Power Line Communication Systems in the Smart Grid Context

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Green Technologies Enabling Energy Saving
2012 Summer School in Information Engineering
University pf Padova – Brixen - Italy

Introduction

Andrea M. Tonello

Andrea M. Tonello
Aggregate professor at Univ. of Udine
Vice-chair IEEE TC-PLC
Steering committee member IEEE ISPLC

- University of Udine: 17.000 students
- WiPLi Lab 15 members, part of the Department of Electrical, Mechanical and Management Engineering (150+ members)
- Activities: Wireless and Power Line Communications
  - Communication theory and signal processing
  - System and protocol design
  - Measurements and emulation
  - RF and base band prototyping
  - Home networking, smart grid, vehicular communications
- Projects: several EU FP5-FP7 and industrial projects

Contents

- Introduction
- **Power line communication applications**
- **Role of PLC in the Smart Grid**
- **Challenges: *Channel and transmission technology***
- **PLC channel**
  - Channel characterization and modeling, Noise and modeling
- **Physical layer techniques**
  - Single carrier modulation (FSK), multicarrier modulation
- **A look at systems and standards**
- **Network and MAC aspects**
- **Conclusions and evolution**
- **References**
- Speaker bio

Power Line Communications

Application Scenarios

- **Idea:** exploit the power delivery network to convey data signals
- It dates back to about 1920 when it was used to transmit data and voice between substations over high voltage (HV) lines
- Ultra narrow band solutions have evolved into narrow band and broad band systems
- The application has become ubiquitous
  - Broad band internet access
  - In-Home networking
  - Smart grid applications
  - In-Vehicle application

Chronological order

PLC Applications

- **Broad band internet access**
  - It enables customer premises to access the Internet through the existing LV net
  - Technology: broad band PLC in the bands 2-30 MHz
  - Deployments: Italy, Austria, Germany, Spain, USA, ….
  - Market suffers of highly penetrated xDSL services

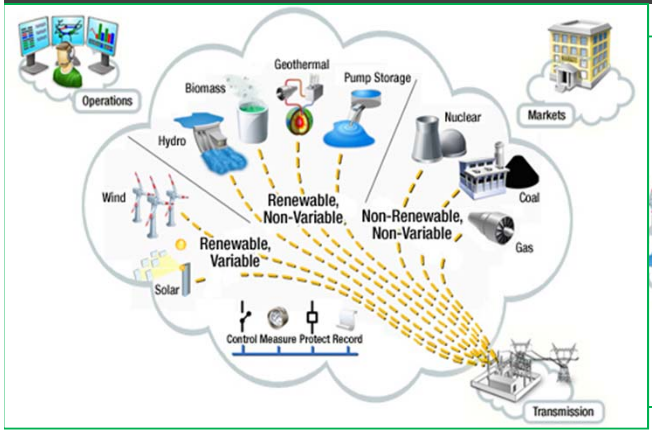
- **Home networking**
  - High speed services delivered through the home gateway
  - Home automation

- **In-vehicle communications via DC/AC lines**
  - Ships, planes, cars
  - Command and control
  - Redundant bus
  - Multimedia services

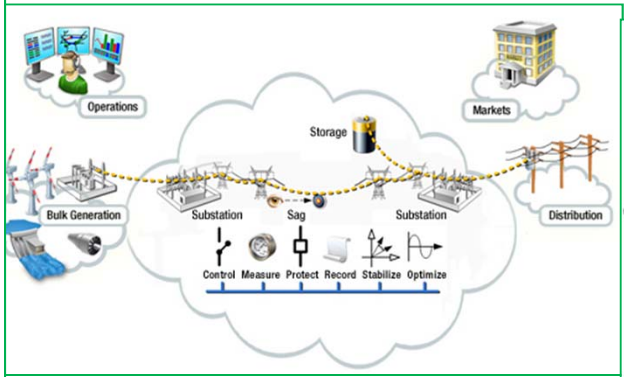
Wipli Lab team in a cruise ship measurement campaign

Role of PLC in the Smart Grid

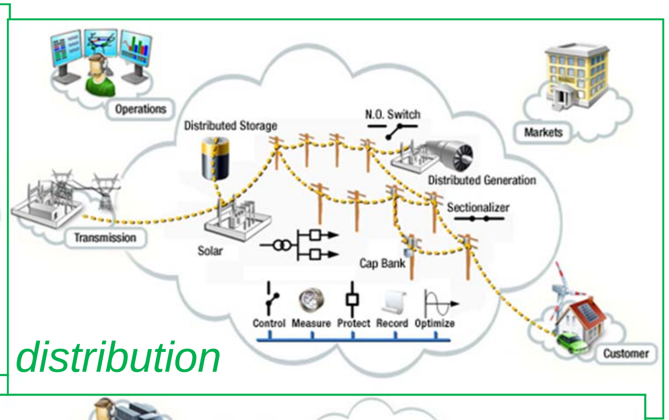
Smart Grid



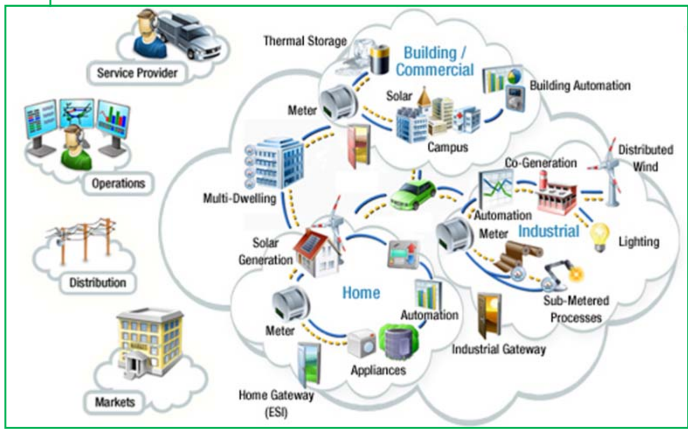
generation



transmission



distribution



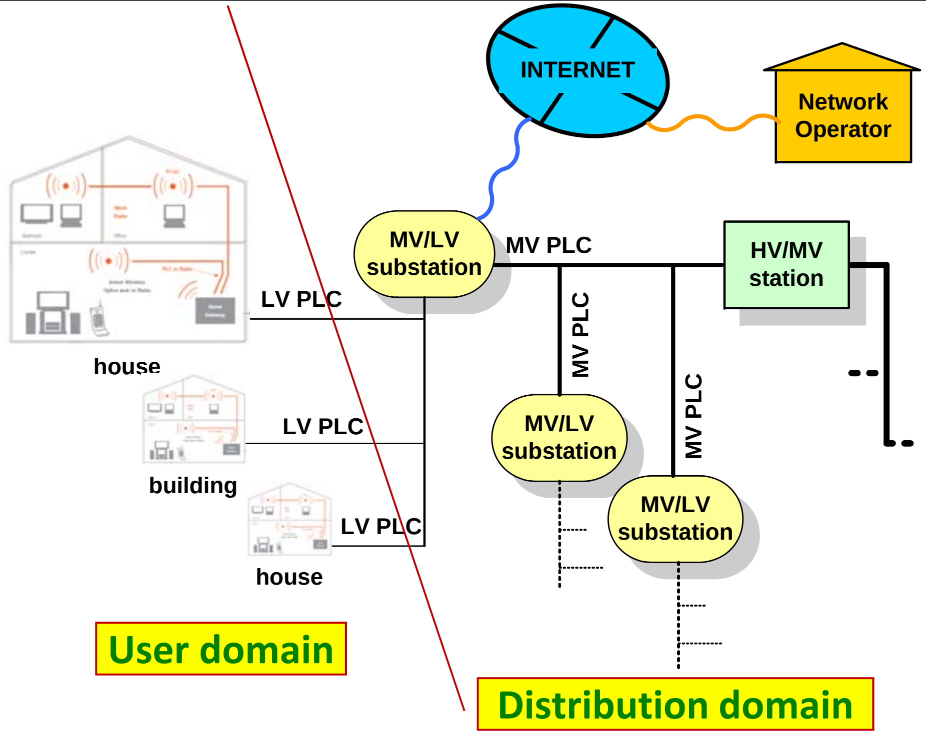
customer

from: http://smartgrid.ieee.org

- A Smart Grid is composed by several domains
  - Generation, Transmission, Distribution, Customer
- Intelligent and dynamic grid with
  - Distributed generation and storage options
  - Active participation by customers
- The Smart Grid elements of each domain are interconnected through two-way communication

Convergence of Communication and Electrical Networks

PLC in the Smart Grid



- ❑ PLC provides an easy to install two way communication infrastructure
- ❑ The user domain is very important for the penetration of SG services

Distribution Domain

- ❑ **Monitoring and control**
  - Fault detection, monitoring of power quality and islanding effects
- ❑ **Energy management**
  - Decentralized production and storage control
  - Charging of electrical vehicles
- ❑ **Smart meter reading**
  - Demand side management
  - Demand response
  - Dynamic pricing
  - Acquisition of user behavior

User Domain

- ❑ **Internet access**
- ❑ **Smart home**
  - Home networking
  - Automation and control

Some Specific Application Areas of PLC

- **Monitoring and control with 2 way communication to ease the integration in the distribution grid of**
  - Renewable energy sources (PV and wind plants)
  - Decentralized storage systems (batteries and e-cars)
  - Control, authentication and payment of e-car charge
- **Smart meter reading (*and power measurement*)**
  - Home energy management systems (HEMS)
  - Demand response and demand side management
  - User behavior profiles

Some Specific Applications of PLC

- **Monitoring and control of the grid**
  - HV/MV line status, faults
  - Islanding of micro grids
  - Power quality (*frequency, voltage/current, harmonics*)
  - Power systems status (*transformers, CBs*)
  - Load and generator shedding in remote areas

Classification of PLC Technologies

- **Extremely Narrow Band PLC**
  - Very low data rates (in the order of bps) for application in large grids

- **Narrow Band (NB) PLC**
  - Low data rate (up to 1 Mbps) and narrow spectrum

- **Broad Band (BB) PLC**
  - High data rate (above 10 Mbps) and large spectrum

Role of NB PLC and BB PLC

- All these services and applications have different requirements:
  - *Data rate, latency, robustness, energy efficiency*

- It is believed that NB PLC is the right choice for SG applications.

  This is because:
  - Low data rates are required
  - Longer distances are covered by NB PLC signals
  - Cheap modems have to be deployed

- BB PLC has been designed for internet access and home networking

Challenges

Challenges

- Communication medium is not designed for data transmission

- Advanced transmission techniques have to be devised

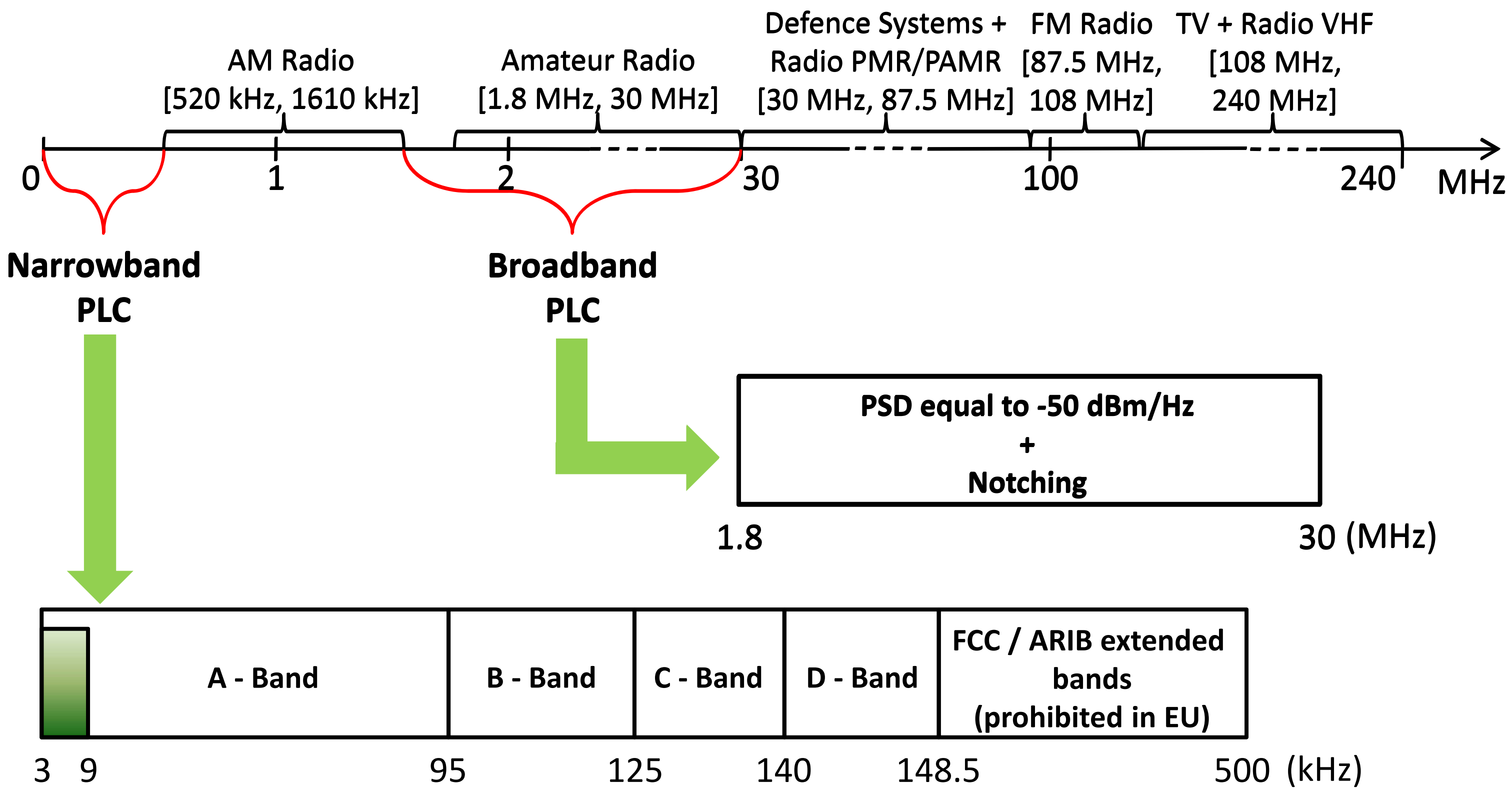
- Protocols and networks for the efficient delivery of etherogeneus services are important

- Standardization

Channel Characterization

Bands and Coupling

PLC Operating Bands

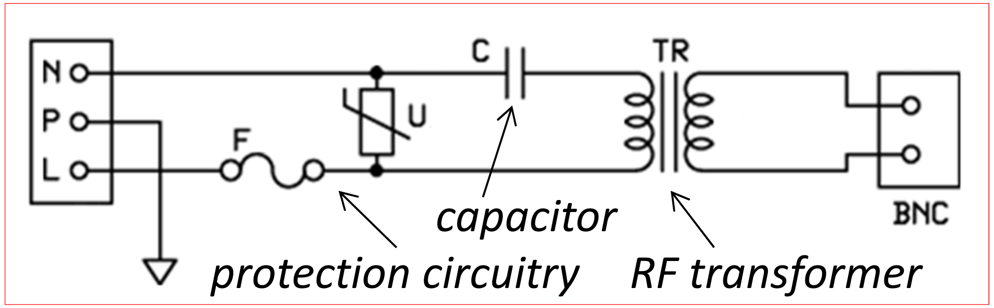


- Spectral masks have been defined to limit the emissions (EMC)
  - Cenelec: A (power utilities), B (any applications), C (home networks with CSMA), D (security applications)
  - Third generation broadband solutions go beyond 30 MHz (80 and even 250 MHz)

REF. IEC, CISPR/I/301/CD, Amendment 1 to CISPR 22 Ed.6.0: Addition of limits and methods of measurement for conformance testing of power line telecommunication ports intended for the connection to the mains, 2009-07-31.

Coupling

- Coupling is necessary to remove the 50/60 Hz power signal
- Capacitive coupling is often used, especially in LV



- Size is an issue if used in MV/HV lines

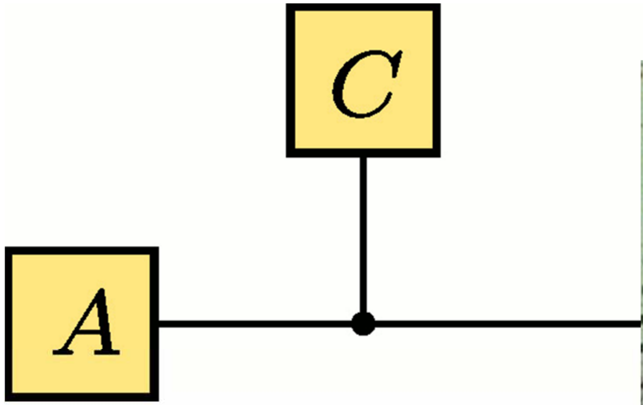
Capacitive coupling in MV lines, courtesy of RSE

- Inductive coupling simplifies installation but has lower pass behavior

Inductive coupling in MV lines, courtesy of RSE

Channel Characteristics

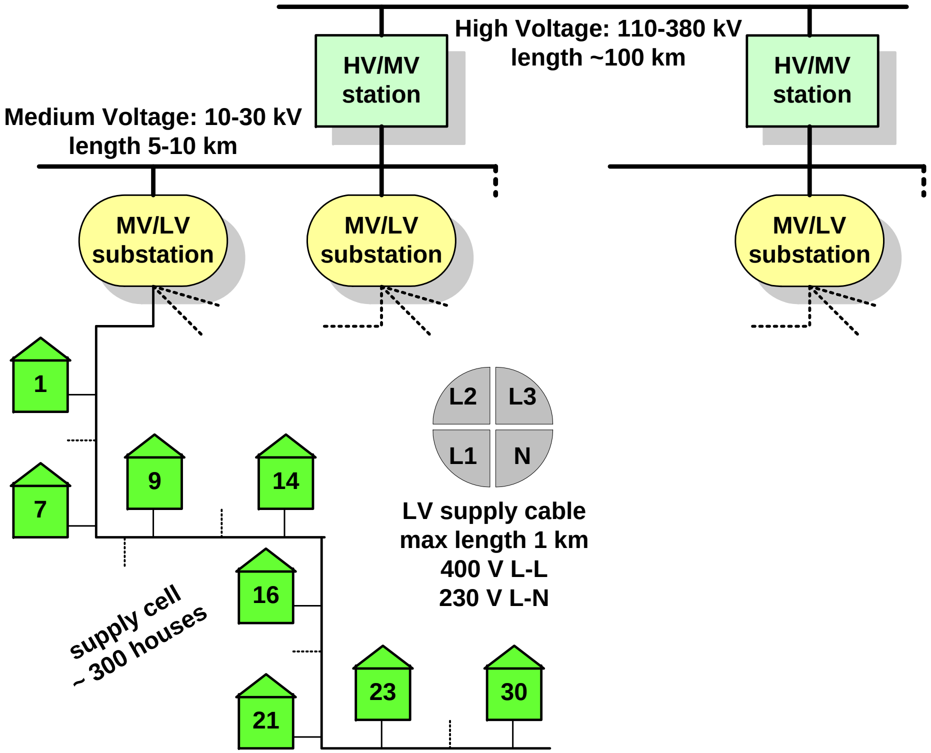
- In general the channel exhibits
  - Multipath propagation due to discontinuites and unmatched loads
  - Frequency Selective Fading
  - Cyclic time variations due to periodic change of the loads with the mains frequency (*mostly bistatic behaviour in home networks*)



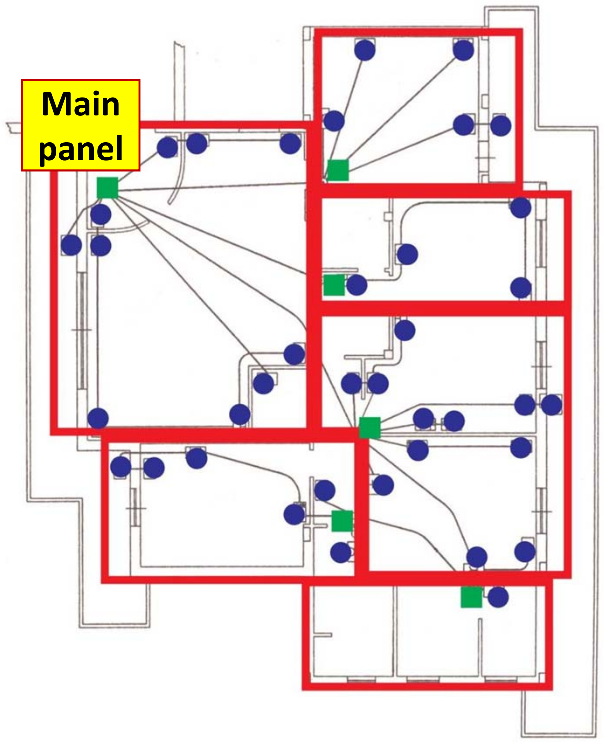
- It is important to perform channel characterization and modeling … *and I enjoy doing that !*

A Look at the Topologies

Distribution Grid



In-home Grid



- ❑ The distribution system is divided in supply cells with a number of houses connected to a MV/LV substation
- ❑ Structure depends on the country

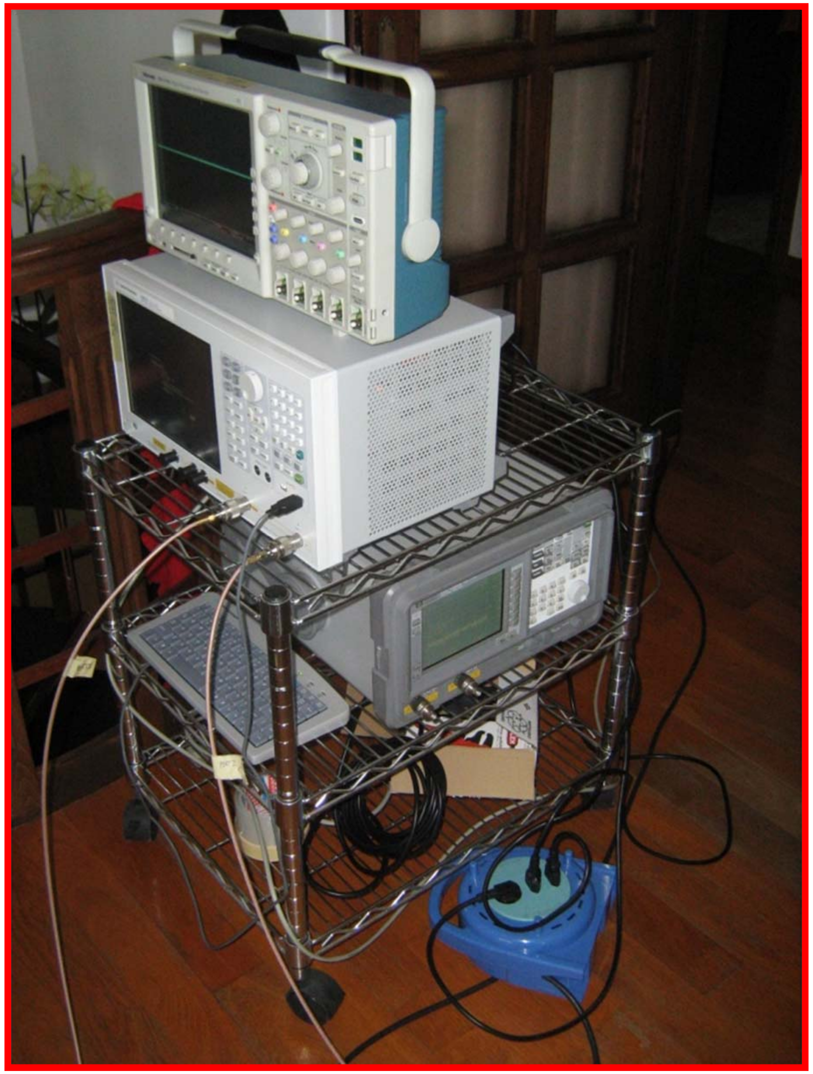
- ❑ Layered tree structure from the main panel with many branches and outlets fed by derivation boxes

Channel Characterization

In-Home Channel

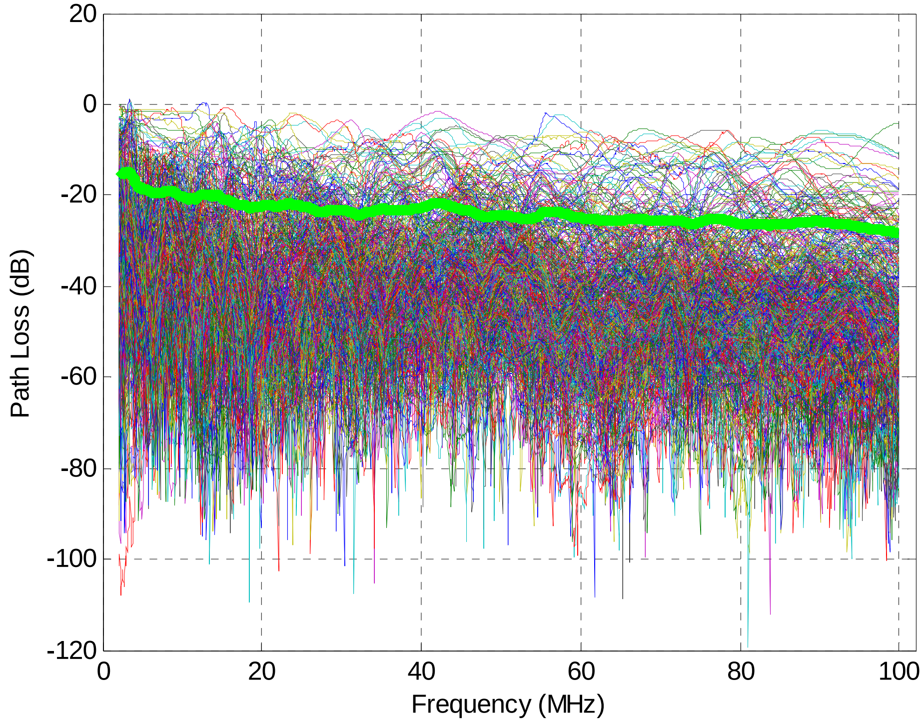
In-Home Channel Characterization

- ❑ Real – life residential sites
  - Italian in-home scenario
- ❑ Up to 100 MHz
- ❑ More than **660** links
  - Channel frequency response
  - Input impedance
- ❑ Static and time variant channel acquisitions



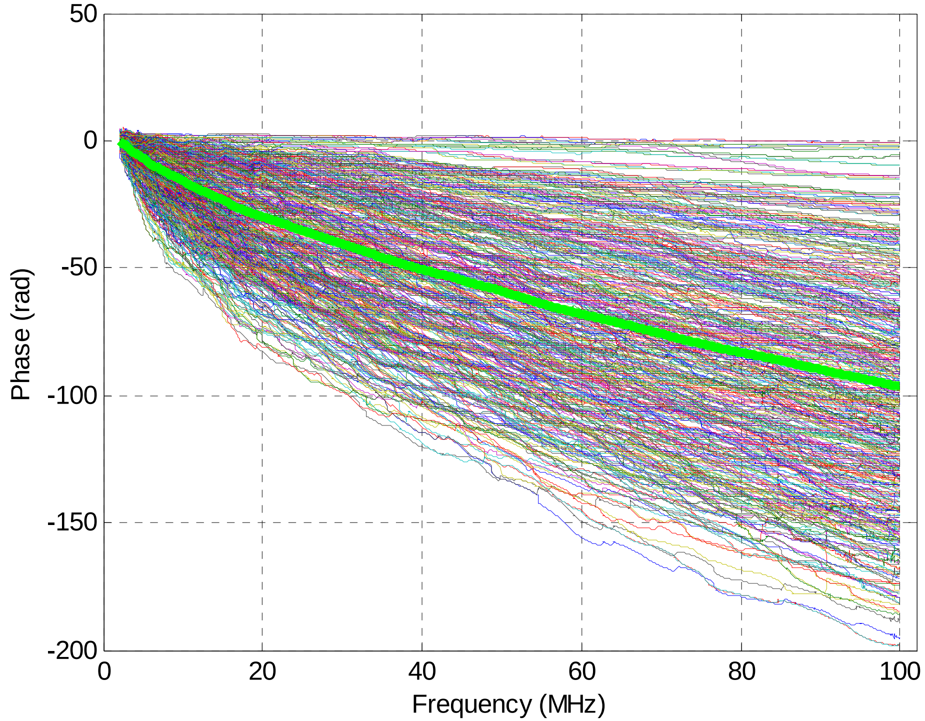
Path Loss and Phase from Measurements

Path Loss



- On average
  - High attenuation
  - Frequency increasing attenuation
- Strong fading effects
  - Average channel gain is log-normal

Phase

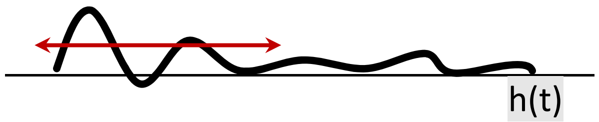


- The phase is not uniformly distributed
- The average phase is not linear at low frequencies

Statistical Analysis

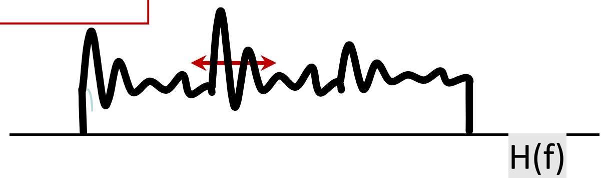
- It is important to characterize statistically the channel
- We define the **Root Mean Square Delay Spread** as

$$\sigma_\tau = \sqrt{\int_0^D \tau^2 P(\tau)\, d\tau - \left(\int_0^D \tau P(\tau)\, d\tau\right)^2}, \quad P(t) = h(t)^2 \Big/ \int_0^D h(\tau)^2\, d\tau$$



- We define the **Coherence Bandwidth** as

$$R(f) = \int_{B_1}^{B_2} H(\lambda) H^*(\lambda + f)\, d\lambda \qquad \left|R\left(B_c^{0.9}\right)\right| = 0.9\left|R(0)\right|$$

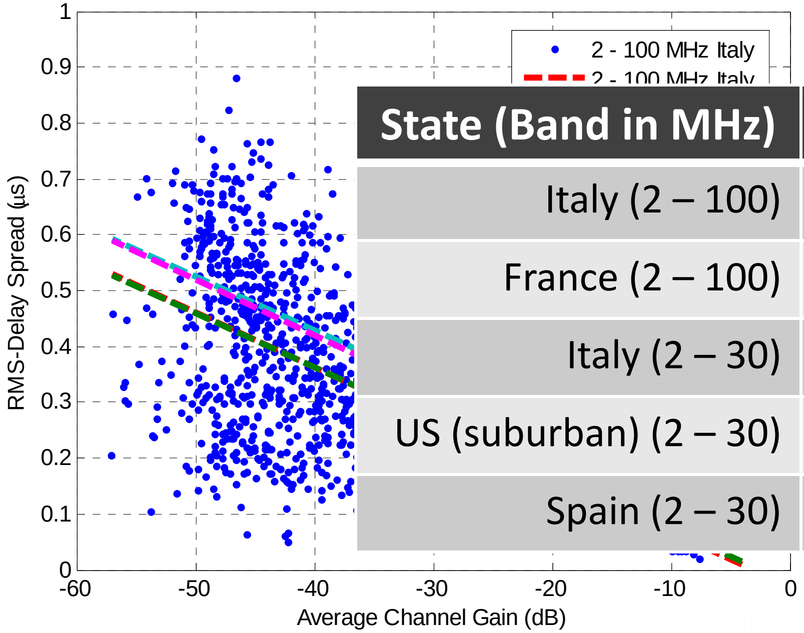


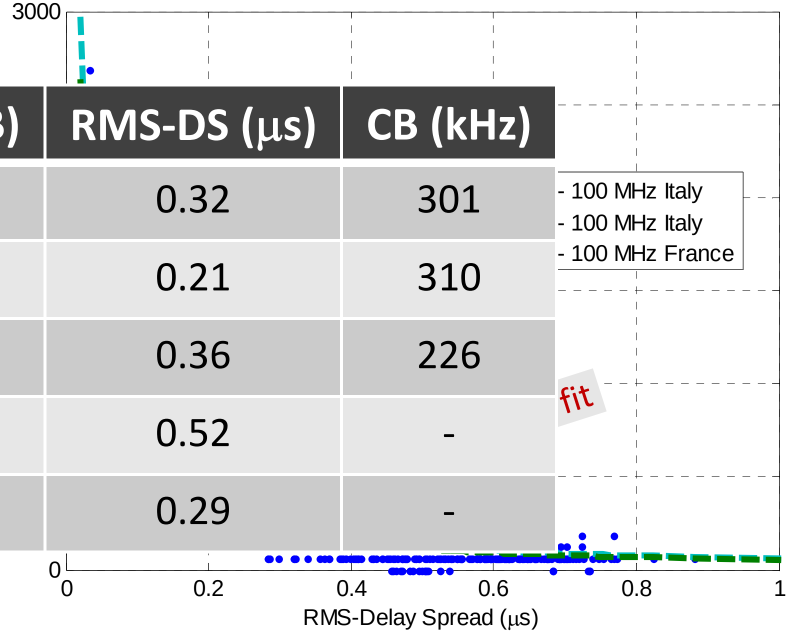
- We define the **Average Channel Gain** as

$$G = 10\log_{10}\left(\frac{1}{B_2 - B_1}\int_{B_1}^{B_2} |H(f)|^2\, df\right)$$

Relations between Metrics

- The higher the channel attenuation, the higher the delay spread
- Coherence bandwidth is an hyperbolic function of the delay spread
- Data from campaigns in Italy, in France, in USA, and in Spain





State (Band in MHz)	ACG (dB)	RMS-DS (μs)	CB (kHz)
Italy (2 – 100)	-35.75	0.32	301
France (2 – 100)	-	0.21	310
Italy (2 – 30)	-32.38	0.36	226
US (suburban) (2 – 30)	- 48.9	0.52	-
Spain (2 – 30)	-30	0.29	-

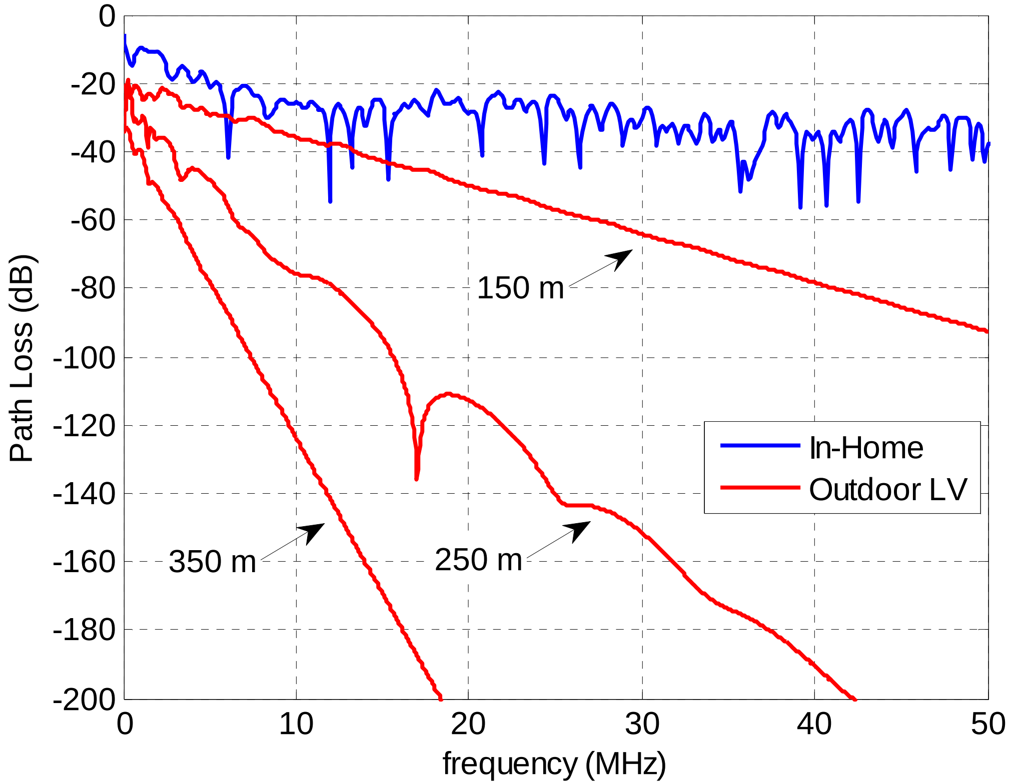
REF. M. Tlich, A. Zeddam, F. Moulin, F. Gauthier, "**Indoor Power-Line Communications Channel Characterization Up to 100 MHz – Part II: Time Frequency Analysis**," *IEEE Trans. Power Del.*, 2008.
REF. S. Galli, "**A Simple Two-Tap Statistical Model for the Power Line Channel**," *in Proc. of ISPLC 2010.*
REF. F. J. Cañete, et al., "**On the Statistical Properties of Indoor Power Line Channels: Measurements and Models**," in Proc. *of ISPLC 2011*.
REF F. Versolatto, A. Tonello, "**On the Relation Between the Geometrical Distance and Channel Statistics in In-Home PLC Networks**," in Proc. *of ISPLC'12*..

Channel Characterization

Outdoor LV and MV Channel

Outdoor LV vs. In-Home PLC Channel

- Comparison between OPERA (Open PLC European Research Alliance) reference channels and a typical In-Home channel



- **In-Home** channels have high frequency selectivity and low attenuation
  - Very high number of branches, discontinuities and unmatched loads
  - Short cables
- **Outdoor LV** channels have high attenuation but negligible fading
  - Cable attenuation dominates

REF. M. Babic et al., "**OPERA Deliverable D5. Pathloss as a Function of Frequency, Distance and Network Topology for Various LV and MV European Powerline Networks**," 2005.

Outdoor MV Channel

- MV channels exhibit in general (but not always) **lower attenuation than Outdoor LV PLC**

- Overhead cables manifest the effect of high-loss earth

- Coupling effects have also to be considered
  - Inductive / Capacitive coupling

REF. A. Tonello, et al. "**Analysis of Impulsive UWB Modulation on a Real MV Test Network,**" in Proc. *IEEE Int. Symp. on Power Line Commun. and Its App. ISPLC'11*, Apr. 2011.

Can We Model the Channel ?

Top-down Modeling Approach

Top-Down Statistical Modeling

- The channel transfer function can be **deterministically** modeled according to the Multipath Propagation Model (MPM)

$$H(f) = A\sum_{i=1}^{N_p} \underbrace{\boxed{p_i(f)}}_{\text{Reflection/transmission effects}} \cdot \underbrace{\boxed{e^{-\left(a_0+a_1 f^K\right)d_i}}}_{\text{Cable attenuation}} \cdot \underbrace{\boxed{e^{-j2\pi f d_i/v}}}_{\text{Propagation phase shift}}$$

- **IDEA:** introduce the variability into the model (**statistical extension**)

N_p: Poisson random variable with intensity $\Lambda L_{\max}$

$p_i(f)$: log-normal frequency-dependent r.v. with a random sign flip

d_i : Erlang random variable (uniform distribution in $[0, L_{max}]$ given N_p)

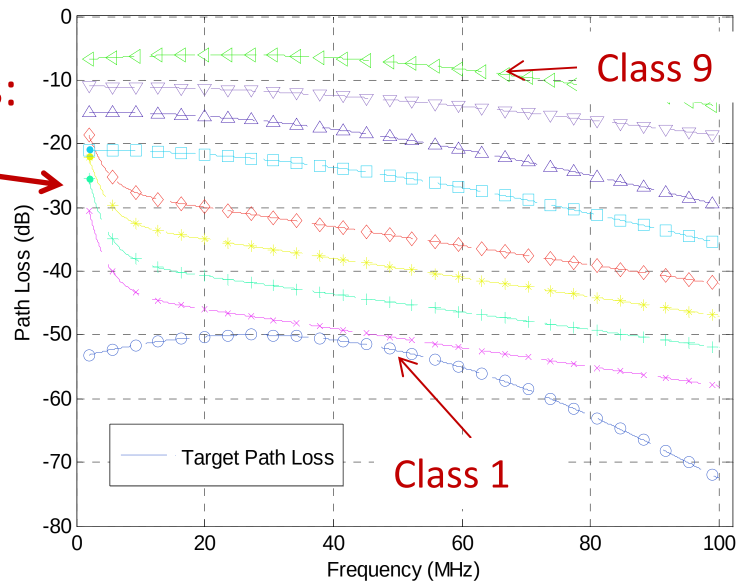
REF. A. Tonello, "**Wide Band Impulse Modulation and Receiver Algorithms for Multiuser Power Line Communications**," *EURASIP Journal on Advances in Signal Processing* 2007.

REF. A. Tonello, F. Versolato, B. Bejar, S. Zazo, "**A Fitting Algorithm for Random Modeling the PLC Channel**," *IEEE Trans. on Power Delivery*, 2012

Fitting the Top-Down Model

- The MPM can be fitted to the experimental measures
  - It requires the knowledge of the average path loss profile and the RMS delay spread of the measured channels
  - To catch the full variability, we define classes of channels. Each class is associated to a certain occurrence probability, and a set of parameters

- Examples of fitting the measures in home nets:
  - EU FP7 Omega project (France campaign)
  - Italian campaign (*discussed before*)



A SW Generator is available at: www.diegm.uniud.it/tonello

REF. A. Tonello et al., "**A Top-Down Random Generator for the In-Home PLC Channel**," *Proc. Global Commun. Conf. (GLOBECOM'11)*, Dec. 2011.
REF. A. Tonello, F. Versolatto, B. Bejar, S. Zazo, "**A Fitting Algorithm for Random Modeling the PLC Channel**", *Trans. on Power Delivery, 2012.*
REF. FP7 Theme 3 ICT-213311 OMEGA, "**PLC Channel Characterization and Modeling**," Deliverable 3.2, Dec. 2008.

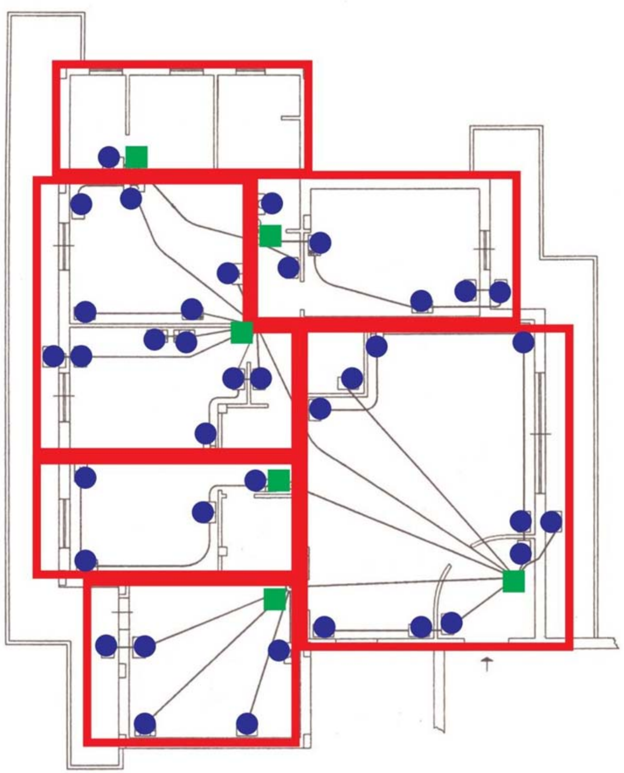
Can We Model the Channel ?

Bottom-up Modeling Approach

Bottom-Up Channel Modeling

- **Idea:**
  - Use transmission line theory to determine the channel transfer function
- **Requirements:**
  - Knowledge of topology, cables and loads
- **Statistical extension:**
  - Develop a statistical model for the topology, etc.
- *In the following, we consider the application to the in-home case*

In-Home : Bottom-Up Statistical Modeling



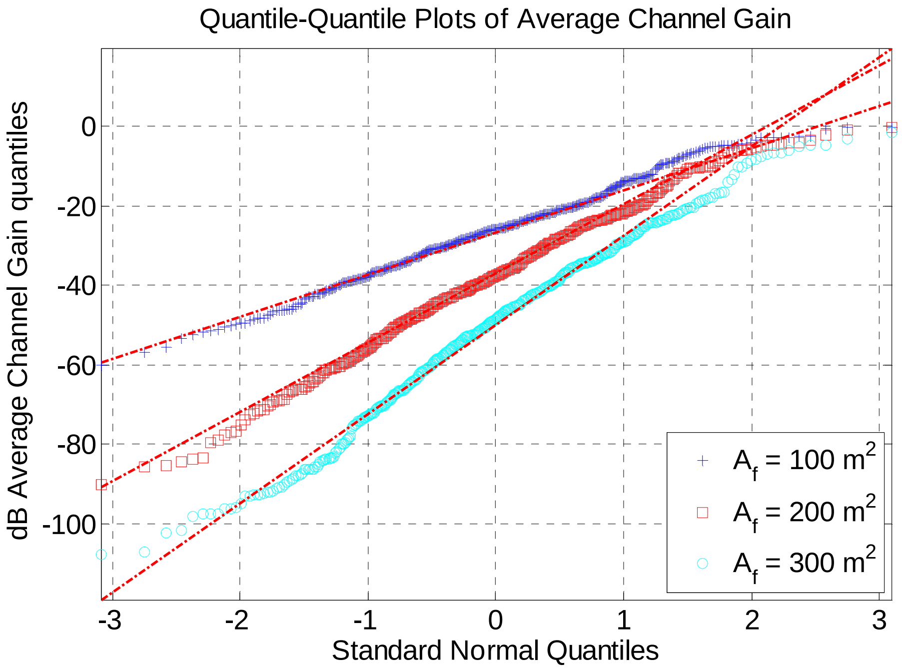
● : outlets

■ : derivation boxes

- Random topology generation
  - Regular structure: the area can be divided in clusters (typically one room/cluster)
  - Each cluster has a derivation box
  - National practices and norms can also be implemented (e.g., UK ring topology)
- Applying Trasmission Line theory we can compute the CTF among any pair of outlets for a topology realization
  - Efficient method based on voltage ratio approach has been developed

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.*, vol. 26, no. 2, pp. 891 – 898, Apr. 2011.

Why a Bottom-Up Approach ?



- The bottom-up approach allows the connection to physical reality (topology, distance, time variant loads …). *But more complex.*
- This theoretical approach matches the measured metric distributions, e.g., log-normality of delay spread and average channel gain.

REF. A. Tonello, F. Versolatto, "**Bottom-up Statistical PLC Channel Modeling – Part II: Inferring the Capacity**," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2356 – 2363, Oct. 2010.

Why a Bottom-Up Approach ?

- The PLC channel can be time variant due to
  - Changes of topology
  - Time variant loads connected to the network

- The channel can be modeled as *linear periodically time variant* (LPTV) because of the periodic change of load impedances with the mains cycle (2-state cyclic behavior)

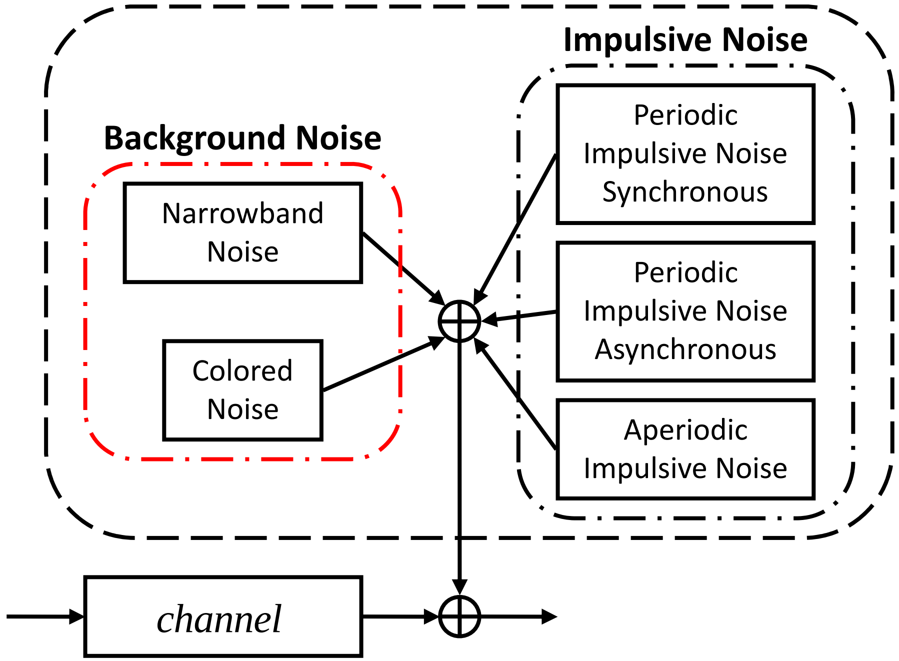
- The bottom-up approach allows to take into account these effects

REF. F. J. Cañete, J. A. Cortés, L. Díez, and J. T. Entrambasaguas, "**Analysis of the Cyclic Short-Term Variation of Indoor Power Line Channels**", *IEEE J. on Sel. Areas in Commun.*, vol. 24, no. 7, pp. 1327-1338, Jul. 2006.

Noise Characterization

PLC Noise Classification

- The PLC noise comprises five components

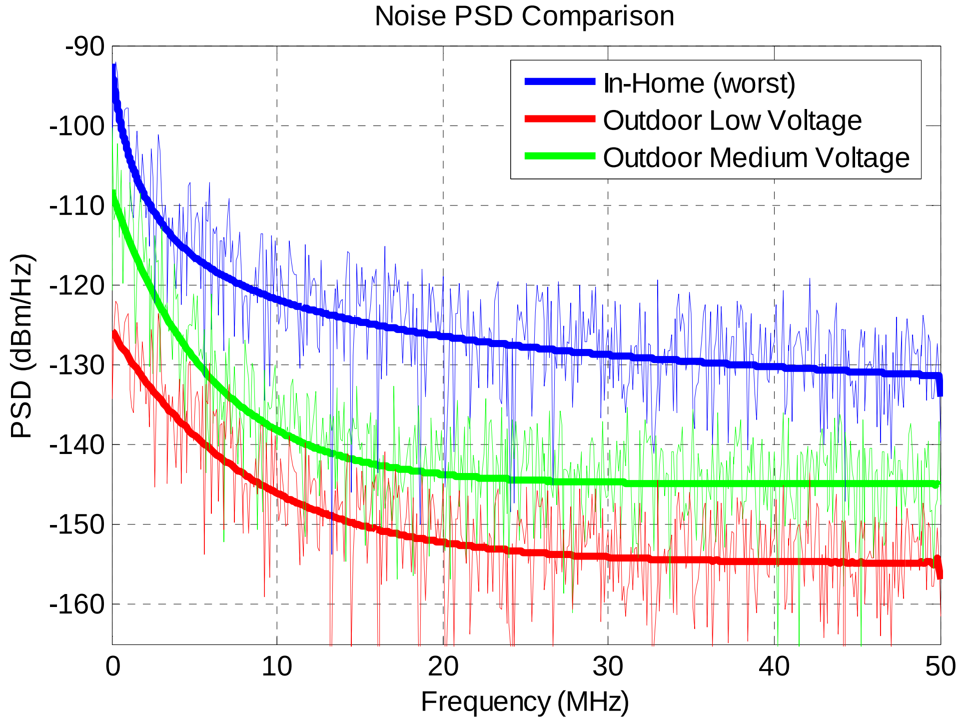


REF. M. Gotz, M. Rapp, K. Dostert, "**Power Line Channel Characteristics and their Effect on Communication System Design**," *IEEE Comm. Mag.*, vol. 42, no. 4, pp. 78 - 86, 2004.

Noise Characterization

Background Noise

Background Noise Comparison



- ❑ Background noise has an exponential PSD
- ❑ Narrowband interference exhist
  - – FM disturbances (> 87.5 MHz)
  - – AM (< 1.6 MHz)
  - – Radio amateur (from 1.9MHz up to SHF)

- ❑ In-Home PLCs experience the highest level of noise
- ❑ Overhead MV background noise due to *corona discharges*
  - – *The strong electric fields determine the avalanche generation of free charges in the surrounding air, which in turn induce current pulses in the conductors*

REF. Noise models from :

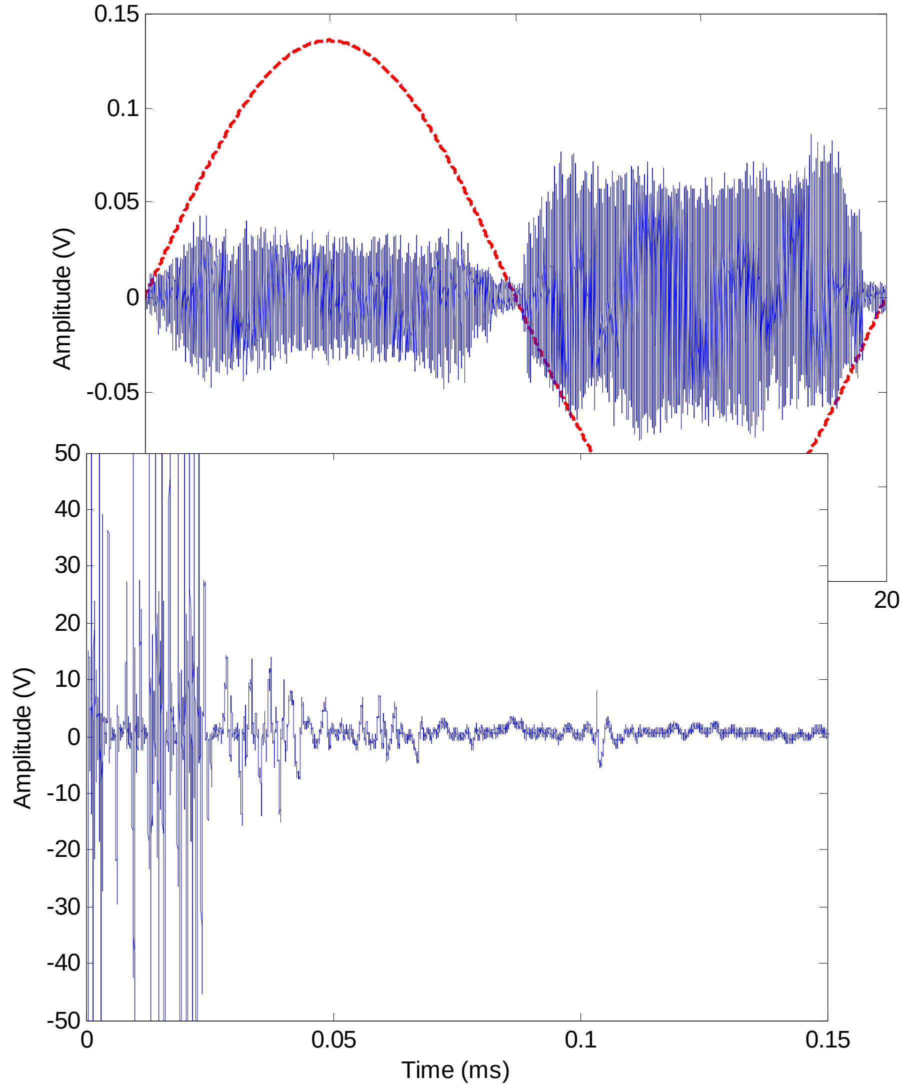
1. T. Esmailian, F. R. Kschischang, and P. Glenn Gulak, "**In-Building Power Lines as High-Speed Communication Channels: Channel Characterization and a Test Channel Ensemble**," *Int. J. of Commun. Syst.*, vol. 16, no. 5, pp. 381-400, Jun. 2003
2. EU OPERA Project, "**Deliverable D5**", 2005.

Noise Characterization

Impulsive Noise

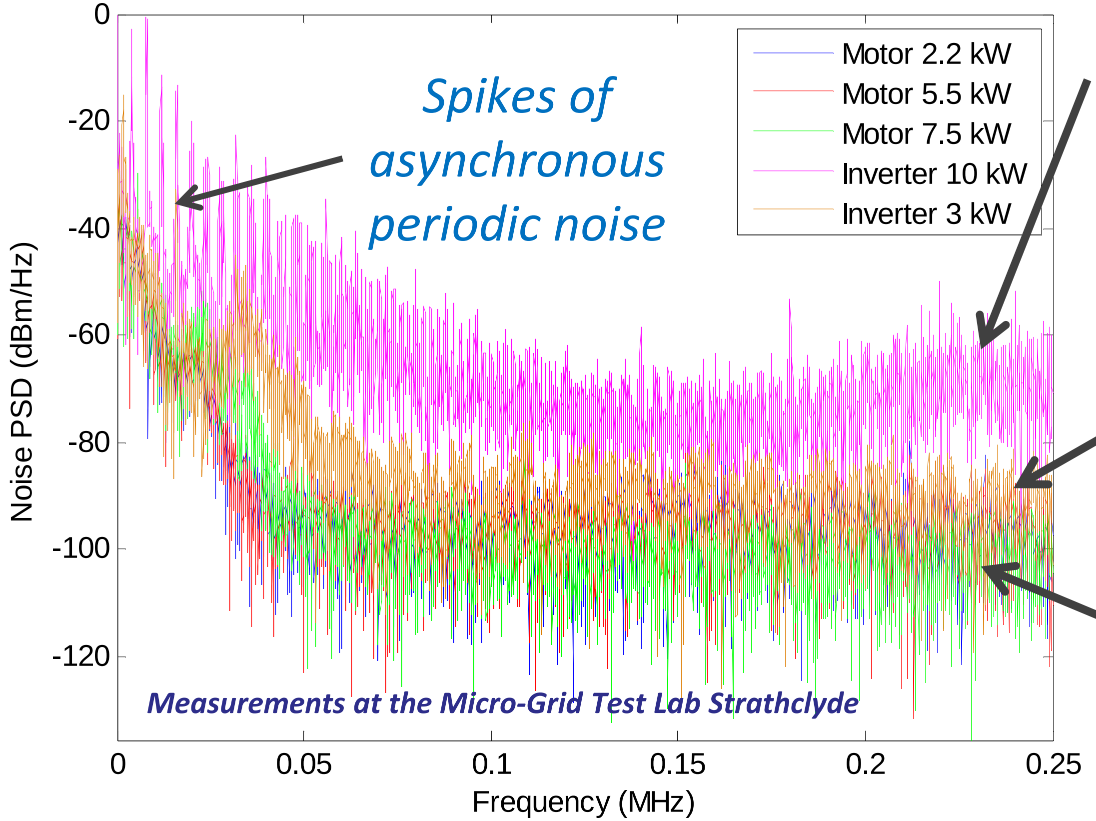
Impulsive Noise Components

- **Periodic impulsive noise**
  - **Synchronous:** components with low rate (50/100 Hz): *rectifiers*
  - **Asynchronous:** components with high rate (200 kHz): *switching devices*
  - The amplitude is small with spectrum confined in frequency
- **Aperiodic impulsive noise**
  - **Bursty nature**: *on-off and plug in-out*
  - Less frequent, but more disruptive
  - High amplitude greater than 50 V



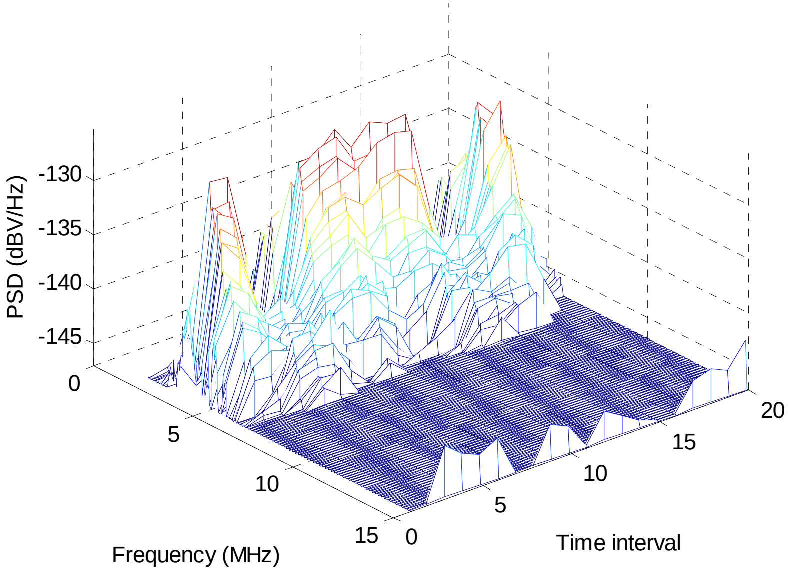
Furthermore…

- Appliances generate asynchronous noise components that are **periodic** with the mains cycle
  - We measured the noise injected by the inverters



Time-Variant Analysis

- The stationary characterization of the noise is not sufficient to get the whole picture of its complex nature



short term PSD during the mains cycle

REF. V. Degardin, M. Lienard, A. Zeddam, F. Gauthie, and P. Degauque, "**Classification and Characterization of Impulsive Noise on Indoor Power Line Used for Data Communications**," *IEEE Trans. Consum. Electron.*, vol. 48, no. 4, pp. 913 – 918, Nov. 2002.

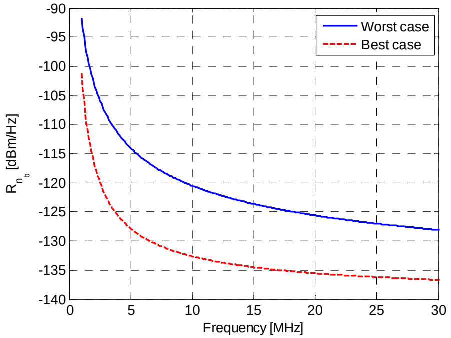
REF. J. A. Cortes, L. Diez, F. J. Canete, and J. J. Sanchez-Martinez, "**Analysis of the indoor broadband power-line noise scenario**," *IEEE Trans. Electromagn. Compat., vol. 52, no. 4, pp. 849–858, Nov. 2010.*

REF. L. Di Bert, P. Caldera, D. Schwingshackl, and A. Tonello, "**On Noise Modeling for Power Line Communications,**" in Proc. *Int. Symp. on Power Line Commun. and Its App.*, pp. 283-288, 2011.

Common Noise Model in the Literature

Common PLC Noise Modeling

Background noise



$$PSD_b(f) = a + b|f|^c \left[\frac{dBm}{Hz}\right]$$

	a	b	c
Best case	-140	38.75	-0.72
Worst case	-145	53.23	-0.337

Two terms Gaussian

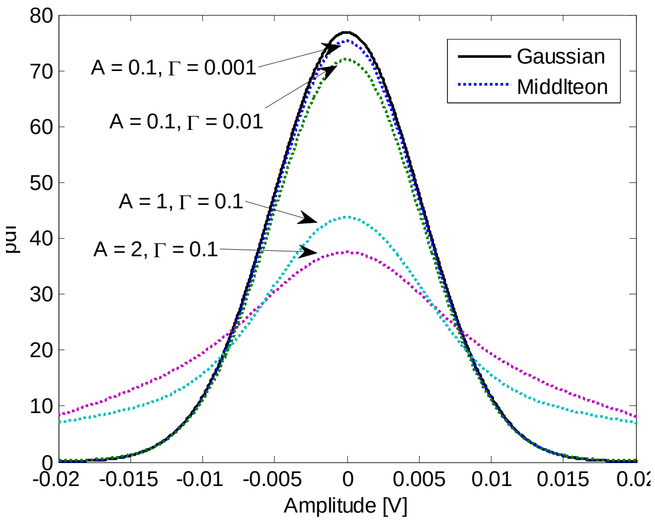
– Sum of two Gaussian PDFs weighted by a Bernoulli process with occurrence probability P

$$p_\eta(v) = (1-P)N\left(0,\sigma_b^2\right) + PN\left(0,K\sigma_b^2\right)$$

Middleton Class A

– Weighted sum of Gaussian PDFs

$$p_\eta(v) = \sum_{k=0}^{\infty} \frac{e^{-A}A^k}{k!} \cdot \frac{1}{\sqrt{2\pi\sigma_k^2}} \exp\left(-\frac{v^2}{2\sigma_k^2}\right) \quad \sigma_k^2 = \left(1+\frac{1}{\Gamma}\right)\left(\frac{k/A+\Gamma}{1+\Gamma}\right)\sigma_b^2$$



Physical Layer Techniques

Single Carrier Modulation (FSK)

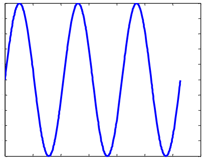
Multi Carrier Modulation

Adaptation: Resource Allocation

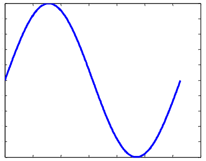
Single Carrier Modulation: FSK

- **Binary FSK**

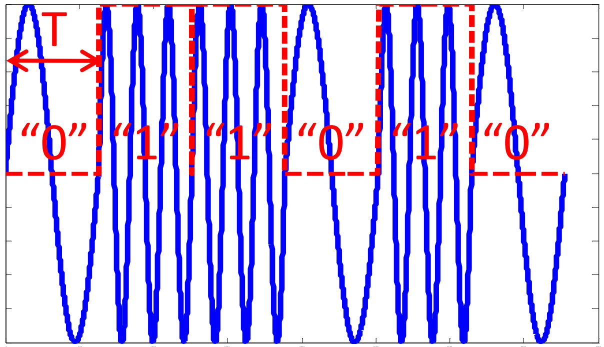
"1" $\Rightarrow \sqrt{\dfrac{2E_S}{T}}\cos\left(2\pi f_H t\right)$



"0" $\Rightarrow \sqrt{\dfrac{2E_S}{T}}\cos\left(2\pi f_L t\right)$



Modulated Signal



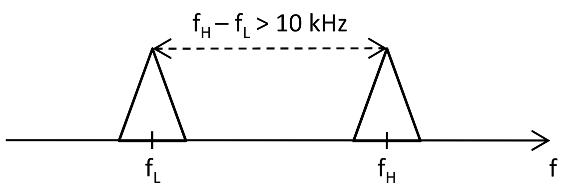
  – Modulation index: $h = \left(f_H - f_L\right)T$

- **M-ary FSK**

"i -th symbol" $\Rightarrow \sqrt{\dfrac{2E_S}{T}}\cos\left(2\pi f_i t\right), \quad i = 0, 1, \ldots, M-1$

Spread Frequency Shift Keying (S-FSK)

- **Spread FSK**
  - Adjustment of FSK for transmission in PLC channels
    - Tones are now placed far from each other (usually 10 kHz)

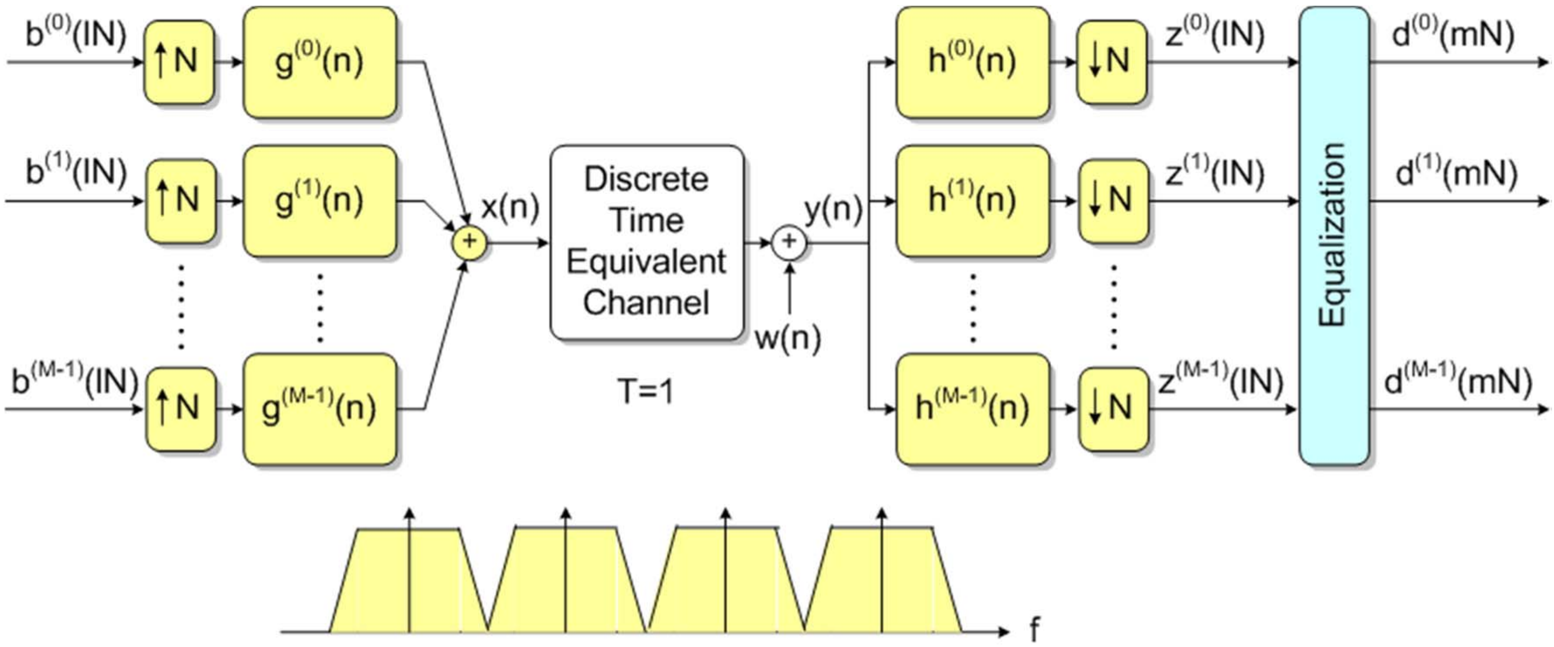


    - M-FSK is suited to be combined with a spreading code (a sort of frequency hopping spread spectrum)
    - Congruential codes have been proposed. They specify the hopping pattern
    - Immunity to narrow band interference can be increased with erasure decoding of spread-FSK
  - The standard *IEC 61334-5-1* uses a form of spread FSK

REF. T. Shaub, "**Spread frequency shift keying**," *IEEE Trans. Commun., pp. 1056-1064, Feb./Mar./Apr. 1994*

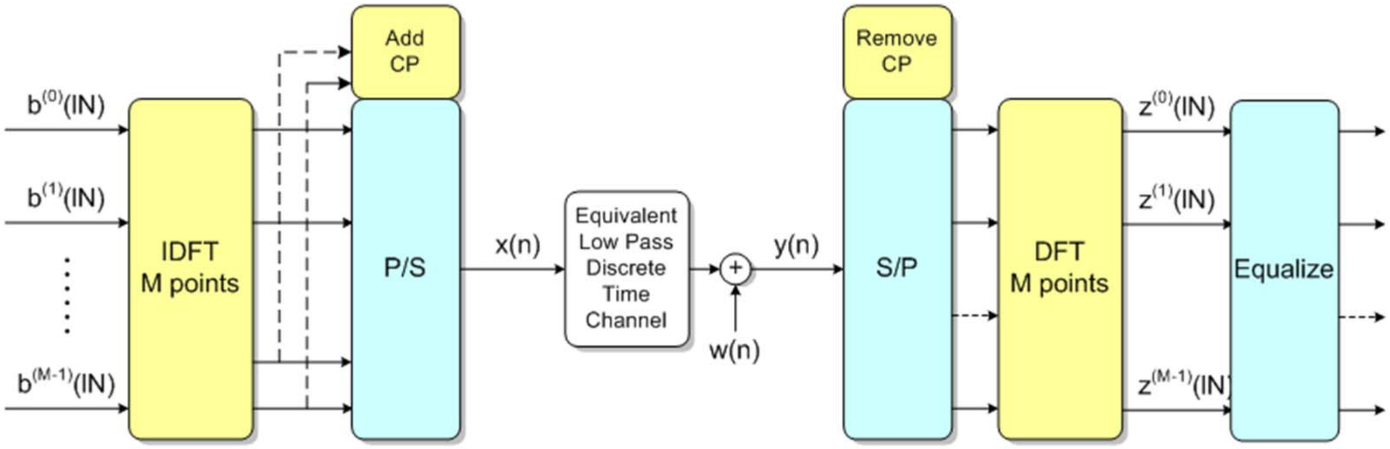
REF. A.J. Han Vinck and J. Haring, "**Coding and Modulation for Power-Line Communications**," in *Proc. of IEEE ISPLC* 2000

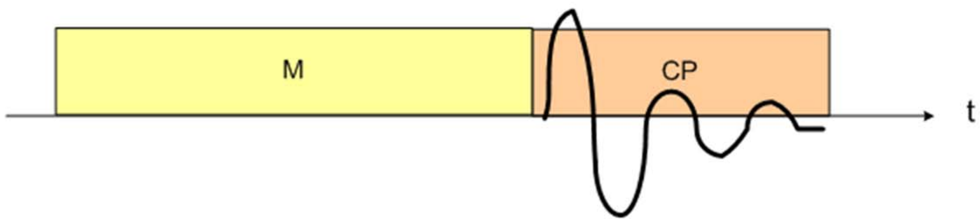
Unified View of MC Modulation



- $b^{(k)}(mN)$: QAM data symbols
- $g^{(k)}(n)$: sub-channel pulses, obtained from the modulation of a prototype pulse
- N: interpolation factor $N \geq M$ number of sub-channels

Cyclically Prefixed OFDM

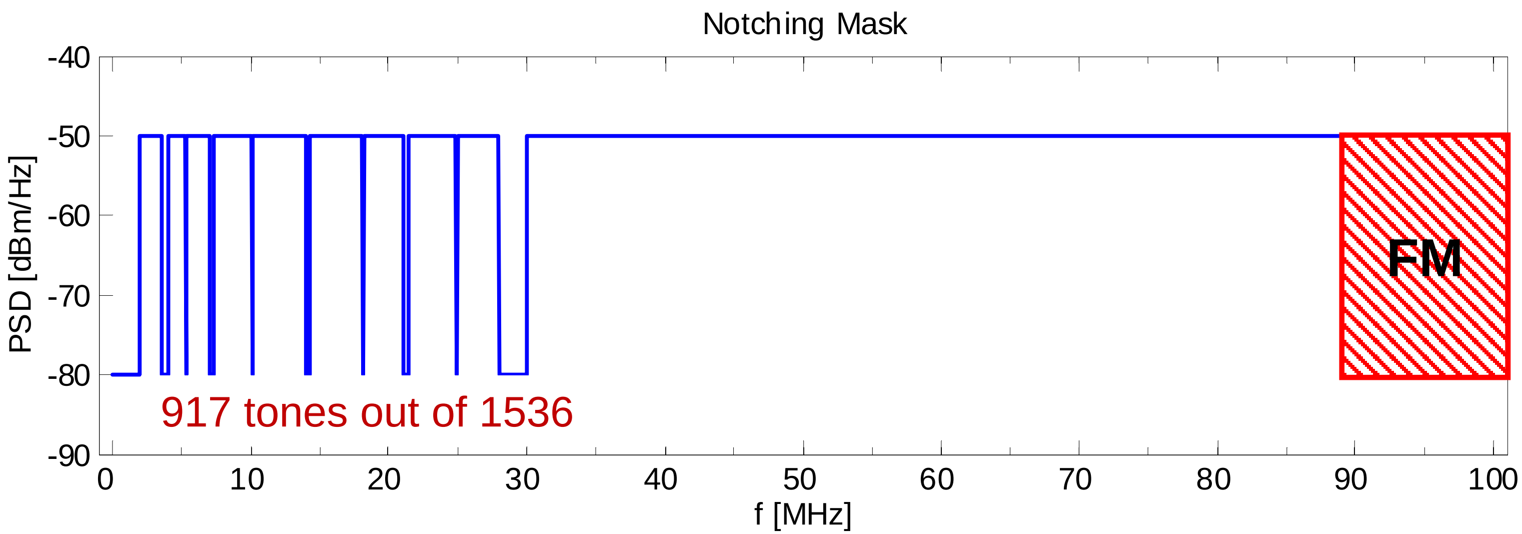




- M tones (sub-channels)
- Rectangular sub-channel pulse (window) of duration $N > M$ samples
- Cyclic prefix (CP) of length μ=N-M samples (typically longer than the channel duration)

Notching

- It is fundamental to generate low radiations in certain parts of the spectrum, e.g., Radio amateur signals
- Further notching can be done beyond 30 MHz to grant coexistence with other systems



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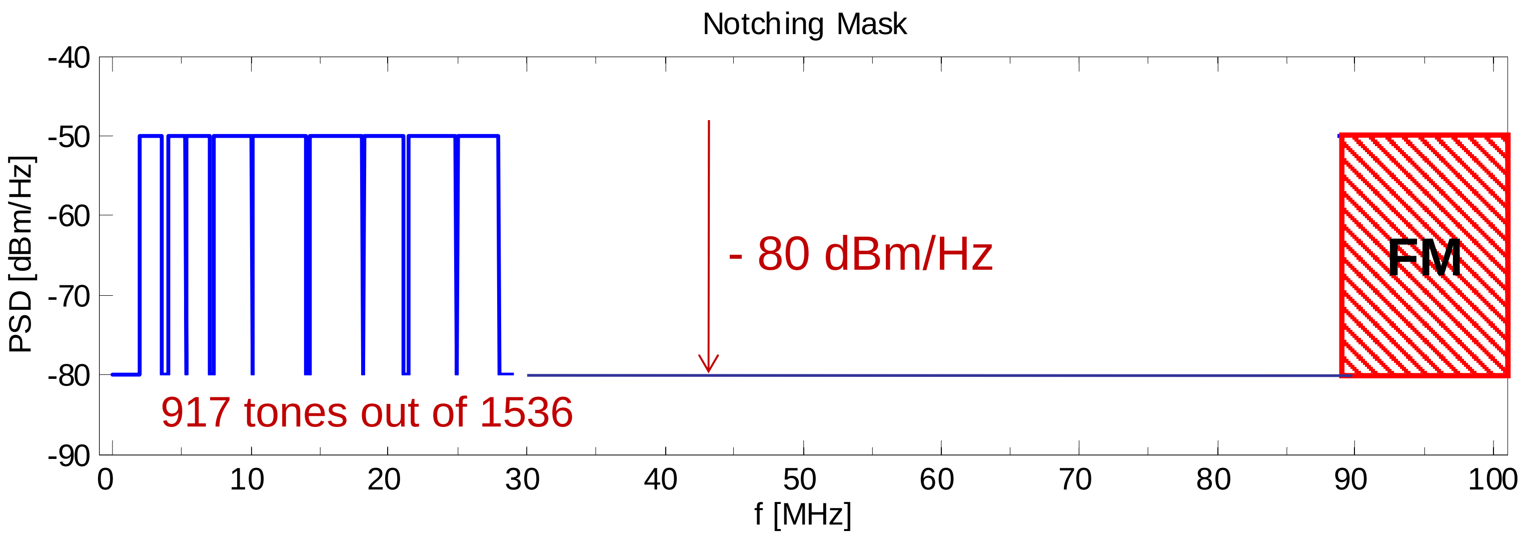
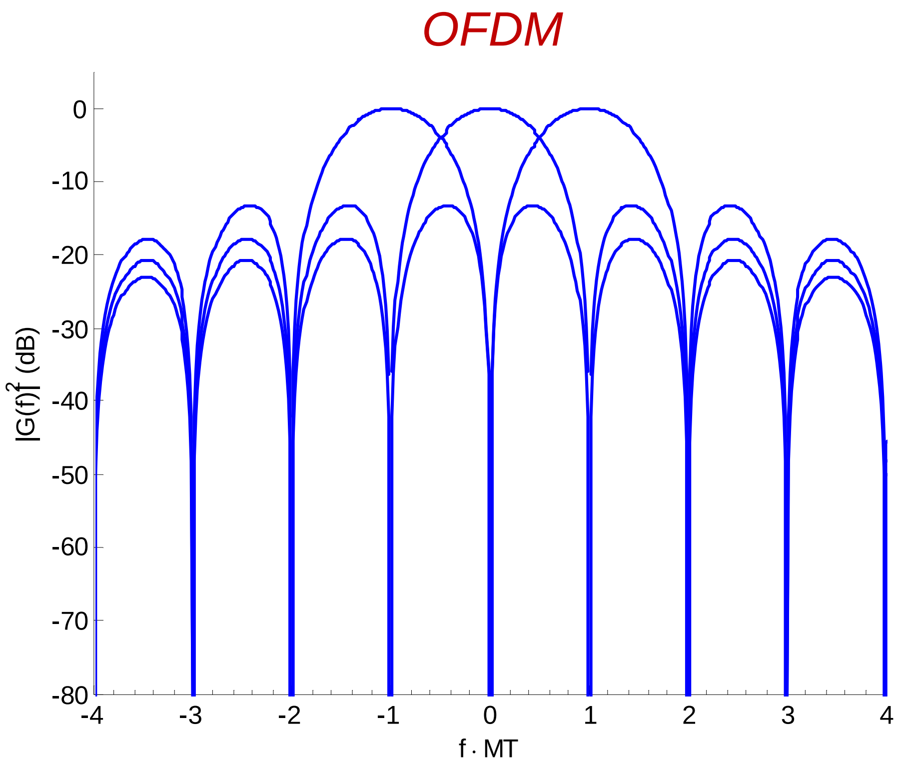
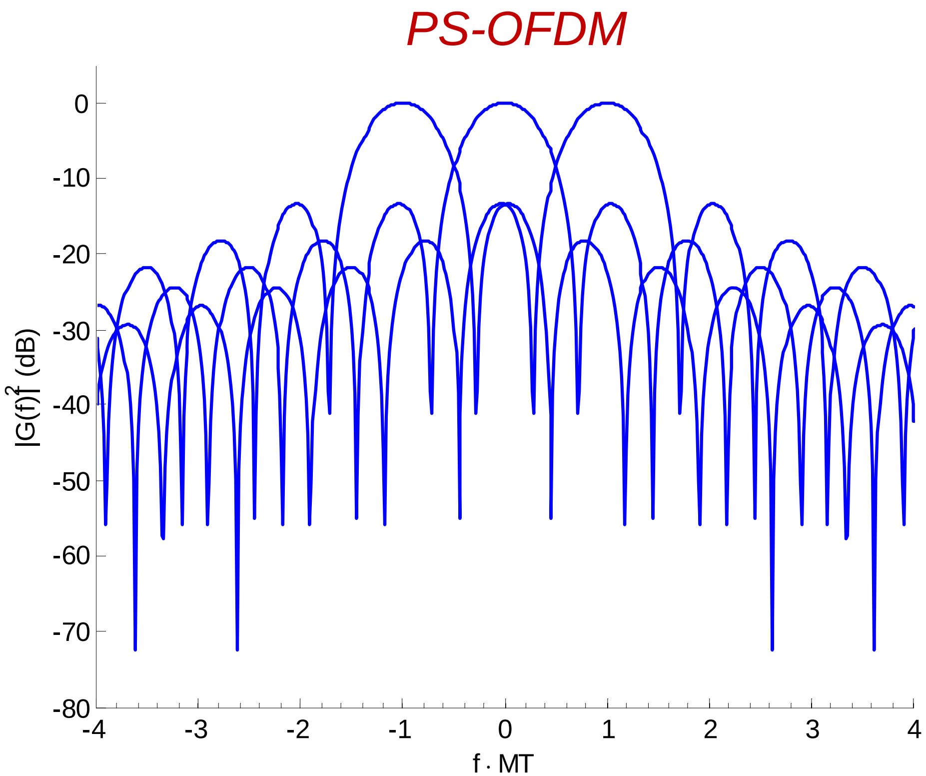


Spectrum of OFDM and PS-OFDM





- Pulse shaped OFDM: Use a root-raised-cosine window (or other), to fulfill the mask with a higher number of active tones.

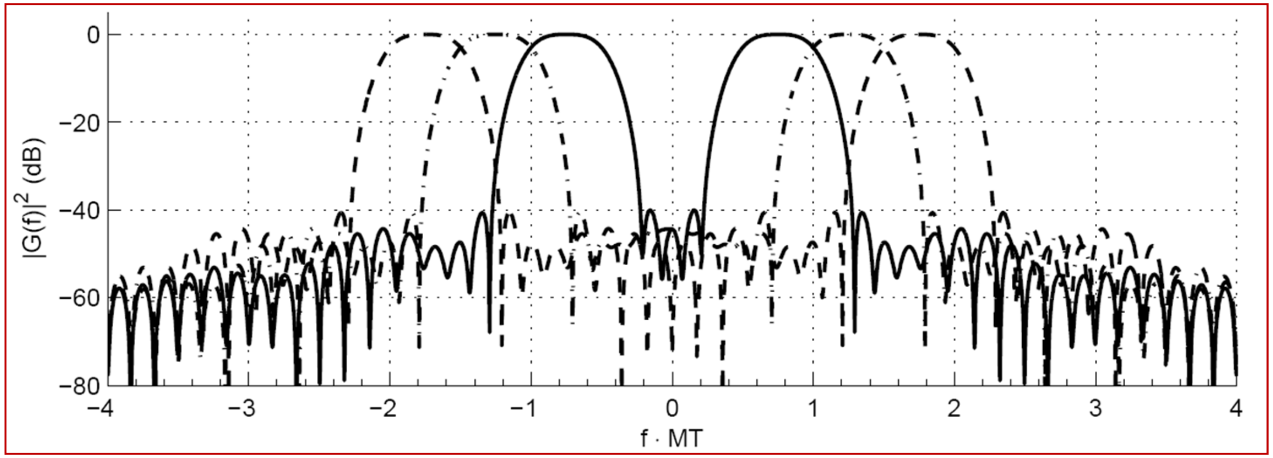
Filter Bank Approaches

- Can we increase the sub-channel frequency selectivity ?
  - Yes, by privileging the frequency confinement

- What schemes are available ?
  - Wavelet OFDM (one solution adopted by IEEE P1901)
  - Filtered Multitone Modulation (FMT)
  - Other FB approaches are also possible (*see the large signal processing literature on FBs*)

Wavelet OFDM

- Wavelet OFDM is a cosine modulated filter bank
- It was proposed in REF1 and called DWMT
- Example of spectrum

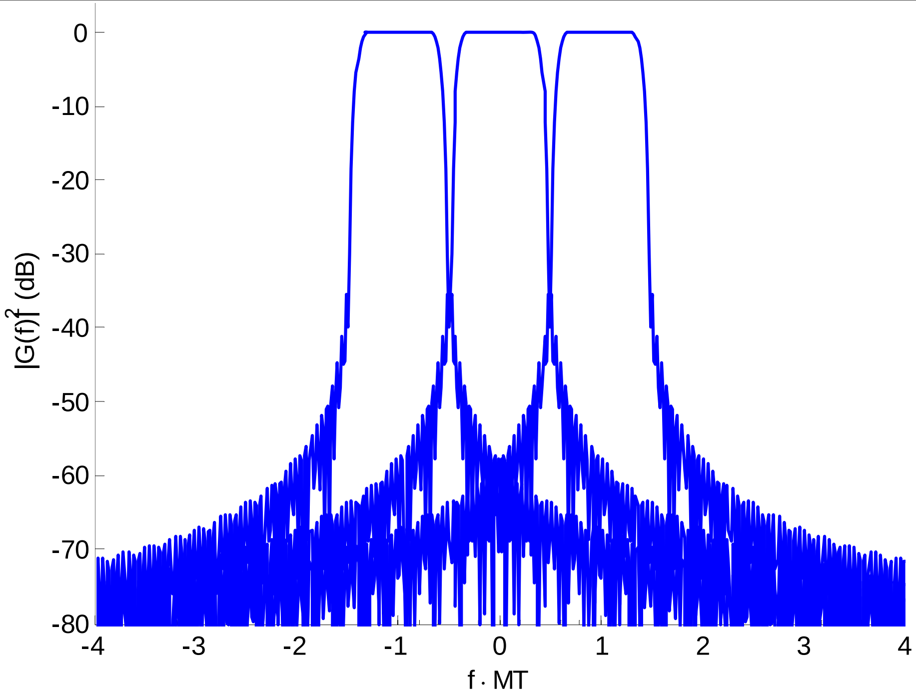


- Sub-channels have high overlapping. Nevertheless, it is possible to construct a perfect reconstruction critically sampled filter bank
- Channel distortion introduces ISI and ICI. Therefore, single tap equalization is not sufficient and multichannel equalizers may be needed

REF1. S. Sandberg, M. Tzannes, "**Overlapped discrete multitone modulation for high speed copper wire communications**," *IEEE JSAC, Dec. 1995.*

REF2. "**Power Line Communications – Theory and Applications for Narrowband and Broadband Communications over Power Lines**," eds. Ferreira, Lampe, Newbury, Swart, Wiley & Sons. Ltd., 2010. Chapter 5.

FMT Basics

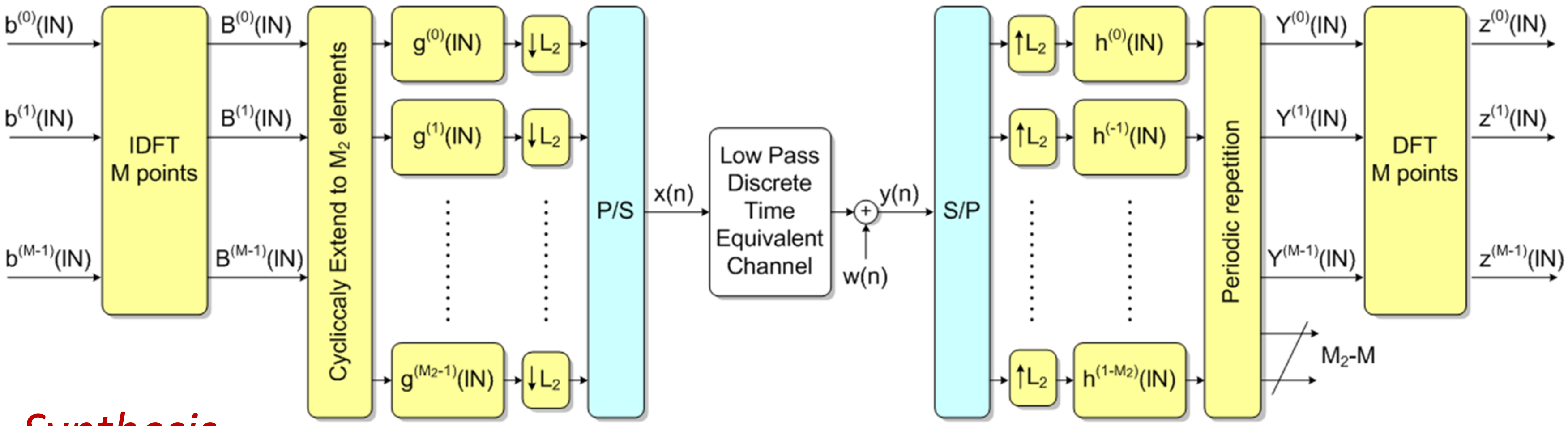


- Pulses obtained from modulation of a prototype pulse
  - Root-raised-cosine
  - Time/Frequency confined pulses
  - Perfect reconctruction solutions provided that $N > M$

REF. G. Cherubini, E. Eleftheriou, S. Olcer, "**Filtered multitone modulation for very high-speed digital subscriber lines**," *IEEE J. Select. Areas Comm. 2002.*

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

Efficient Realization



- *Synthesis*
  - M point IDFT and Cyclic extension to $M_2 = l.c.m.(M,N) = L_1M = L_2N$
  - **Pulses**: PP components of order *N*, i.e., $g^{(i)}(nN) = g(i+nN) \quad i = 0,...,N-1$
  - Sample with period L_2
- *Analysis*
  - Dual operations
- *Complexity:* $M \log_2 M + L_{g,h}$ (pulse length) operations/sample

REF. N. Moret, A. Tonello, "**Design of Orthogonal Filtered Multitone Modulation Systems and Comparison among Efficient Realizations**," *EURASIP Journal on Adv. In Signal Processing, 2010.*

How to Increase Performance ?

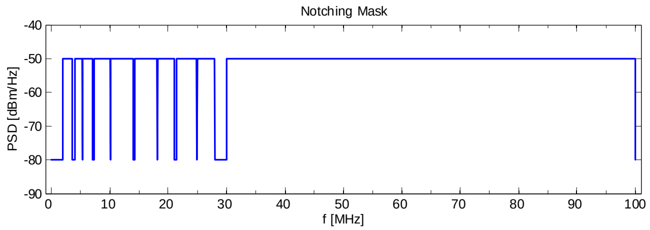
- ❑ Increase bandwidth
  - up to 100 MHz or even above for BB PLC
  - up to 500 kHz for NB PLC
- ❑ Use powerful channel coding
- ❑ Perform adaptation of the transmitter parameters:
  - bit and power loading
  - adaptive scheduling (exploiting cyclic SNR variations)
  - cognitive use of spectrum
- ❑ Use MIMO transmission

REF. A. Tonello, S. D'Alessandro, L. Lampe, "**Cyclic Prefix Design and Allocation in Bit-Loaded OFDM over Power Line Communication Channels**," *IEEE Trans. on Communications, Nov. 2010.*

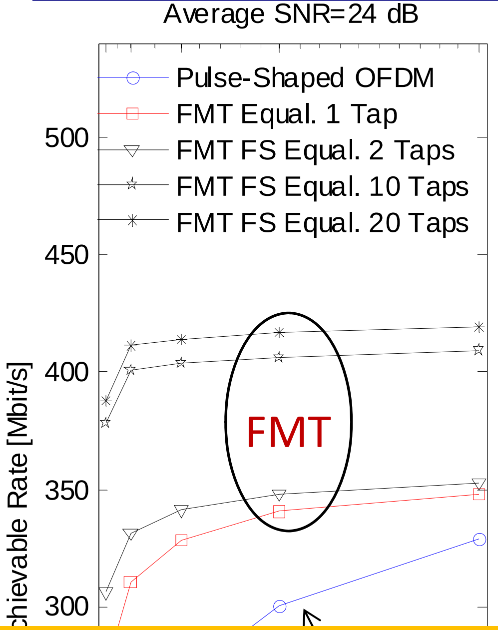
REF. "**Power Line Communications – Theory and Applications for Narrowband and Broadband Communications over Power Lines**," eds. Ferreira, Lampe, Newbury, Swart, Wiley & Sons. Ltd., 2010. Chapter 5.

Achievable Rate as a Function of N. of Tones

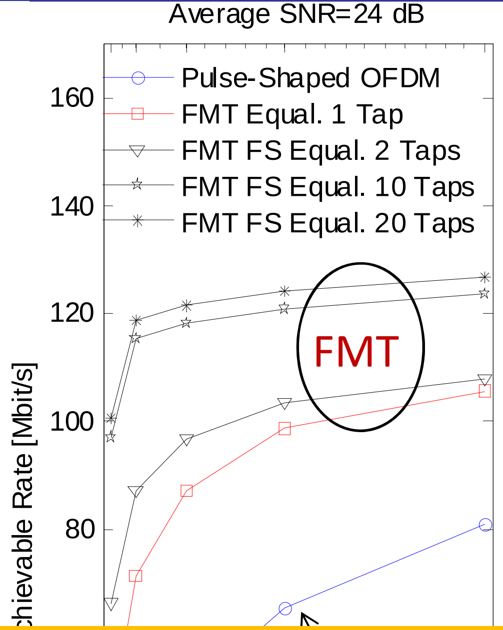
Target notching mask below 30 MHz: HPAV



Masked 2-100 MHz



Masked 2-28 MHz

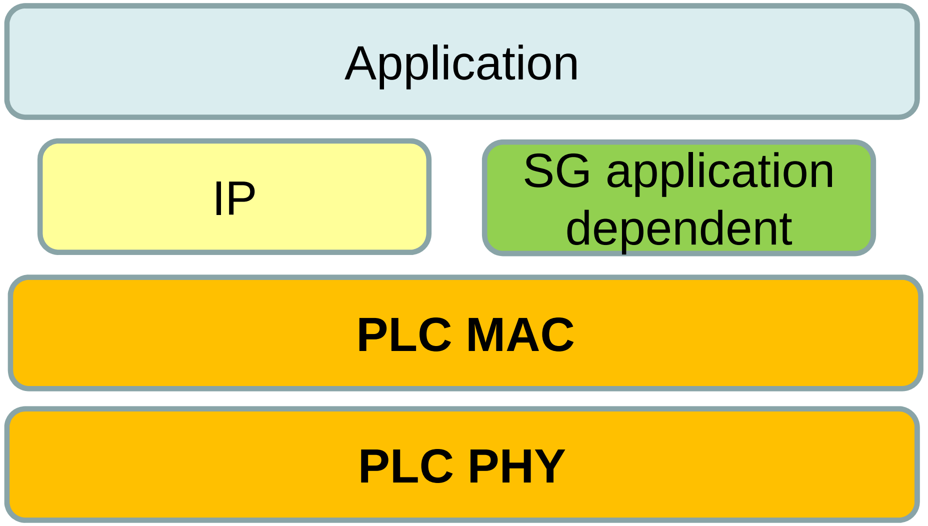


- ❑ FMT outperforms PS-OFDM
- ❑ The lower the SNR the higher is the advantage of FMT w.r.t. PS-OFDM
- ❑ FMT has better notching capability
- ❑ FMT achieves the maximum rate with a smaller number of tones

A Look at Systems and Standards

Protocol Stacks

- PLC specifications and standards typically cover layer 1 and 2 (PHY and MAC)
- Network layer and above, up to application:
  - is specified by other standards, e.g., AMR (IEC 61334-4-32)
  - convergent layers are under investigation, e.g., from IPv4 to IPv6 and/or protocols for certain applications



MAC Aspects

- The media access scheme depends on the application and type of data traffic
  - Metering, sensor network, QoS traffic (audio/video),…
  - Throughput but also latency are important
- Contention free and contention based schemes are used in PLC
  - CSMA/CA (hidden node problem)
  - Dynamic TDMA (some overhead is required)
- Network synchronization can exploit the mains cycle
- Scheduling of resources can exploit SNR cyclic behavior

Narrow Band PLC Systems and Standards

	Insteon	Konnex	X10	CEBus	UPB Universal PLC bus	HomePlug C&C	Meters & More (Enel, Endesa)	G3-PLC	PRIME PowerLine Intelligent Metering	G.Hnem ITU-T 9955	IEEE P1901.2
	Home Automation					*Command and Control*	*Automatic Meter Reading*			*NB standard*	*NB standard*
Standard body	**Single carrier Low data rate: some kbits/s**							**Multicarrier data rate: hundred of kbits/s**			
Spectrum	CENELEC C	CENELEC B	CENELEC B	CENELEC FCC ARIB	CENELEC A	CENELEC A C FCC ARIB	CENELEC	CENELEC A FCC	CENELEC A	A, B,C,D FCC	A, B,C,D FCC
Modulation	BPSK	S-FSK	PPM	Spread Spectrum	PPM	DCSK *differential code shift keying*	BPSK	OFDM DQPSK DBPSK	OFDM D8PSK DQPSK DBPSK	OFDM QPSK 16-QAM	-
Bit-rate	2.4 kbps	1.2 kbps	50 or 60 bps	8.5 kbps	240 bps	0.6 to 7.5 kbps	Up to 4800 bps	34 to 240 kbps	128 kbps	up to 1 Mbps	-
MAC	ND	CSMA	CSMA/CD	CSMA/CD	-	CSMA/CA	-	CSMA/CA	CSMA/CA TDMA	CSMA/CA	-

Broadband PLC Systems and Standards

	HomePlug AV	HP Green PHY	HD-PLC	IEEE P1901	ITU-T G.hn ITU-T G.9960
Standard body	HomePlug Consortium	HomePlug Consortium	High Definition PLC Alliance	IEEE	ITU
Modulation & Coding	OFDM (1536 tones) Bit-loading Up to 1024-QAM Convolutional, Turbo codes	OFDM (1536 tones) QPSK	Wavelet OFDM (512 tones) Bit-loading Up to 16-PAM RS, Convolutional, LDPC	OFDM (HP AV) (3072 tones) Bit-loading Up to 4096-QAM W-OFDM (HD-PLC) (1024 tones) Bit-loading Up to 32-PAM	OFDM (up to 4096 tones) Bit-loading Up to 4096-QAM LDPC
Bit-rate	200 Mbit/s	3.8-9.8 Mbit/s	190 Mbit/s	540 Mbit/s	>200 Mbps Up to 1Gbps
MAC	TDMA-CSMA/CA	CSMA/CA	TDMA-CSMA/CA	TDMA-CSMA/CA	TDMA-CSMA/CA

Multicarrier
data rate:
Over 200 Mbits/s

A Look at Systems and Standards

IEEE and ITU Standards

Standards: IEEE P1901 and ITU-T G.hn

- **IEEE P1901 covers both indoor (in-home) and outdoor PLC (last mile)**
  - Two frequency bands
    - **2-30 MHz:** rate up to 200 Mbit/s. **2-60 MHz:** rate up to 545 Mbit/s
  - **PHY 1:** Windowed OFDM with turbo coding (*from HPAV*)
  - **PHY 2:** Wavelet OFDM with RS/CC and LDPC (*from Panasonic HD-PLC*)
  - **MAC:** TDMA for QoS traffic and CSMA for best effort traffic. Coexistence mechanism for the two PHYs (*IPP, inter PHY protocol*)
- **ITU-T G.9960 (G.hn)**
  - PHY and MAC for in-Home devices that use **power line, coax, and phone lines**
  - Frequency bands
    - **2-50 MHz** (optional 50-200 MHz): rate up to 1 Gbit/s
  - **PHY:** scalable windowed OFDM (2048 tones for PLC)
  - **MAC layer:** TDMA for QoS traffic, CSMA for best effort traffic
  - Coexistence with IEEE P1901 devices but not interoperability

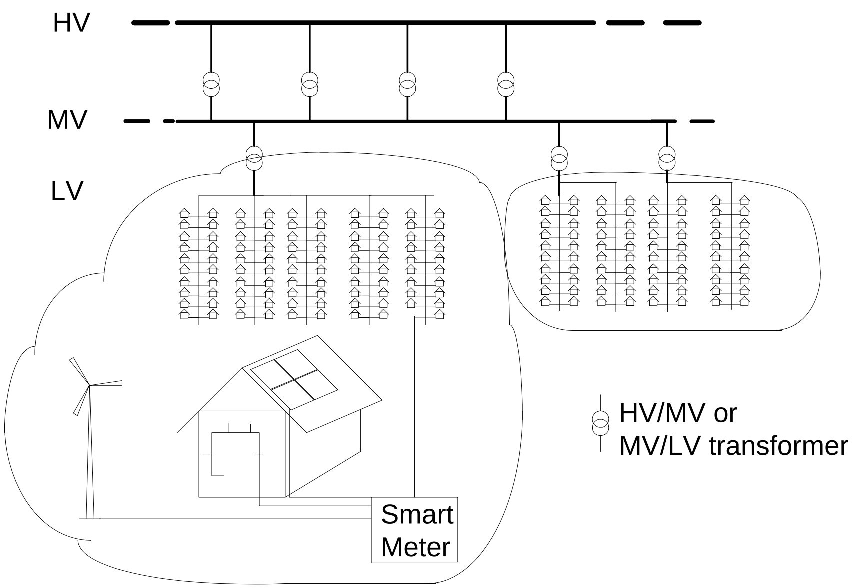
Standards: IEEE P1901.2 and ITU G.hnem

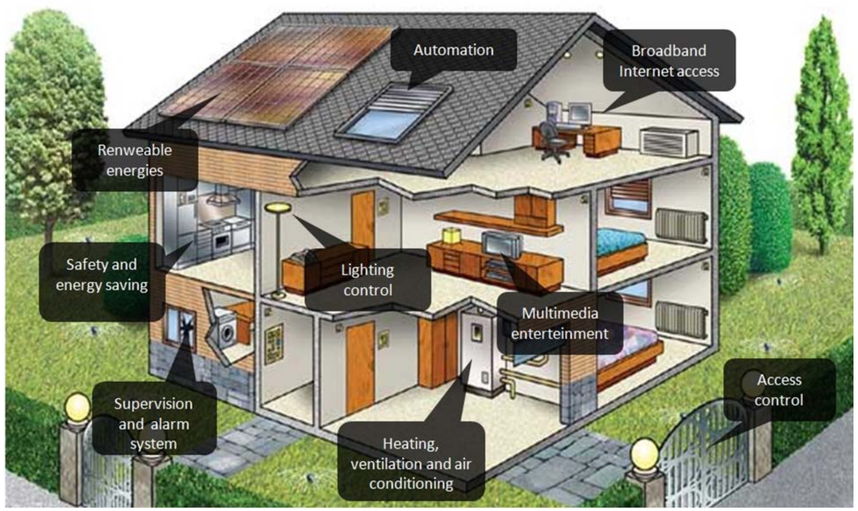
- **IEEE P1901.2: *to be ratified in 2012***
  - Narrow band (less than 500 kHz) PLC standard for both AC and DC lines
    - low voltage indoor/outdoor, as well as medium voltage in both urban and in long distance (multi-kilometer) rural communications
  - Operating in the Cenelec and FCC bands (up to 500 kHz)
  - Scalable data rates up to 500 kbps depending on the requirements
  - It addresses communication for:
    - Grid to utility meter, management of local energy generation devices
    - Electric vehicle to charging station
    - In-home networking for command-and-control
- **ITU-T G. hnem: *ratified in 2011***
  - MAC & PHY for in-home energy management, and LV metering
  - Operating in the Cenelec and FCC bands (up to 500 kHz) up to 1 Mbps

Network and MAC Aspects

Organization in PLC Networks

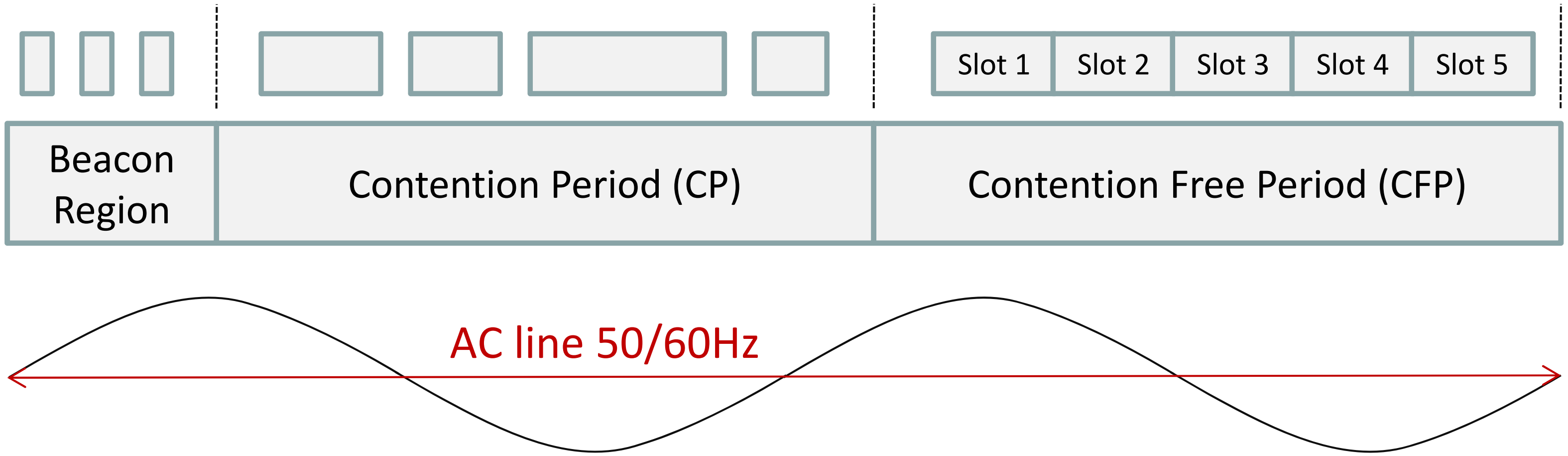
- The Smart Grid renders the PLC network similar to a sensor network
- Network organization is important
  - The network is subject to changes: new nodes, faults, change of loads
  - PLC technologies shall coexist, interconnet and interoperate with other communication technologies, *e.g., WiMax, WLAN, ZigBee, Coax*
- Network organization depends on the application and is implemented through PHY and MAC mechanisms





Mains Cycle: Key for Synchronization

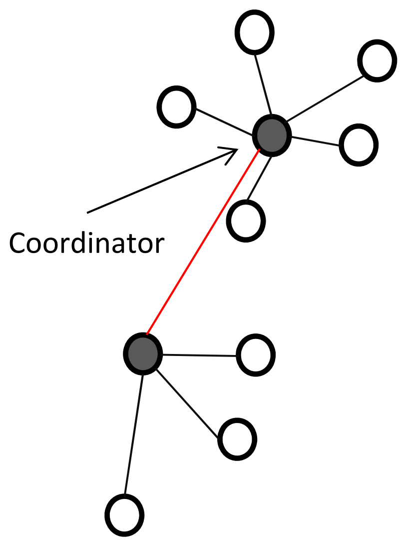
Essence of synchronization in BB PLC: HPAV, IEEE P1901, ITU G.hn



- Beacons are sent by the coordinator to provide info on **CP** and **CFP** periods
- Nodes are synchronized with the AC line
- Stations can contend the channel using CSMA/CA
- Slots assigned by the coordinator to stations (TDMA)

NB PLC Networks

- **Narrowband Devices**
  - Usually, the medium access is not synchronized, *e.g., G3-PLC, ITU-T G.hnem*
  - The nodes contend the channel with CSMA/CA and send the data to the concentrator whose receiver is always on
  - Based on the non synchronized access of IEEE 802.15.4 (Zigbee)
  - The network coordinator (concentrator) defines the network IDs
  - Nodes can be leafs or switches (routers)



Conclusions and Evolution of PLC

Conclusions

- PLC technology has reached a certain maturity
  - The in-home BB market is significantly increasing
  - PLC will play an important role in the SG (both NB and BB PLC)
- Importance of definition of applications and requirements in the SG (many domains)
  - Is AMR/AMI the killer application ?
  - Will demand side management and demand response be widely implemented in the near term ?
- Coexistence of technologies is fundamental
- Standardization needs to be completed for mass deployment

Evolution

- New applications
- EMC, coexistence/interoperability mechanisms also with other technologies
- Advances at the PHY, e.g.,
  - filter bank modulation, MIMO, *optimal* channel coding, mitigation of interference and impulsive noise….
- Advances at the MAC, e.g.,
  - adaptation and *applicable* resource allocation algorithms, cooperative techniques, …
- New grid topologies, new cables, and possible new bandwidths might come out

References

Useful Information Source

- **PLC DocSearch** (http://www.isplc.org/docsearch/)
  - links to papers published in IEEE journals and conferences since 1986, in Wiley, Elsevier, and Hindawi journals (likely incomplete)
  - full text papers contained in the proceedings of ISPLC, the International Symposium on Power Line Communications, from 1997 to 2004 (those proceedings were not published by the IEEE)
  - full text papers contained in the proceedings of WSPLC, the Workshop on Power Line Communications, from 2008

- **Best Readings on Power Line Communications** (http://www.comsoc.org/best-readings)
  - a collection of selected books, articles, and papers on PLC.

- **IEEE Communications Society Technical Committee on Power Line Communications** (http://cms.comsoc.org/eprise/main/SiteGen/TC_PLC/Content/Home.html)
  - a good gateway to PLC research world

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2) F. Versolatto, A. M. Tonello, "On the Relation Between Geometrical Distance and Channel Statistics in In-Home PLC Networks," Proc. of IEEE ISPLC 2012, Beijing, China, March 27-30, 2012.
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4) F. Versolatto, and A. Tonello, "An MTL Theory Approach for the Simulation of MIMO Power Line Communication Channels," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1710-1717, Jul. 2011.
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Multicarrier Modulation and Resource Allocation

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2) A. Tonello, S. D'Alessandro, F. Versolatto, and C. Tornelli, "Comparison of Narrow-Band OFDM PLC Solutions and I-UWB Modulation over Distribution Networks," to appear in *Proc. Smart Grid Commun. Conf. (SmartGridComm'11)*, Oct. 17-20, 2011, Bruxelles, Belgium.
3) A. Tonello, M. Antoniali, F. Versolatto, and S. D'Alessandro, "In-car PLC Advanced Transmission Techniques," in *Proc. of the 5th Biennial Workshop on Digital Signal Processing for In-Vehicle Systems*, Kiel, Germany, Sep. 2011.
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Short Bio of the Speaker

Andrea M. Tonello Bio

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- 1996-2002: Member of Technical Staff, and then technical Manager and Director at Bell Labs-Lucent, Whippany NJ, USA.
- 2003-to date: Aggregate professor at the University of Udine.
- PhD in Electrical Eng. from University of Padova, Italy.
- Founder and chair of WiPli Lab since 2005.
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- *Awards:* Bell-Labs Lucent Recognition of Excellence Award 1999, Royal Academy of Engineering (UK) Distinguished Visiting Fellowship Award 2010, IEEE Vehicular Technology Society Distinguished Lecturer Award for years 2011-12.
- *Paper awards:* EURASIP Best Journal Paper Award 2007, IEEE ISPLC 2010 Best Student Paper Award (co-author with F. Versolatto), IEEE ISPLC 2011 Best Student Paper Award (co-author with. M. Antoniali, M. Lenardon and A. Qualizza), IEEE VTC 2011 Spring Best Paper Award MIMO Track (co-author with N. Moret and S. Weiss).
- *IEEE positions:* Vice Chair of IEEE TC-PLC, Chair of Awards and Nominations Committee of TC-PLC, Steering Committee Member of IEEE ISPLC.
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