Power Line Communications and the Smart Grid

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Prologue

- The Power Grid is a commodity delivery system where the commodity (electric power) has a production to consumption cycle time of zero: generation, delivery and consumption happen *all at the same* instant in time!
  - This creates unique challenges in sensing, communications, and control because electrical power moves just as fast as communication signals do
- These challenges will be compounded due to the integration of new technologies aimed at addressing in a sustainable manner energy independence and modernization of the aging power grid:
  - Integration of utility scale Renewable Energy Sources (RES) feeding into the transmission system
  - Distributed Energy Resources (DER) feeding into the distribution system or home
  - Storage to compensate for the time varying nature of some renewables
  - Plug-in (Hybrid) Electric Vehicles (PHEV) that may cause large load increases on sections of the grid
  - Demand Side Management (DSM)
- Balancing generation and demand of this “perfect just-in-time system“ will then require “Smart” solutions in the integration of additional protection and control technologies that ensure grid stability - not a trivial patch to the current power grid control network (SCADA)

Prologue

- As the physical network dynamics and the cyber system data spread at comparable speeds, decoupling communications from control and management is very problematic because separation of time scales is impossible!
- Nevertheless, the topic of what types of communications are to be used for the monitoring and control of the power grid is today the subject of intense debate and strong choices are being made even before a full understanding of the sensing and control aspects of the problem is achieved
- This process has reverse the natural order of design: information network infrastructures, modulation and coding as well as routing and clustering primitives are chosen from rather generic models that are not specifically tied to energy distribution, thus dictating ultimately the delays that the control needs to work with, not the other-way around!
- In order not to fall in the methodological mistake of giving prematurely specific design recommendations, this talk will be limited to analyzing the strengths and weaknesses of PLC in the smart grid
- Although a sense of optimism on the important role of PLC will be conveyed, a solid quantitative conclusions can be made only after a unitary framework for addressing sensing, communications, and control is set forth

Ultra Narrowband (UNB) PLC

- Technologies operating at very low data rate (<100 bps) in the ULF band (0.3-3 kHz) or in the upper part of the SLF band (30-300 Hz)
- Typically, UNB-PLC systems use disturbances of the voltage waveform for outbound (substation to meter) communication and of the current waveform for inbound (meter to substation) communication
- Examples
  - ➢ Ripple Carrier Signaling (RCS) for direct load control - operating in the in the 125 - 2,000 Hz band, conveying several bps, using ASK
  - ➢ The Turtle System – conveying few bph (per hour!) 200+ km away!
  - ➢ Two-Way Automatic Communications System (TWACS) - conveying 60 bps, 150+ km range

Narrowband (NB) PLC, aka DLC

- Technologies operating in the VLF/LF/MF bands (3 - 500 kHz), worldwide common band 10-148.5 kHz (CENELEC A, B, C, and D)
- Low Data Rate (LDR), up to few kbps
  - ISO/IEC 14908-3 (LonWorks), ISO/IEC14543-3-5 (KNX), CEA-600.31 (CEBus), IEC 61334-3-1, IEC 61334-5-1
  - Non-SDO examples: Insteon, X10, HomePlug C&C,Ariane Controls, BacNet
- High Data Rate (HDR), 100-1,000 kbps
  - ITU-T G.hnem, IEEE 1901.2
  - Non-SDO examples: PRIME and G3-PLC

Path loss (dB/km)	$f = 100$ kHz
Low Voltage	1.5-3
Medium Voltage (OH)	0.5-1
Medium Voltage (UG)	1-2

Broadband (BB) PLC, aka BPL

- Technologies operating in the HF/VHF bands (1.8-250 MHz) and having a PHY rate ranging from several Mbps to several hundred Mbps.
- PSD mask constant until 30 MHz, then goes down 30 dB
- Available solutions convey up to 200 Mbps, but low range
  - TIA-1113, IEEE 1901, ITU-T G.hn (G.9960/G.9961) recommendations.
  - Non SDO examples: HomePlug 1.0, HomePlug AV (Extended), HD-PLC, UPA Powermax, and Gigle MediaXtreme

Path loss (dB/km)	$f = 10$ MHz
Low Voltage	160-200
Medium Voltage (OH)	30-50
Medium Voltage (UG)	50-80

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The Role of PLC for Utility Applications

- A first advantage of using existing PLs as a communications channel is that utility applications almost always require redundancy in protection and control, and the need for redundancy includes the availability of redundant communications channels
  - The availability of an existing wired infrastructure greatly reduces the cost of deploying a redundant communication channel
  - PLC can compete with wireless in cost because the lines are already there
- Another important advantage of using PLCs is that the traditionally separated functions of sensing and communicating blur together and thus a PLC transceiver could be designed to switch between functioning as a "sensor" and as a communications device.
  - This has applications in fault location and detection and also in Power Quality (PQ) which are an important concern for utilities because of the economic value of predicting and avoiding electric disturbances

S. Galli, A. Scaglione, Z. Wang, "For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid," submitted to the *Proceedings of the IEEE, May 2010*.

Transmission Side – PLC over HV

- The availability of a reliable communication network on the transmission side is critical for the support of several applications such as state estimation (PMU over WAMS), protective relaying, SCADA expansion to remote stations, and remote station surveillance
- Traditional communications technologies for the HV network are based on either fiber optical or microwave links, but trials of PLC over HV are today ongoing in US, Italy, South Korea, and Spain
- Besides for providing connectivity on the transmission side, PLC over HV lines is also being considered for remote fault detection:
  - Detection of broken insulator, insulator short circuit, cable rupture, circuit breaker opening and closing
  - Determination of the change in the average height above ground of horizontal HV overhead conductors (real-time sag monitoring)

Transmission Side – PLC over HV

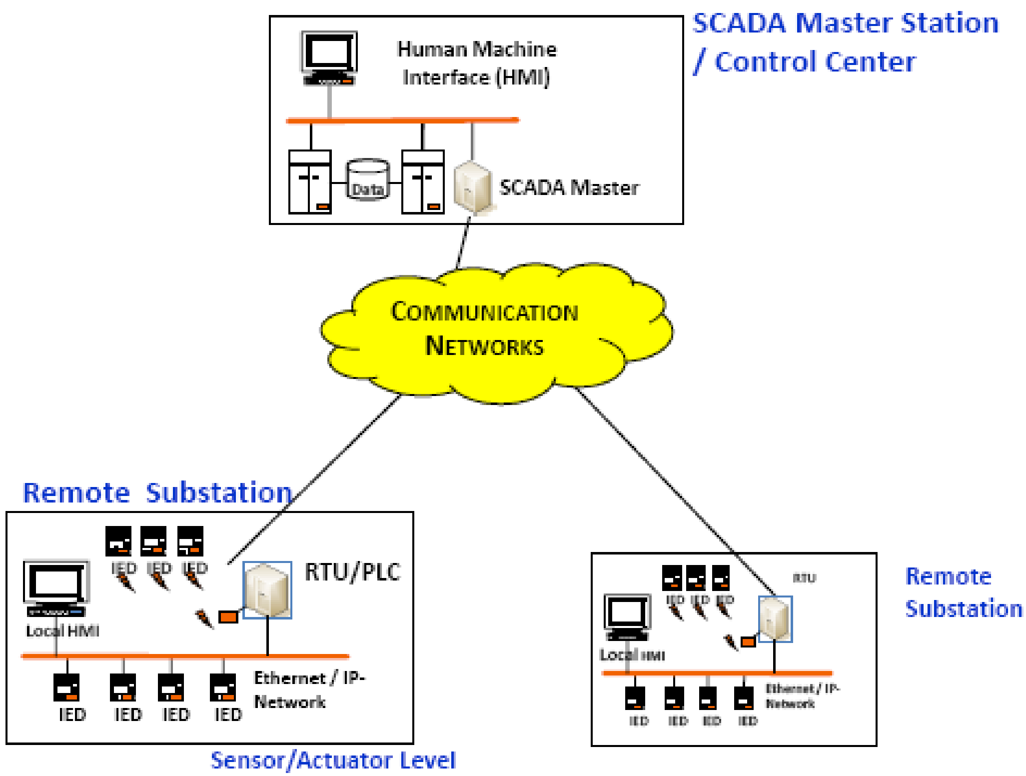
- HV lines are decent waveguides as channel attenuation characteristics show a benign pass-band and time invariant behavior
  - The noise is mainly caused by corona effect and other leakage or discharge events, and corona noise power fluctuations of some tens of dB can be observed due to climatic dependency
  - Compared to LV/MV lines, HV are a better communications medium characterized by much lower attenuation – the main issue is coupling
- An ongoing joint US DoE, AEP, and Amperion project is testing BB-PLC over 69 kV and 138 kV PLs and reported data rates of 10 Mbps and latency under 5ms on 69 kV links of 8 km (no repeaters)
- More attention to PLC over HV is today being given now that the IEC TC57/WG20 started to work on updating the obsolete PLC standard IEC 60495 to include digital PLC for HV
- At this time, it is possible to express only cautious optimism about the use of PLCs in the transmission side as further testing is needed

Distribution Side – PLC over MV

- A large portion of MV equipment in the world has been installed more than 40 years ago so that fault detection and monitoring are a true operational, safety and economical necessity that can be implemented via PLC
  - There are several successful reports on the use of NB-PLC (Cenelec A) for online diagnostic data transfer over MV
- Some substation automation functions need the substation IEDs to communicate with external IEDs:
  - In the case of fault location, fault isolation and service restoration, substation IEDs must communicate with external IEDs such as switches, reclosers, or sectionalizers
  - In the case of voltage dispatch, communication between substation IEDs and distribution feeder IEDs served by the substation are needed
- DG systems can supply unintentional system islands isolated from the remainder of the network – it is very important to quickly detect islanding because of safety issues
  - Multiple reports confirm that NB-PLC-based islanding prevention offers superior islanding prevention over any other existing method

Distribution Side – PLC over MV

- Data connectivity is also important for sharing the state of equipment and power flow conditions between substations and to support the new generation of distribution PMUs



- **Use of the existing PL infrastructure represents an appealing alternative to the installation of new communications links!**

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The Issue of the Distribution Transformer

- Do PLC signals pass the MV/MV or LV/LV transformer?
  - It depends!
- UNB-PLC signals propagate easily through several transformers and do not require any kind of PL conditioning
  - UNB-PLC can cover very large distances 150+ km
- NB-PLC can sometimes pass a transformer (although with an SNR hit), but this depends on the kind of NB-PLC technology and on the type of transformer.
  - Difficult to draw general conclusions since there is no statistical model
  - Multicarrier based NB-PLC may have better chances if programmable notching is supported
- BB-PLC signals do not pass the transformer and coupling is required to by-pass it

Distribution Side – PLC over LV

- On the LV side, there are many Smart Grid applications that can be supported using PLC:
  - Meter reading (AMR/AMI)
  - Vehicle-to-Grid communications (V2G)
  - Demand Side Management (DSM)
  - Home/Building Energy Management Systems (xEMS)
- PLC technology is certainly well suited for AMR/AMI as there are 100+ million UNB/NB-PLC equipped meters deployed around the world
  - Since the late 80s, UNB-PLC system have experienced growing success in the market especially in rural areas because of their range
  - LDR NB-PLC have been used mostly in Europe
  - Multicarrier based HDR NB-PLC are also gaining traction

Distribution Side – PLC over LV

- A PHEV charges its battery when connected to an EVSE which, in turn, is connected to premises wiring or to distribution cables (airport, parking lots, etc.)
- A variety of applications scenarios can be envisioned in enabling a communication link between the PHEV and the utility/xEMS:
  - Control of the localized peak load that the increasing penetration of PHEVs would inevitably create
  - Use of the battery to support the home during a back-out
- The first distinctive advantage of PLC for V2G communications is the fact that a unambiguous physical association between the vehicle and a specific EVSE can be established
- In terms of cost and worldwide regulations, NB-PLC solutions are currently considered the preferred V2G choice with respect to BB-PLC
  - Since NB-PLC are also excellent choices for meters and appliances, the availability of a single class of PLC technologies for the inter-networking of different actors in the same applications is of course tempting

Distribution Side – PLC over LV

- Demand Response is one of the primary applications for reducing peak demand and refers to the ability to make demand able to respond to the varying supply of generation that cannot be scheduled deterministically
- Implementation of DR requires establishing a link (either direct or indirect, e.g. via a xEMS in the home) between utility and household appliances
- xEMS will play an important role in DSM and they can provide at the same time financial advantages to the consumer (optimizing home/building energy consumption, reacting to real time energy prices) and added reliability to the grid (shifting load, shaving peaks, feeding PV energy to the grid, etc.)
- The data rate requirements for DSM are still object of intense debate but there is still no quantitative analysis justifying the need of high data rates
  - Just think that the largest direct load control system in the world (~1 million devices, 2 GW of load) is working using only 60 bps (TWACS)

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Final Considerations

- All PLC types can find their space of application and the choice of which PLC technology best fits the application scenario also depends on:
  - Regulations on emissions, which vary by country
  - Number of customers per transformer, which vary by country
- UNB-PLC will certainly continue to succeed wherever range and coverage are more important than data rate
- NB-PLC do have advantages when compared to BB-PLCs:
  - Much lower path loss < 2dB/km
  - Ease of upgrade to future versions (DSP-based soft modem)
  - Worldwide harmonization with common frequency band
  - Hopefully single ITU/IEEE standards for the HDR case
  - Coexistence scheme proven in the field
  - Optimized design targeting smart grid applications, whereas BB-PLC where originally designed for home networking or Internet access only

Final Considerations

- BB-PLC appear to be less suited for use outside the home:
  - Most Smart Grid applications do not require high data rate
  - HF band has high path loss (~150 dB/km on LV, and ~60 dB/km on MV)
  - HF band not available everywhere in the world
  - Require coupler to by-pass distribution transformer
  - Technology not designed for AMI or not mature yet
- NB-PLC do have disadvantages with respect to BB-PLC solutions – especially when the current rush to deploy equipment in the field is taken into consideration
  - HDR NB-PLC solutions such as PRIME and G3-PLC have just come out and further validation in the field of these technologies and their effective range, throughput, and capability of passing the transformer is needed
  - Standardization efforts in ITU/IEEE are still in their infancy
  - NB-PLCs offer data rates of several kbps or at most up to 500 kbps, and there is a concern that higher throughputs may one day be required

Putting PLC in the field

- In the deployment of Smart Grid devices and PLC-enabled sensors in particular, it is important to devise network planning tools to establish coverage
  - A first element is to have accurate and flexible channel modeling tools, especially statistical ones
  - A second element is a network model based on topological properties of the PL network as the power grid is not only the *information source* but also the *information delivery system* when PLC are used
- Both elements have received very little attention in the literature, and the lack of planning tools adds to the confusion of what PLC to deploy
- Very recent results on these topics are reported here:
  - S. Galli, “A Novel Approach to the Statistical Modeling of Wire-line Channels,” to appear in the *IEEE Transactions on Communications.*
  - S. Galli, A. Scaglione, Z. Wang, "For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid," submitted to the *Proceedings of the IEEE*, May 2010.

Two Final Considerations on Methodological Aspects

- We are generally very good at designing optimal sub-systems, but a systems engineering approach is necessary to tackle the issues that arise in a massive system of interconnected sub-systems like the power grid
  - The biggest risk is to wind up not designing a Smart Grid but simply designing a Dumb Grid composed of many Smart Sub-Systems
- A fundamental priority is then to accelerate the work on the development of an architectural framework that not only maps existing standards to the ultimate vision of what the Smart Grid will be, but also individuates standards and technological gaps that must be addressed with a forward looking mindset

Two Final Considerations on Methodological Aspects

- The pressure to accelerate the deployment of the Smart Grid is often pushing the collective thinking into making two questionable assumptions:
  - Off the shelf technologies, even if designed and implemented for completely different applications, can be massively and seamlessly utilized in the Smart Grid – even before fully understanding Smart Grid
  - The choice of a single technology for the implementation of certain Smart Grid applications will accelerate reaping Smart Grid benefits since it would allow the industry to align behind a common technology
- However, the Smart Grid is still an *ongoing experiment* and this means that our choices today should encompass a diversity of solutions and implementations in order to be able to achieve a better understanding of the very complex problem of implementing the Smart Grid