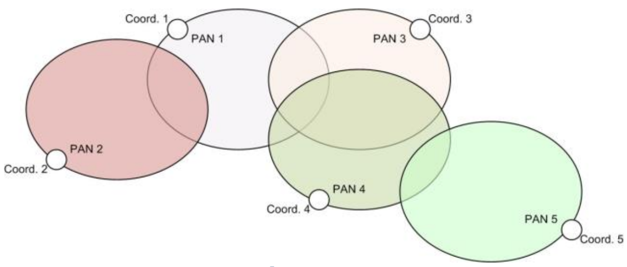

Figure 4: Adjacent G3-PLC PANs

Different situations shown in figure 4 can be identified, for example:

- PAN devices of PAN 1 may also join PAN 2, PAN 3 and PAN 4.
- PAN devices of PAN 2 may also join PAN 1.

They can be mapped into simple telecommunications management rules:

- PAN coordinator 1 advertises information related to alternate PANs 2, 3 and 4.
- PAN coordinator 2 advertises information related to alternate PAN 1.

All alternate PAN information received by a PAN device is locally stored in dedicated tables.

MV grid reconfiguration detection

The main challenge to address resides in the quick detection of MV grid reconfiguration. Yet, frequent periodic signalling as carried out in cellular networks has been excluded not to jeopardize network performances. A good trade-off consists in event-based aperiodic signals sent by G3-PLC PAN coordinators of a same area when grid reconfiguration is suspected (in case of too many communication errors, routing errors, loss of mains detection, etc.). In the SOGRID project this signal has been implemented by defining a new ICMP [8] message type: "MV Grid Event".

In addition, G3-PLC PAN devices do not question their current association unless communication failure over an extended period of time is detected. They also ignore data frames received from other PANs. Nevertheless, it is proposed to benefit from an untapped lower layer mechanism described in the G3-PLC specifications [1]. In fact, when a PAN device receives a frame stemming from an alternate PAN (i.e. a PAN it is not currently associated with), it triggers a dedicated MAC layer primitive containing an ALTERNATE_PAN_ID flag together with the PAN identifier (PAN ID) and the MAC address of the frame's originator. Thus, a PAN device can occasionally question its current association.

In this way, when referring to figure 4, a suspected MV grid reconfiguration detected by PAN coordinator 1 will lead to the generation of a MV Grid Event message by PAN coordinators 1, 2, 3, and 4.

On one hand, PAN devices that were not affected by a physical topology change of the MV grid will just forward the MV Grid Event message received without further actions.

On the other hand, PAN devices having incurred a physical topology change will not process the MV Grid Event message as a data frame but they will be notified that a frame from an alternate PAN was received. This will trigger handover to the alternate PAN detected as explained in the following subsection.

Note that false-positive detection of a possible MV grid reconfiguration is painless as the logical topology of the G3-PLC network will remain unchanged.

Joining a new PAN after MV grid reconfiguration

Upon reception of an ALTERNATE_PAN_ID flag, a PAN device's higher layers trigger handover:

- Step 1: for security reasons, the PAN ID contained in the generated MAC layer primitive is compared with the alternate PAN information stored locally. If a match is found, the G3-PLC modem is automatically reconfigured with all early-provisioned configuration information related to the newly detected PAN, including the local ciphering key.
- Step 2: the PAN device notifies its new PAN coordinator using a NOTIFICATION message (extension to the G3-PLC 6LoWPAN adaptation layer specifications [1]) ciphered using the local ciphering key.
- Step 3: upon reception of the NOTIFICATION message, the PAN coordinator acknowledges the presence of the PAN device by sending a dedicated and ciphered ACK message (extension to the G3-PLC 6LoWPAN adaptation layer specifications [1])
- Step 4: upon reception of the ACK message, the PAN device is operational in its new PAN. Then, it generates a new MV Grid Event message

intended for neighbour PAN devices so they can also recover connectivity throughout the new PAN.

As a result, repeating this lightweight notification and acknowledgement pattern allows all PAN devices affected by MV grid reconfiguration to progressively perform handover as depicted in figure 5.

Limitations and further improvements

Field testing in the SOGRID project has shown that the handover mechanism was operational on a simple MV grid reconfiguration, although some stability issues were encountered in areas were crosstalk between different G3-PLC PANs was significant. However, crosstalk issues due to the immediate proximity of different power cables belonging to separate MV grid sections (corresponding to the propagation channels for different G3-PLC PANs) could be easily solved by adding a signal-to-noise ratio threshold as to better control the generation of the ALTERNATE_PAN_ID flag, triggering handover.

CONCLUSION

This paper highlighted how one of the main technical challenges encountered in the SOGRID project was addressed. After a presentation of the general context of the project and related technical constraints, this paper presented how to enhance the G3-PLC technology to make it compatible with both real-time application requirements and grid topology changes. The custom-designed handover concept was successfully tested in the field while some minor improvements are still needed. It is to be noted that MAC and IPv6 addressing strategies as well as system level aspects are out of scope of this paper. Finally, the G3-PLC handover mechanism is not limited to the MV grid applications as experimented in the SOGRID project and paves the way for any other similar situation encountered in the LV grid.

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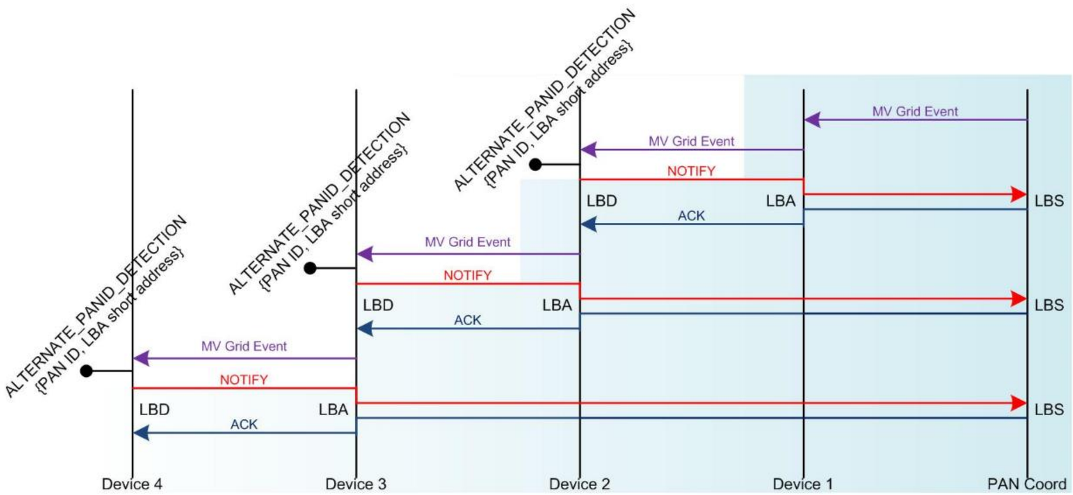

Figure 5: Handover mechanism over a multi-hop G3-PLC PAN (see [1] for details about LBD, LBA, LBS terminology)