UNIVERSITÄT KLAGENFURT

EcoSys Lab

# Power Line Communications: a Brief Introduction

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IEEE ComSoc TC-PLC and TC-SGC Webinar on the **Potential of Power Line Communications for Smart Grid, Residential and Industry Applications**

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# Contribution

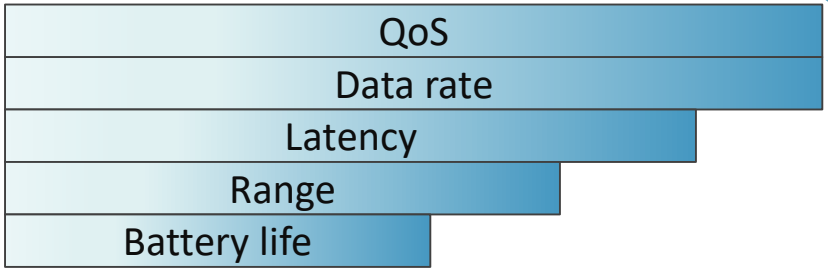
- Introduce you to the world of powerline communications
- Illustrate key research domains
- Open the floor to Cedric Lavenu's and Marcos Martinez' talks

# The rationale behind PLC

# Diversity of requirements

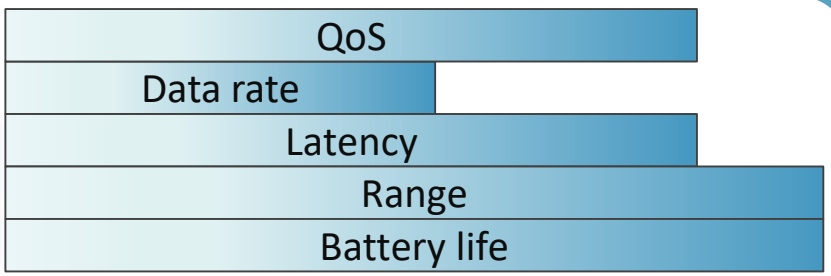
## Consumer applications

- Internet access, mobile services, gaming
- Smart and assisted living
- Children, pet tracking
- …



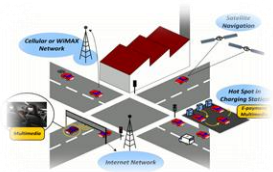

## Energy - resources

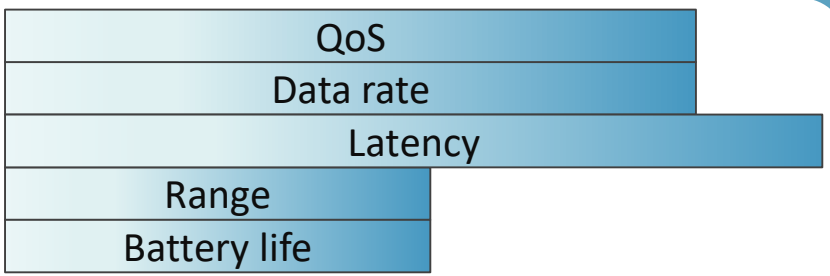
- Smart grids, renewables
- Metering (electricity, water, gas)
- Asset management, maintenance
- …




## Transportation

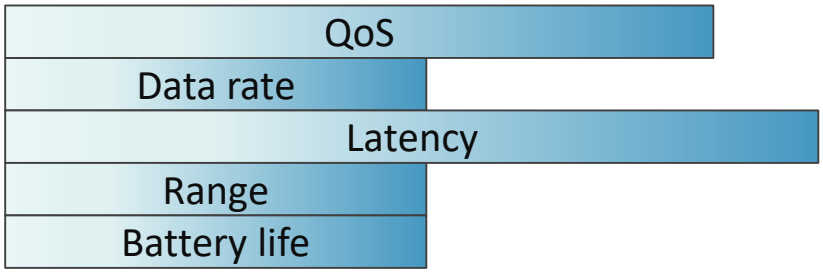
- Autonomous driving
- Safety, intelligent transportation
- Aerial taxis navigation
- …



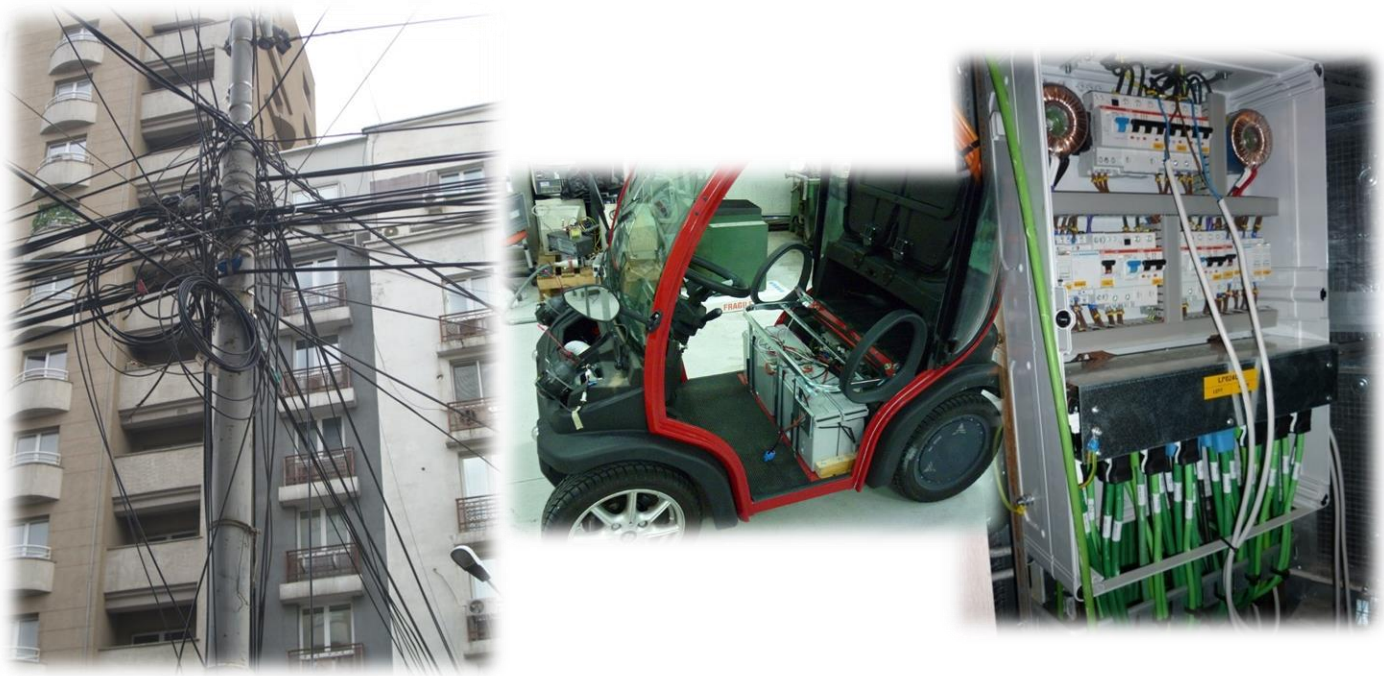



## Industry

- Robotics
- Asset and process management
- Agricolture
- …



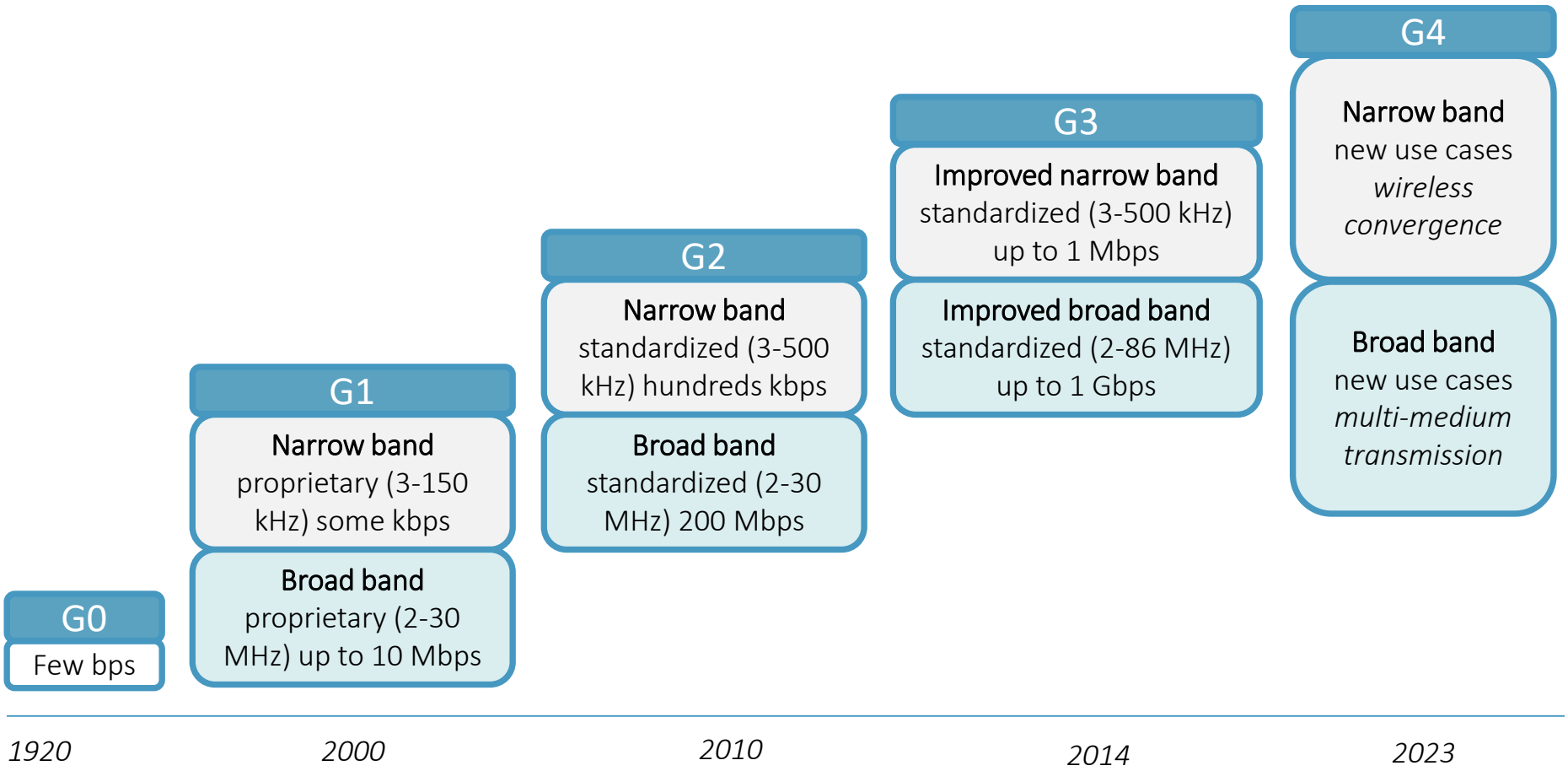
# It is not all about wireless



Power lines are pervasively deployed to deliver electrical energy

PLC has a role !

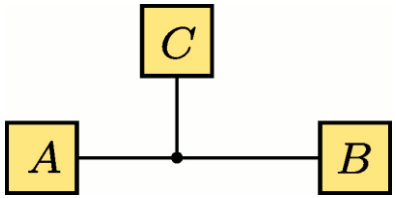
# Evolution of PLC technology



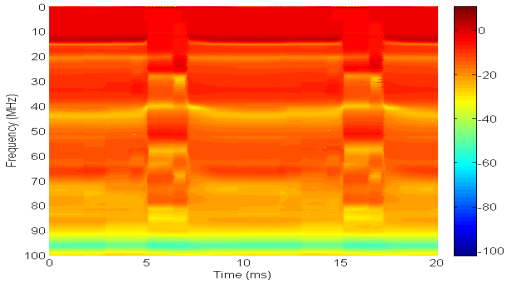
# Channel characterization and modeling

# What we have learnt

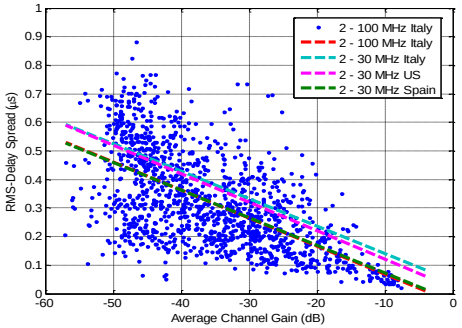
## Multi-path propagation



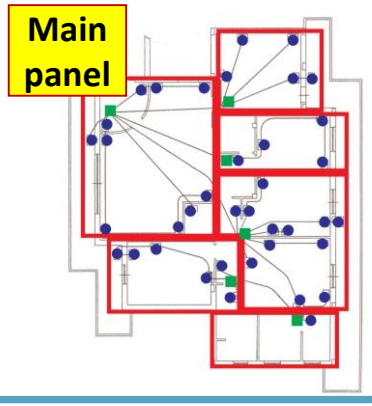

## Cyclic time variations: LPTV channel




## Log-normal path loss: delay spread inversely proportional to gain




## Topology matters and can be modeled




## MIMO and common mode



REF. Zimmermann et al.,, "A multi-path signal propagation model for the powerline channel in the high frequency range", *IEEE ISPLC 1999*

REF. Cañete et al., "Analysis of the Cyclic Short-Term Variation of Indoor Power L. Channels", *IEEE JSAC* 2006

REF. Galli, "A Simple Two-Tap Statistical Model for the Power Line Channel," *IEEE ISPLC 2010.*

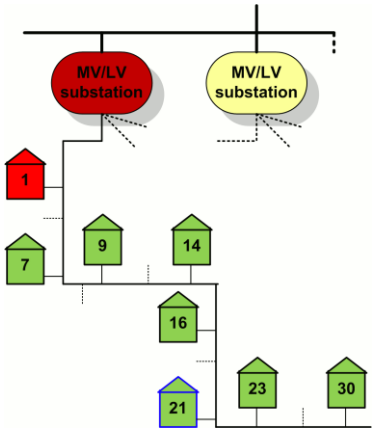
REF. Tonello et al., "Bottom-up Statistical PLC Channel Modeling – Part I: Random Topology Model and Efficient Transfer Function Computation," *IEEE Trans. Power Del.*, 2011

REF. Schwager et al., "MIMO PLC: Theory, Measurements and System Setup," *IEEE ISPLC 2011*

# Channel modeling approaches

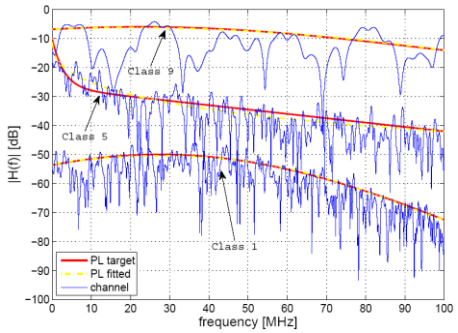
- **Bottom-up:**

  from topology to channel response using transmission line theory



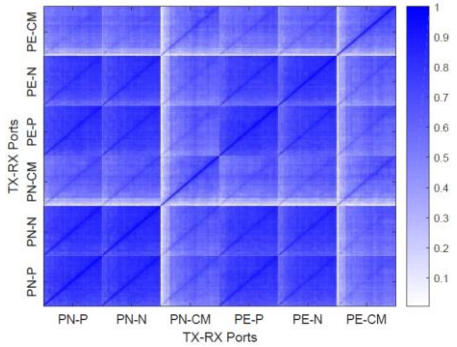

- **Top-down:**

  analytic model of the response fitted with measurements data




- **Synthetic:**

  from statistical analysis purely phenomenological





REF. Zimmermann et al., "A Multipath Model for the Powerline Channel," *IEEE Trans.* Commun., 2002.

REF. Esmailian et al., "In-Building Power Lines as High-Speed Communication Channels: Channel Characterization and a Test Channel Ensemble," *Int. Journ. of Commun. Syst.*, 2003.

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

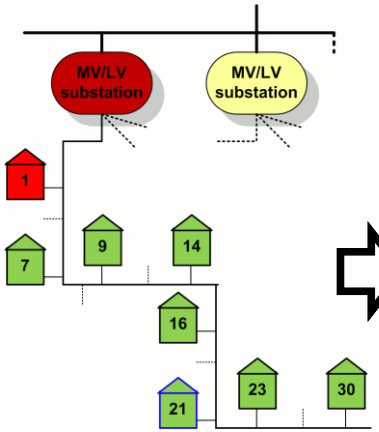
REF. Tonello et al., "A Fitting Algorithm for Random Modeling the PLC Channel," *IEEE Trans. on Power Delivery, 2012*

REF. Pittolo, et al., "A Synthetic Statistical MIMO PLC Channel Model Applied to an In-Home Scenario," *IEEE Trans. Comm. 2017.*

# Statistical modeling and emulation

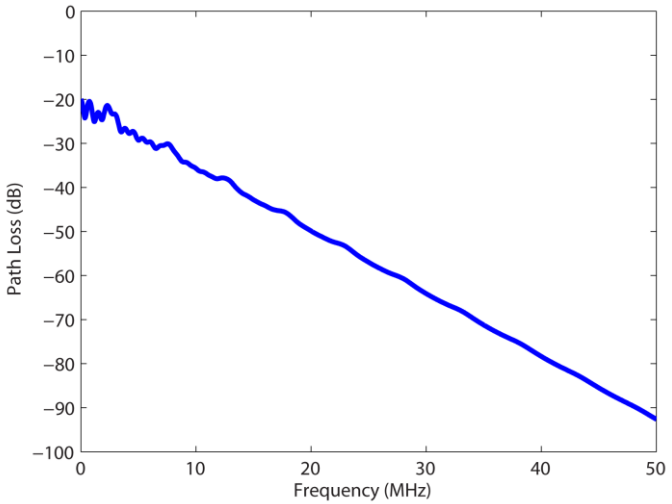
- Bottom-up:

  from topology to channel response using transmission line theory



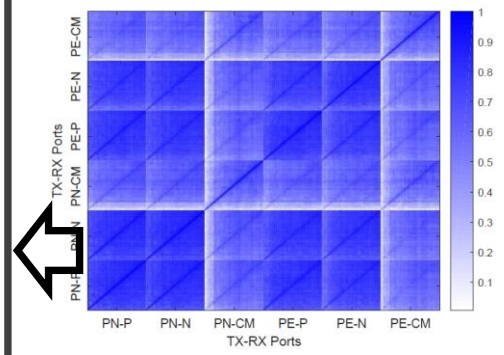

- Top-down:

  analytic model of the response fitted with measurements data



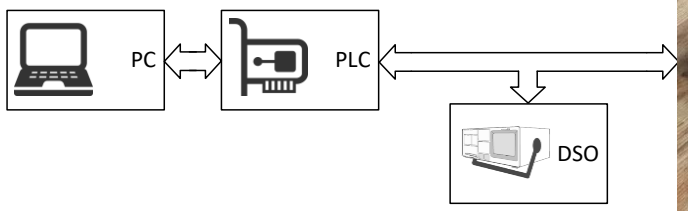

- Synthetic:

  from statistical analysis purely phenomenological




## From SW to hardware channel emulation

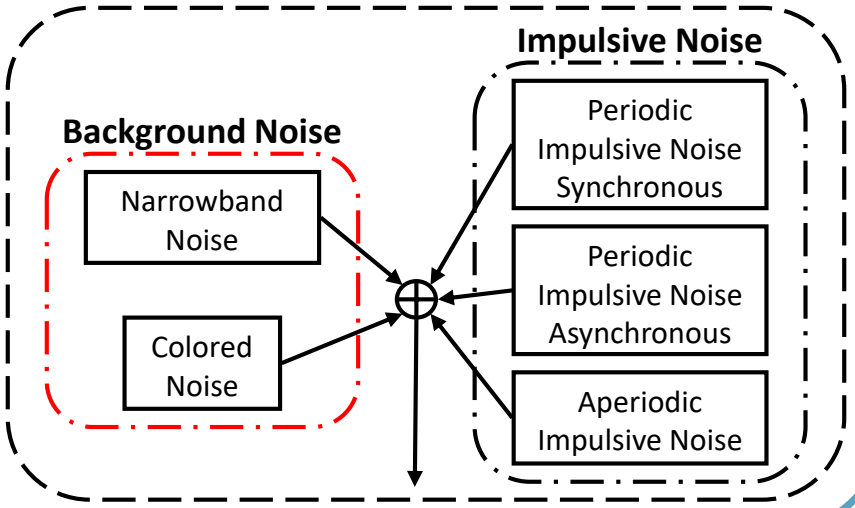
- Impedance and response synthesis



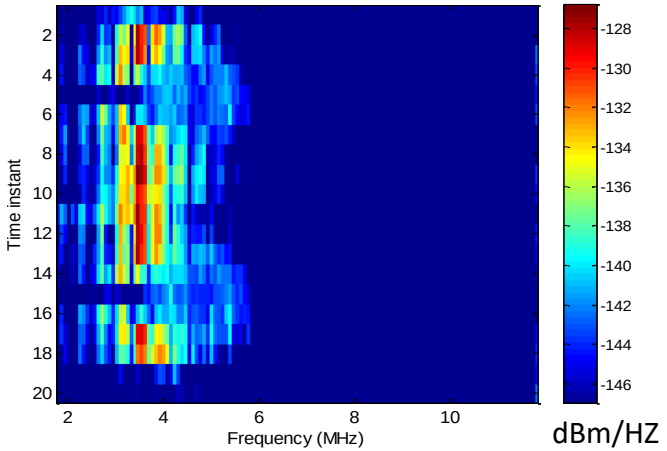

# Noise characterization and modeling

# What we have learnt

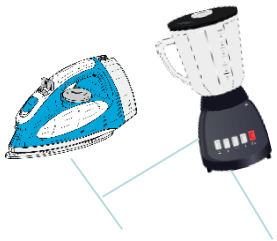
- 5 noise categories




- Cyclic noise variations are high especially at lower frequencies




- We can model noise at the source or at the receiver

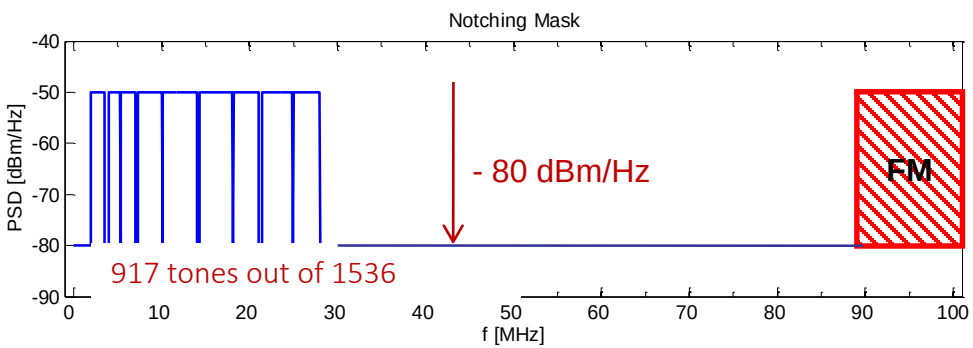


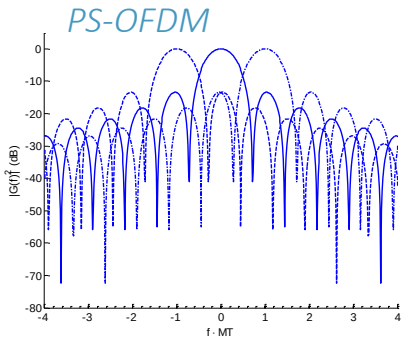
- We have some *partial* models:
  - Middleton model
  - Katayama NB model
  - Fresh filter model
  - …

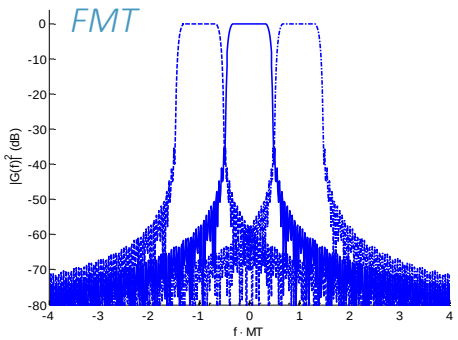

REF. Zimmermann et al., "**Analysis and Modeling of Impulsive Noise in Broad-Band PowerLline Communications**," *IEEE Trans. Electr.* Compat., 2002.
REF. Cortés et al., "**Analysis of the indoor broadband power-line noise scenario**", *IEEE Trans. Electromagn. Compat., 2010.*
REF. Antoniali et al." **An Experimental Characterization of the PLC Noise at the Source**," *IEEE Trans. on Power Delivery, 2016.*

# Physical layer

# Filter bank modulation at the heart of PLC



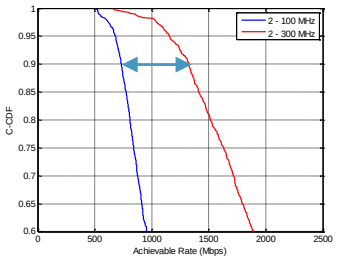




- The need to provide spectrum confinement and notching capabilities have brought to the study and adoption of filter bank modulation:
  - **Pulse-shaped OFDM** (adopted in ITU and IEEE NB/BB standards)
  - **Wavelet OFDM** (essentially DWMT, adopted in IEEE BB standard)
  - **FMT:** Filtered multitone
  - **CB-FMT:** Cyclic block FMT
  - **OQAM/OFDM:** Offset QAM OFDM
  - …
- Channel coding: interleaved CC, Turbo and LDPC codes
  - No specific design, if not the decoding metric to take into account the noise statistics
- Adaptation is a key concept:
  - Bit-loading, coding rate, number of tones, spectrum management, cyclic prefix length

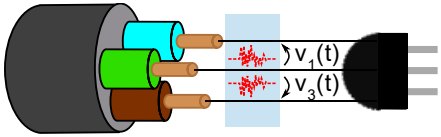
REF. Lampe et al., "Power Line Communications: principles, standards, applications from multimedia to smart grid," Wiley 2016.

# How to increase throughput ?

- Increase bandwidth up to 300 MHz
  - Gains are possible depending on the scenario
  - The channel is low pass, though
  - Attenuation and radiation increases

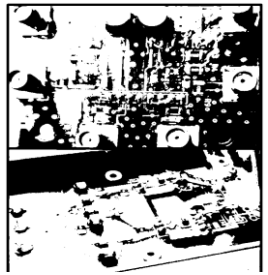



- MIMO
  - Multiple conductors may be available
  - Exploit both differential and common mode transmission




- In-band full duplex
  - Double bidirectional throughput, ideally
  - High levels of self interference are generated because of impedance mismatches
  - Need to implement analog and digital cancellation stages
  - *In short:* quite challenging and with unclear use cases

*First IBFD AFE prototype in 2x2 MIMO 300 MHz band (Righini et al. 2021)*



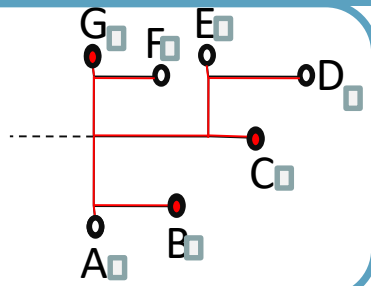

REF: Versolatto et al. "PLC Channel Characterization up to 300 MHz: Frequency Response and Access Impedance," *IEEE Globecom 2012.*
REF. Berger et al., "MIMO Power Line Communications: Narrow and Broadband Standards, EMC, and Advanced Processing," *Taylor&Francis, 2014.*
REF. Prasad et. al, "In-band full duplex broadband power line communications," *IEEE TCOM 2016.*

# MAC and above layers

# MAC and above

## MAC in PLC

- CSMA, Flooding for large PLC sensor networks
- Adaptive TDMA to exploit the cyclic variations of the channel and noise
  - This is unique of PLC and brings to beautiful RA strategies




## Relaying and routing

- To improve coverage repeaters and relays are used
  - The relay cannot be placed anywhere differently from wireless
- For large networks, such as metering networks, routing is very relevant. The conceivement of light protocols is a current research topic

## Coexistence, interoperability and convergence layer

- Different PLC standards can coexist through an inter-system coexistence protocol
- Interoperability is implemented at the network and IP layer
- Convergence with other technologies (wireless, VLC, …) is realized at L3

## Second use case: PLC enabled power grid diagnostics

- Sensing of faults, cable degradation, and grid topology reconstruction etc.


REF. Lampe et al., "**Power Line Communications: principles, standards, applications from multimedia to smart grid**," *Wiley 2016.*
REF. Passerini et al., "**Smart Grid Monitoring Using Power Line Modems: Anomaly Detection and Localization**," *IEEE Tr. on Smart Grid, 2019.*

# Final remarks

# What is next in PLC ?

- Reduce the market receptivity barriers
- Harmonize standards
- Keep technology evolving
  - Look for new applications (see next presentations)
  - Still space to invent something in all L1-L3 layers
    - Two domains where work has just started are:
      - AI for complex PLC network management
      - ML to design and analyze PLC technology


**Machine Learning Tips and Tricks for Power Line Communications**

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*IEEE Access 2019*

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# Thank you !

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