Some Areas for PLC Improvement

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Contribution to ETSI TC PLT Meeting – 1 July 2015 – Sophia Antipolis, France

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Introduction

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Core Research
- Communications theory
- Statistical signal processing
- Measurement methods
- Electronics and embedded systems prototyping
- Applications: smart grid, smart systems, automotive
Content

- Background
  - PLC for IoT and smart city
  - Some areas for PLC improvement

- Foreground
  - Going ultra wide band
  - MIMO
  - Can we still look at modulation?
    - Filter bank modulation
    - Impulsive PLC

- Conclusions
PLC for the IoT and the Smart City

Power line communications in the “Smart Domains”

- Smart building (a lot has been done ...)
- Smart grid (a lot has been done ...)
- Smart factory (something has been done ...)
- Smart car, smart vehicle (something has been done ...)
- Smart city (not much has been done ...)

Smart city

- The novelty is to provide reliable connectivity supporting **mixed traffic flows**
  - Low/high speed, low-high latency, small-large coverage, low-high robustness, etc...
  - Design shall be done for high interactivity and low energy consumption
- A challenge is the identification of applications and requirements
What are the applications of PLC?

Objects connectivity

- Sensors (*from meters to video cameras*)
- Traffic monitoring devices
- Public lights
- Peripherals (*cable replacement*)
- Machines (*M2M*)

Networks connectivity

- Range extenders
- Backbone for heterogeneous networks
- Backhauling
Are we happy with current standards?

Broadband PLC

- We are good, but it is time to improve

Narrowband PLC

- The *feeling* is that there is some pessimism about it
  - CENELEC bands do not offer the most benign propagation environment (low impedance and high noise)
  - Throughput is below requirements for *real* smart applications that are not just about meter reading

Too many standards, we need interoperability not only coexistence
What are the areas of improvement?

PHY Layer areas for improvement (not comprehensive though)

- Increase bandwidth (both for low speed and high speed PLC)
- Spectrum flexibility and adaptation (cognitive PLC)
- Better exploitation of MIMO and usage of hybrid MIMO (PLC + wireless)
- Improve modulation and coding schemes
- Use signal processing for mitigating interference and impulsive noise
- Lower energy consumption

MAC Layer areas for improvement (not comprehensive though)

- Resource allocation and scheduling for periodically time variant channels
- Look into FDMA-OFDM and not only TDMA-OFDM
- Relay cooperative networks and routing (layer 2-3) can be beneficial

Convergent protocols
Bandwidth Increase
Going beyond 100 MHz has potential

- We have measured up to 300 MHz for in-home PLC
- Topologies and wirings do change the behavior

Sites area: 50-200 m², Band: 1.8-300 MHz

\[ P_{tx}(<30 \text{MHz}) = -50 \text{ dBm/Hz, } P_{tx}(>30 \text{ MHz}) = -80 \text{ dBm/Hz} \]

\[ P_W(f) = 10 \log_{10}(f^2 + 10^{-15.5}) \text{ dBm/Hz} \]

REF. F. Versolatto, A. Tonello, "PLC channel characterization up to 300 MHz: Frequency response and line impedance," IEEE GLOBECOM 2012.


Noise in MIMO

Exploiting noise correlation in MIMO

- PSD measurements provided by the STF-410 are not sufficient. Spatial correlation not fully characterized: if taken into account better performance.
- Going ultra wide band with MIMO requires new campaigns

STF-410 measurements, Band: 1.8-100 MHz
\[ P_{tx}(<30\text{MHz})=-50 \text{ dBm/Hz}, \ P_{tx}(>30 \text{ MHz})=-80 \text{ dBm/Hz} \]

WHITE in frequency & Spatially uncorrelated

COLORED in frequency (STF-410) & Spatially uncorrelated

“Standardized” channel and noise measurements are needed for the development of reference models

Software simulation

- Reference top-down and bottom-up channel models can be developed

Hardware emulation

REF. WiTiKee Hace “PLC HW Channel Emulator”, www.witikee.com
The spectrum is not free *(this is obvious)*

- Can we go beyond 500 MHz? It depends on what application we are looking at...
- Flexible spectrum management is a must!
Flexible Spectrum Management
The best way to realize a flexible spectrum solution is with the use of filter bank modulation

What schemes?

- **Filtered multitone modulation (FMT)**
- **Cyclic block filtered multitone modulation (CB-FMT)**
  - It resembles FMT but it uses block transmission and cyclic convolutions in the filter bank

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**Filter bank modulation (FBM)**


## PS-OFDM vs. FMT vs. CB-FMT

### OFDM (PS-OFDM)
- Prototype pulse confined in time domain
- Efficient implementation (FFT based)
- Poor frequency selectivity (notching capability)
- Sensitive to synchronization errors
- Affected by time variant channels
- High PAPR

### FMT
- Prototype pulse confined in frequency domain
- Efficient implementation (FFT based)
- Out-of-band interference reduced
- High notching selectivity
- Robust to synchronization errors and channel time selectivity

### CB-FMT
- The filter bank uses cyclic convolution
- High sub-channel spectral confinement w.r.t. PS-OFDM
- Applicable to NB and BB PLC
- Low complexity w.r.t. to conventional FMT: efficient FFT based implementation can be done
- High notching capability w.r.t. PS-OFDM
- High throughput
- Low PAPR
Flexible spectrum management in NB PLC

Instead of using a hard coded solution, deploy a flexible spectrum software defined solution

REF. M. Girotto, A. Tonello, “Improved Spectrum Agility in Narrow-Band PLC with Cyclic Block FMT Modulation,” IEEE GLOBECOM 2014
Flexible spectrum solution in BB PLC

Example: In-building scenario
We may need less sub-channels
Higher spectral efficiency with FBM

CB-FMT 2048 sub-channels

PS-OFDM 2048 sub-channels (many carriers are wasted!)

Going beyond 100 MHz

- If we extend the band up to 500 MHz and beyond
  - Radiated emissions can be problematic
  - Very low PSD must be used
  - Protect defense radio system and broadcasting bands
- Probably less problematic if we look at *(short) cable replacement* applications
- Again, FBM modulation allows flexibility

![Graph showing PSD levels](image-url)
Impulsive PLC
a flexible low complexity solution
Filter bank modulation is not the only solution

If we want to realize a **PLC sensor network**, then simplicity, robustness, energy efficiency are of paramount importance

Impulsive wide band PLC is a good choice
- Very simple solution based on impulsive waveform transmission
- Operates at very low PSD levels
- Spectrally flexible
- Coexistent with others schemes
- Robust to impulsive noise and multipath
- Suitable for:
  - sensor networks
  - grid monitoring, metering
  - ...

Coexistence is important
Let’s see an example in the context of sensor networks
Coexistence between I-PLC and OFDM

- Let us consider **I-PLC designed for moderate data rate applications** (in-home and grid)
- Let us consider an **uncoordinated overlaying solution** together with NB OFDM (CENELEC A 32-95 kHz) or BB OFDM (2-30 MHz)
- Can they all coexist without any coexistence mechanism (worst case)?
  - Very little mutual interference effect without any coordination
  - I-PLC has much higher rate than NB OFDM with very low transmitted PSD

**I-PLC performance in the presence of NB or BB OFDM**

- In-home w/o BB OFDM up to 60 Mbps
- LV outdoor w/o NB OFDM up to 18 Mbps

**BB OFDM and NB OFDM performance in the presence of I-PLC**

- In-home w/o I-PLC up to 400 Mbps
- LV outdoor w/o I-PLC Up to 1 Mbps

Conclusions

- More to investigate in the channel domain especially for new applications
- PHY layer can be improved further
- Bandwidth expansion is potentially beneficial
- Flexible spectrum management is essential
  - *Filter bank modulation is an excellent option*
  - *Impulsive PLC is another simple solution especially in the context of PLC sensor networks*