Some Areas for PLC Improvement

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Introduction

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Chair of IEEE TC PLC

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University of Klagenfurt - Austria

EcoSys Lab Klagenfurt Universität
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FAKULTÄT FÜR TECHNISCHE WISSENSCHAFTEN

Wireless and Power Line Communication Lab
University of Udine - Italy

Wipli Lab Università degli Studi di Udine

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

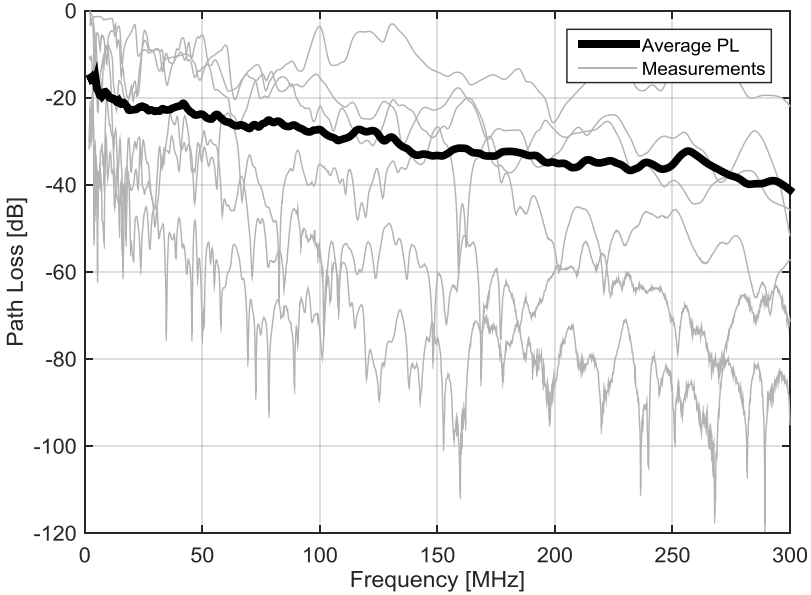
Convergent protocols

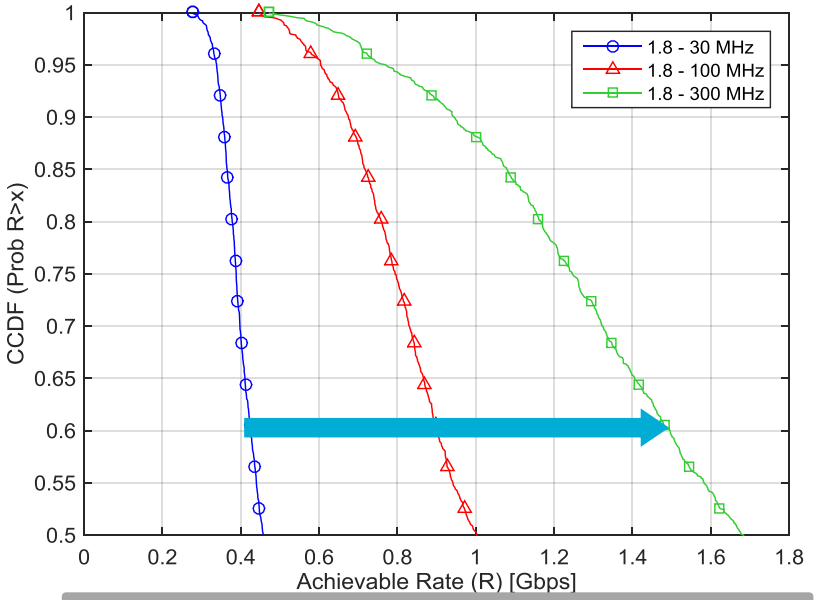
Bandwidth Increase

Channel beyond 100 MHz

Going beyond 100 MHz has potential

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





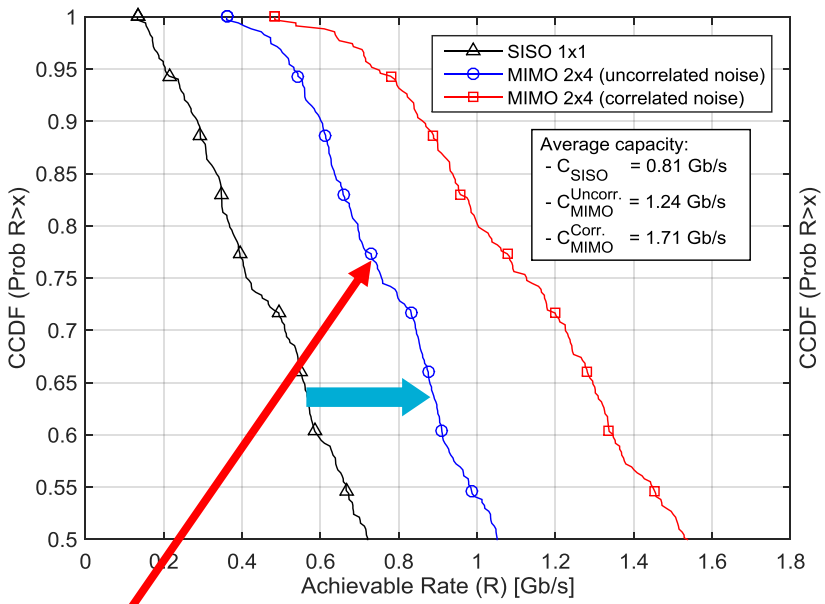
Sites area: 50-200 m^2, Band: 1.8-300 MHz
P_{tx}(<30MHz)=-50 dBm/Hz, P_{tx}(>30 MHz)=-80 dBm/Hz
$P_W(f) = 10\log_{10}(f^2 + 10^{-15.5})$ dBm/Hz

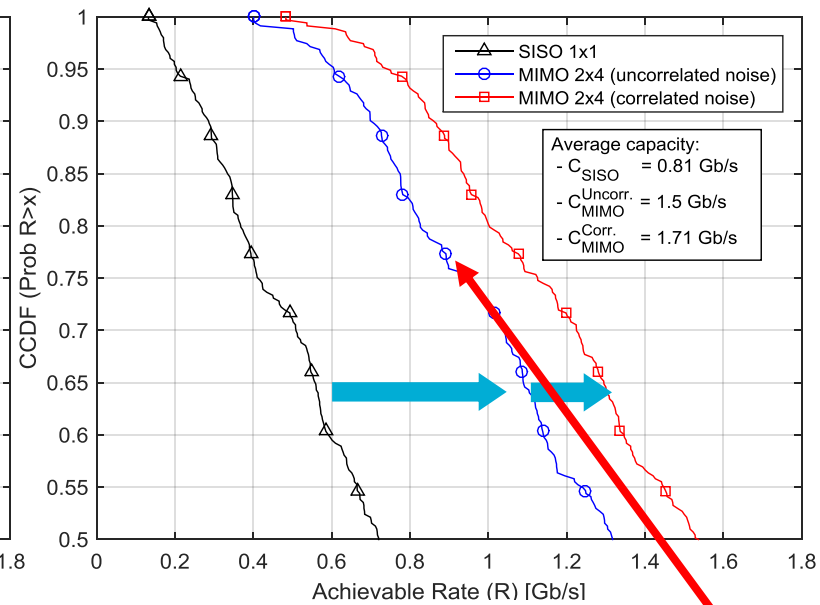
REF. F. Versolatto, A. Tonello, "**PLC channel characterization up to 300 MHz: Frequency response and line impedance**," *IEEE GLOBECOM 2012.*
REF. A. Tonello, F. Versolatto, A. Pittolo, "**In-Home Power Line Communication Channel: Statistical Characterization**," *IEEE Trans. on Comm. 2014*.
REF. A. Tonello, A. Pittolo, M. Girotto, "**Power Line Communications: Understanding the Channel for Physical Layer Evolution Based on Filter Bank Modulation**", *IEICE Trans on Comm. 2014.*

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





WHITE in frequency & Spatially uncorrelated

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

COLORED in frequency (STF-410) & Spatially uncorrelated

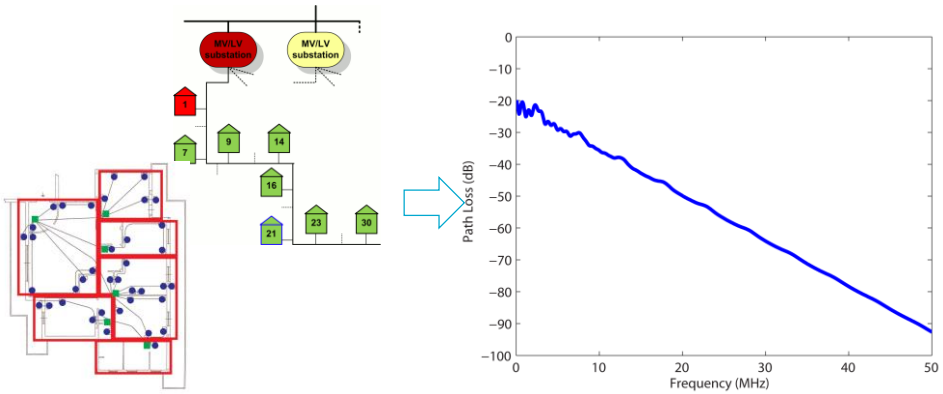
REF. A. Pittolo, A. M. Tonello, F. Versolatto, "**Performance of MIMO PLC in measured channels affected by correlated noise**," *IEEE ISPLC* 2014
REF. A. Schwager, D. Schneider, W. Bäschlin, A. Dilly, and J. Speidel, "**MIMO PLC: Theory, Measurements and System Setup**," *IEEE ISPLC 2010*

Channel models

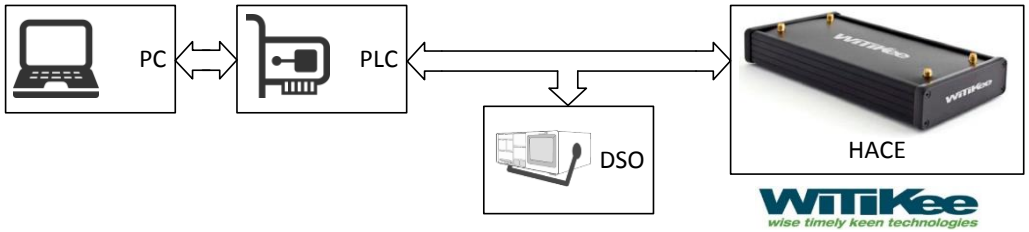
- "Standardized" channel and noise measurements are needed for the development of reference models

Software simulation

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



Hardware emulation

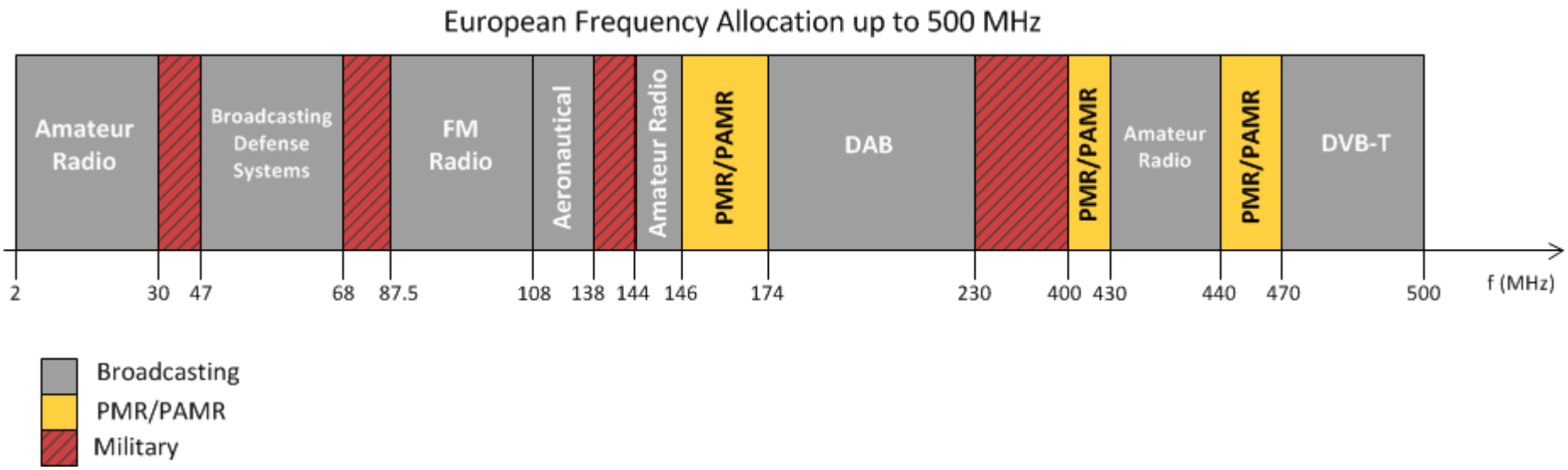


REF. A. Tonello, F. Versolatto et al. "**A Fitting Procedure to Statistically Model the PLC Channel**," *IEEE Trans. Power Del.* 2012.

REF. A. Tonello, F. Versolatto, "**Bottom-up Statistical PLC Channel Modeling – Part I: Random Topology Model and Efficient Transfer Function Computation**," *IEEE Trans. Power Del.* 2011.

REF. WiTiKee Hace "**PLC HW Channel Emulator**", *www.witikee.com*

What spectrum to use ?

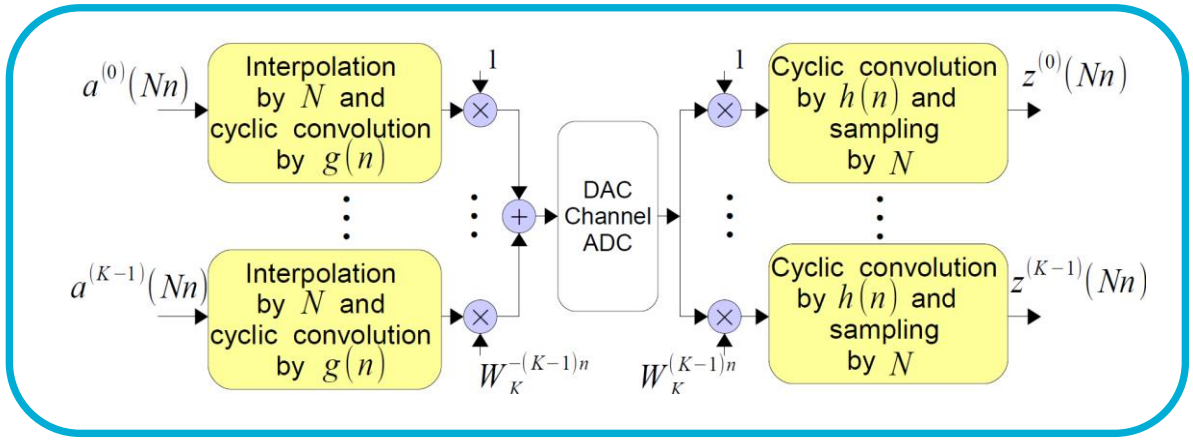


- The spectrum is not free (*this is obvious*)
- Can we go beyond 500 MHz ? It depends on what application we are looking at …
- Flexible spectrum management is a must !

Flexible Spectrum Management

Filter bank modulation (FBM)

- 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



REF. A. Tonello, F. Pecile, "**Efficient Architectures for Multiuser FMT Systems and Application to Power Line Communications**," *IEEE Trans. on Comm. 2009*

REF. A. Tonello, M. Girotto, "**Cyclic Block Filtered Multitone Modulation**," *EURASIP Journ. Advances in Signal processing 2014*

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

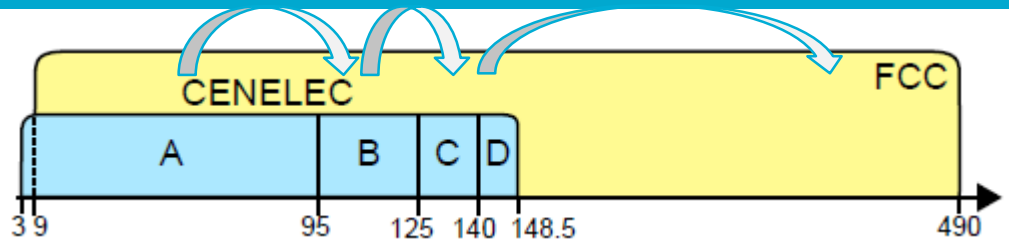
FMT

- 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

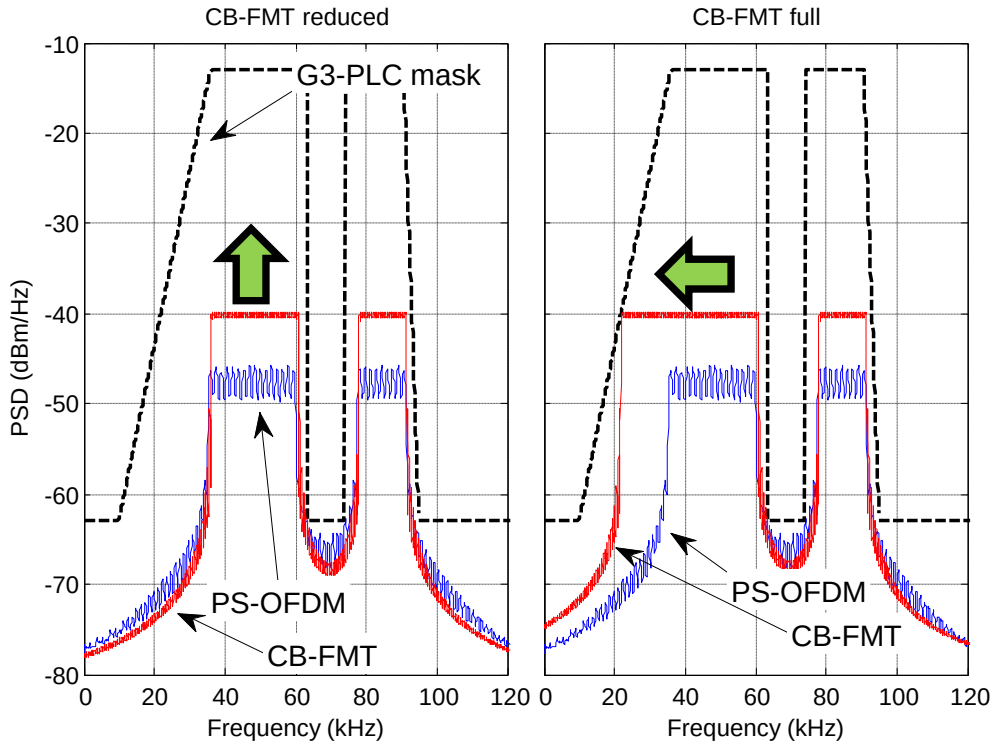
CB-FMT

- 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 implementaion can be done
- High notching capability w.r.t. PS-OFDM
- High throughput
- Low PAPR

Flexible spectrum management in NB PLC



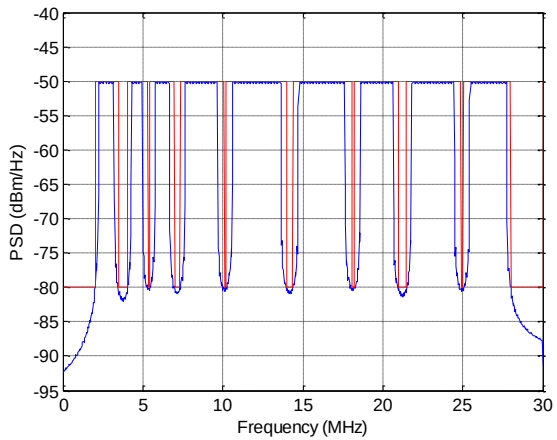
Instead of using a hard coded solution, deploy a flexible spectrum software defined solution



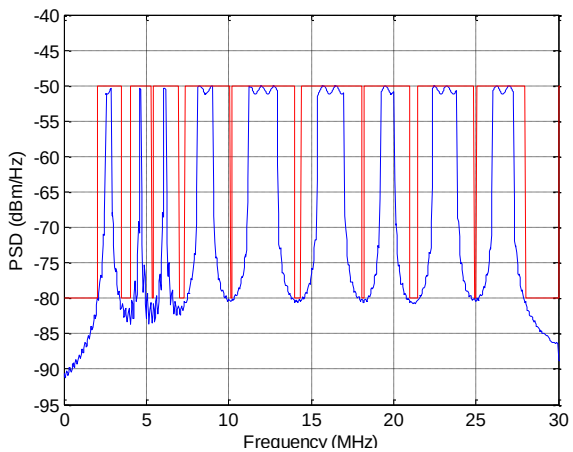
higher throughput and lower delay are achievable

REF. M. Girotto, A. Tonello, "**Improved Spectrum Agility in Narrow-Band PLC with Cyclic Block FMT Modulation**," *IEEE GLOBECOM 2014*

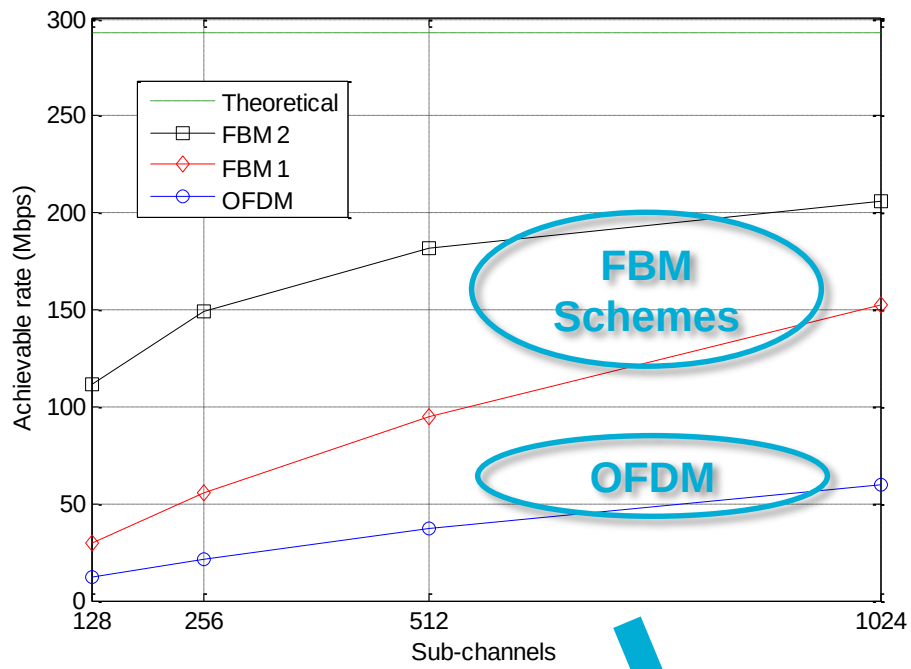
Flexible spectrum solution in BB PLC



CB-FMT 2048 sub-channels



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

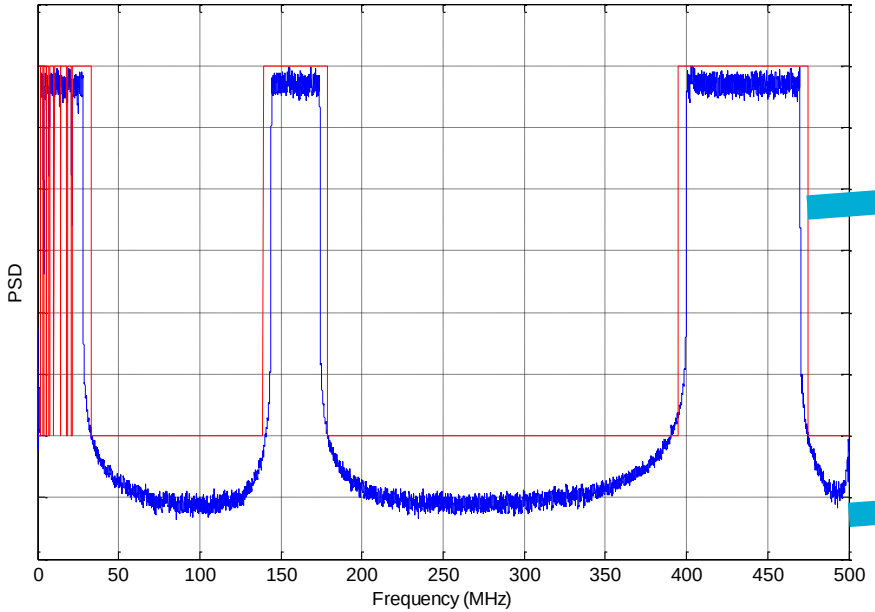


Example: In-building scenario
We may need less sub-channels
Higher spectral efficiency with FBM

REF. A. Tonello and M. Girotto, "**Cyclic Block FMT Modulation for Broadband Power Line Communications**," *IEEE ISPLC 2013.*

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



Higher PSD in "non-critical" bands (e.g., amateur radio and PMR) Value ?

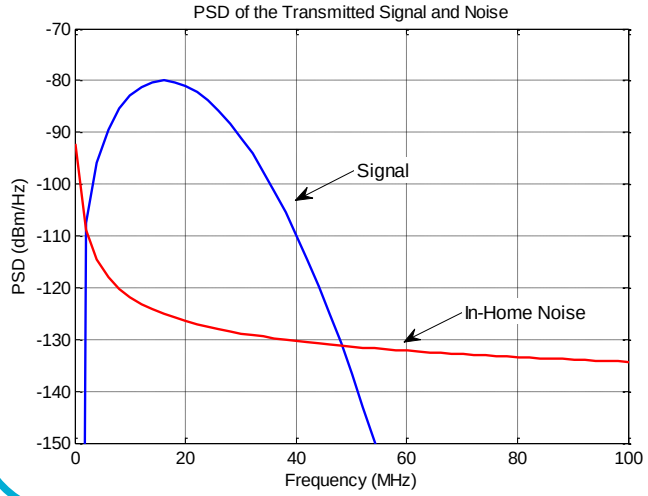
Very low PSD in critical bands must be granted Value ?

Impulsive PLC
a flexible low complexity solution

Impulsive PLC

- 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
    - …

spectrum example



REF. A. Tonello, **"Wideband Impulse Modulation and Receiver Algorithms for Multiuser Power Line Communications,"** *EURASIP Journal on Advances in Signal Proc.* 2007.

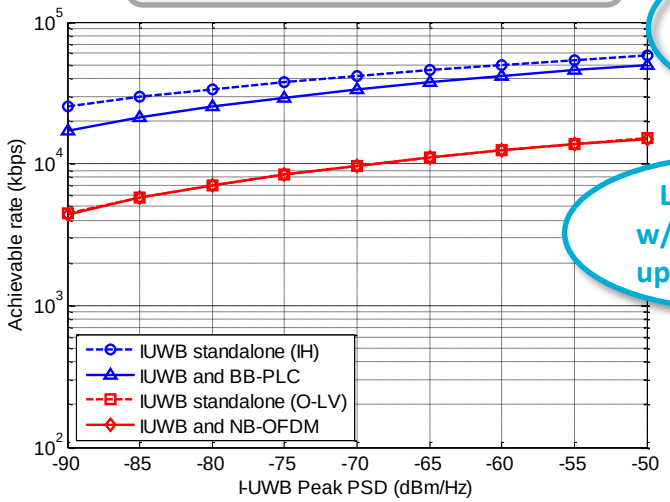
Coexistence is important

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

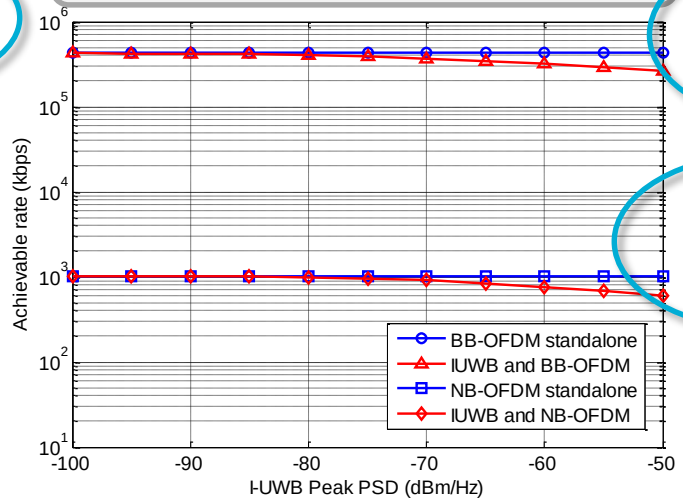
I-PLC performance in the presence of NB or BB OFDM



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

REF. A. Tonello, F. Versolatto and M. Girotto, "**Multi-Technology (I-UWB and OFDM) Coexistent Communications on the Power Delivery Network**," *IEEE Trans. on Power Delivery* 2013.

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*