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Advances in Power Line Communications and Application to the Smart Grid

Andrea M. Tonello

Wireless and Power Line Communications Lab
University of Udine, Italy

tonello@uniud.it
www.diegm.uniud.it/tonello

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Introduction
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 *(ranked in the top‐ten)*

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
Acknowledgment

A. Tonello acknowledges the work of his PhD students:
- M. Antoniali, S. D’Alessandro, F. Versolatto
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  - Impulsive noise

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Power Line Communications and Smart Grids

History and Application Scenarios of PLC
Application Scenarios

- **Idea:** exploit the power delivery network to convey data signals
- Application of power line communications is ubiquitous
  - Broad band internet access
  - In-Home
  - In-Vehicle
  - Smart grid applications
Some History about PLC Technology

- PLC exists since early 1920s
  - Used by power utilities for voice and data communications over HV lines.
  - Original solutions were based on ultra low data rate transmission (below 3 kHz)
  - A *first generation* of narrow band (NB) technologies has been then developed, most of them using FSK in Cenelec bands (say below 130 kHz) and rates in the order of some tens of kbps.
  - A *second generation of NB modems* has then been designed using multicarrier modulation (OFDM, below 500 kHz) to achieve higher rates below 1 Mbps.
  - In parallel, there has been a lot of activity in *broad band (BB) PLC* (2-30 MHz). *First generation* with rates up to 10 Mbps, *Second generation* with rates up to 200 Mbps, *Third generation* with rates up to 500 Mbps and possibly above.

- Development has been fostered by industry, initially, with proprietary solutions and only recently standardization has been started
- Some credit in fostering interactions and disseminations can be given to
  - IEEE ComSoc Technical Committee on PLC (TC-PLC) started in 2004
  - International Symposium on PLC (ISPLC), started in 1997 (in Essen, Germany), and fully sponsored by IEEE from 2006. Next year will be held in Johannesburg.
Outdoor – Broad Band Internet Access

- Services
  - High Speed Internet connection, video on demand, voice over IP, ...

- Technology
  - Broad band PLC in the bands 2-30 MHz

- Deployments
  - Italy, Austria, Germany, Spain, USA, .... under development countries
  - Market suffers of highly penetrated xDSL services

- It enables customer premises to access the Internet through the existing electrical infrastructure
Home Networking

- In-Home high speed services delivered through the home gateway
  - Home office networking, video conferences, ...
  - IPTV, 3D games, video streaming

- Integration of different technologies is advisable
  - PLC, Wireless (WiFi), UWB, visible light communications
  - This objective can be realized with the use of a convergent layer where PLC provides a high speed backbone
    - Example 1: inter-MAC approach developed in the EU FP7 Omega project
    - Example 2: convergence at network layer

- Narrow band PLC for home automation and energy management

In-Vehicle PLC

- In-vehicle communications via DC/AC power lines:
  - Alternative or redundant communication channel (e.g., to CAN bus)
  - Command and control of devices and sensors
  - Multimedia services distribution (music, video, games, etc.)

- Benefits
  - Weight reduction
  - Lower the costs

Power Line Communications and Smart Grids

Application and Role of PLC in the Smart Grid
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 metering**
  - Demand side management
  - Demand response
  - Dynamic pricing
  - Acquisition of user behavior

**User Domain**

- **Internet access**
- **Smart home**
  - Home networking
  - Automation and control
Some Specific Applications of PLC

- Monitoring and control with 2 way communications 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 metering
  - Home energy management systems (HEMS)
  - Demand response and demand management
  - User behavior profiles
Some Specific Applications of PLC

- Monitoring and control of the grid
  - HV/MV lines status, faults
  - Islanding of micro grids
  - Power quality (*frequency*, *voltage/current*, *harmonics*)
  - Monitor power systems status (*transformers*, *CBs*)
  - Load shedding and generator control 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 Narrow Band and Broad Band 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
Channel Characterization

Bands and Coupling
PLC Operating Bands

- AM Radio: [520 kHz, 1610 kHz]
- Amateur Radio: [1.8 MHz, 30 MHz]
- Defence Systems + Radio PMR/PAMR: [30 MHz, 87.5 MHz]
- FM Radio: [87.5 MHz, 108 MHz]
- TV + Radio VHF: [108 MHz, 240 MHz]

Narrowband PLC

Broadband PLC

PSD equal to -50 dBm/Hz + Notching

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
- Inductive coupling simplifies installation but has lower pass behavior

Capacitive coupling in MV lines, courtesy of RSE
Inductive coupling in MV lines, courtesy of RSE
The channel exhibits

- Multipath propagation due to discontinuities 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)
Channel Characterization

In-Home Channel
In-Home Channel Characterization

- Real – life residential sites
  - Italian in-home scenario
- Up to 100 MHz
- More than 1200 links
  - Channel frequency response
  - Line impedance
- Static and time variant channel acquisitions

Wipli Lab
Università degli Studi di Udine
Layered tree structure from the main panel with many branches and outlets fed by derivation boxes. This is typical of EU networks.
Path Loss and Phase from Measurements

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

- The phase is not uniformly distributed
- The average phase is not linear at low frequencies
It is important to characterize statistically the channel

We define the **Root Mean Square Delay Spread** as

\[
\sigma_r = \sqrt{\int_0^D \tau^2 P(\tau) d\tau - \left( \int_0^D \tau P(\tau) d\tau \right)^2}, \quad P(t) = h(t)^2 / \int_0^D h(\tau)^2 d\tau
\]

We define the **Coherence Bandwidth** as

\[
R(f) = \int_{B_1}^{B_2} H(\lambda) H^* (\lambda + f) d\lambda \quad \left| R(B_c^{0.9}) \right| = 0.9 \left| R(0) \right|
\]

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

<table>
<thead>
<tr>
<th>State (Band in MHz)</th>
<th>ACG (dB)</th>
<th>RMS-DS (μs)</th>
<th>CB (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy (2 – 100)</td>
<td>-35.75</td>
<td>0.32</td>
<td>301</td>
</tr>
<tr>
<td>France (2 – 100)</td>
<td>-</td>
<td>0.21</td>
<td>310</td>
</tr>
<tr>
<td>Italy (2 – 30)</td>
<td>-32.38</td>
<td>0.36</td>
<td>226</td>
</tr>
<tr>
<td>US (suburban) (2 – 30)</td>
<td>-48.9</td>
<td>0.52</td>
<td>-</td>
</tr>
<tr>
<td>Spain (2 – 30)</td>
<td>-30</td>
<td>0.29</td>
<td>-</td>
</tr>
</tbody>
</table>

Narrowband Channel Measurements

- Results from Italian campaign measurements (20 kHz - 2 MHz)
- Lower average attenuation than broad band
Channel Characterization

Outdoor LV/MV Channel
### European LV power supply grid
- LV (230/400 V) 3-phase distribution system divided in supply cells
- Each supply cell is connected to a MV/LV transformer station
  - 300 houses connected via branches (30 houses/branch)
  - Maximal branch length ~1 km

### Asian/American LV power supply grid
- LV (125/250 V) single or split phase
- Many MV/LV transformers
- Smaller supply cells: few houses
- Maximal branch length ~100 m
- Three wires (neutral grounded at the main panel)

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**Reference:**
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

Outdoor MV Channel

- MV channels exhibit in general (but not always) lower attenuation than Outdoor LV PLC
  - Further investigations have to be done

- Coupling effects have also to be considered
  - Inductive / Capacitive coupling
Measurement Results in MV Test Network

- Measurements in a real test network (RSE) with loop length 300 m
- Three representative channels are here shown
- Full statistical analysis in REF

**Graph:**
- Amplitude (dB) vs. Frequency (MHz)
- Phase (rad) vs. Frequency (MHz)

**Network Diagram:**
- Test network of RSE, Italy

**Reference:**
Channel Characterization

Effect of Circuit Discontinuity Elements
Effect of Circuit Discontinuities

- Broadband PLC benefits of strong coupling effects at high frequencies
- Broadband may also help to mitigate the low line-impedance problem

- Crossing an open switch
  - LV Circuit-Breaker

- Cross-phase communications
  - Industrial environment

- Bypass MV/LV transformer

![Graphs and diagrams illustrating the effects of circuit discontinuities.](image-url)
Can We Model the Channel?

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

\[
H(f) = \sum_{i=1}^{N_p} p_i(f) \cdot e^{-\left(a_0 + a_1 f^K d_i\right)} \cdot e^{-j2\pi f d_i / v}
\]

- Reflection effects
- Propagation phase shift
- Cable attenuation

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

- \(N_p\): Poisson random variable with intensity \(\Lambda L_{\text{max}}\)
- \(p_i(f)\): log-normal frequency-dependent r.v. with a random sign flip
- \(d_i\): Erlang random variable (uniform distribution in \([0, L_{\text{max}}]\) given \(N_p\))


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

- The generated channels (with the simulator) show the same ACG spread of the measures.
- The best fit (in dB) is given by the *normal distribution*.
- Average ACG= -35.59 dB (*Italian case*)

![Graph showing quantiles of average channel gain (dB) for different setups and measurements.](image)
- Excellent fit with measured data in terms of RMS delay spread

- The best fit is given by the log-normal distribution

- Average RMS-DS=0.257 μs (Italian case)
Again, good fitting of the generator with data

Average CB = 390 kHz (Italian case)
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

- 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 Transmission 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

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TL Theory Application

- From topology to graph representation
- From graph representation to electrical quantities representation
- TL theory approach based on efficient methods are fundamental: e.g., the voltage ratio approach (VRA), a scalar version of the ABCD method

![Diagram](attachment:image.png)

$$H_b (f) = \frac{V_{b-1}}{V_b} = \frac{1 + \rho _{L_b}(f)}{e^{\gamma_b(f)\ell_b} + \rho _{L_b}(f)e^{-\gamma_b(f)\ell_b}}$$

$$H(f) = \prod_{b=1}^{N} H_b(f)$$

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., delay spread and average channel gain.

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 bottom-up approach allows to take into account these effects
- Examples of time variant loads are:
  - AC/DC converters and chargers
  - Compact fluorescent lamps (CFL)
  - Dimmers
  - Variant load banks
  - Industrial machinery
  - Overall “home load” changing with time
Time Variant Loads and Effect of the Topology

- Time variance is less pronounced when the receiver is far away from the time variant load

Channel acquisition 1

Channel acquisition 2

- 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)

MIMO Channel:
Multiple-Input Multiple-Output
MIMO Channel Main Characteristics

- In the presence of more than two conductors, multiple input – multiple output links are available.

- The channels are strongly correlated:
  - The ratio between the minimum and the maximum eigenvalue has been shown to be constant in frequency and equal to 0.2 on average (for in-home channels).

- The noise is correlated as well:
  - Higher correlation in the lower frequency range.
  - P-PE and N-PE noises are the most correlated (more than P-N).


An Approach to MIMO Channel Generation

- We combine multiple transmission line theory with the bottom-up approach to obtain random MIMO PLC channel responses.

Model Validation

- We have realized a T-shaped MTL test network
- We have simulated and measured the coupled insertion loss

\[ l_1 = 5.22 \, m \]
\[ l_2 = 2.30 \, m \]
\[ l_3 = 3.60 \, m \]

- Strong matching between the measured and generated insertion loss

Noise Characterization
The PLC noise comprises five components:

- Background Noise
  - Narrowband Noise
  - Colored Noise

- Impulsive Noise
  - Periodic Impulsive Noise
  - Asynchronous
  - Aperiodic

Noise Characterization

Background Noise
Background Noise Comparison

- 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

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

REF. Noise models from:
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 by the inverters

![Graph showing noise PSD vs frequency for different appliances](image)

*Measurements at the Micro-Grid Test Lab Strathclyde, by WiPli Lab team within FP7 EU DERri Project*
The stationary characterization of the noise is not sufficient to get the picture of its whole complex nature.

**Time-Variant Analysis**

- **short term PSD during the mains cycle**

**References**


Periodic and Synchronous Noise

- Time-frequency characterization of the noise
  - The noise PSD varies within the mains cycle of 20 ms
- Example of synchronous noise measurement at the source
  - Laptop PC battery charger

- Typical rate of 100 Hz
  - The synchronous periodic noise is generated by the input stage of the rectifier circuit of the power supply unit

- Noisy devices
  - Laptop PC battery chargers
  - LCD monitors, desktop PC, ...
  - Light dimmers
Periodic and **Asynchronous** Noise

- The asynchronous noise causes spectral lines in the PSD
  - It can be isolated from the synchronous noise components
- Example of asynchronous noise measurement at the source
  - Flat LCD monitor

- The asynchronous periodic noise is generated by the switching activity of the power supplies
- It is concentrated below 10 MHz
Aperiodic Impulsive Noise

- The impulsive noise is generated by
  - plugging in/out devices
  - switching on/off devices

- It is characterized by
  - Amplitude $A$
  - Inter-arrival time $t_{IAT}$
  - Duration $t_W$

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Common Noise Model in the Literature
Common PLC Noise Model

- **Background noise**

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

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best case</td>
<td>-140</td>
<td>38.75</td>
<td>-0.72</td>
</tr>
<tr>
<td>Worst case</td>
<td>-145</td>
<td>53.23</td>
<td>-0.337</td>
</tr>
</tbody>
</table>

- **Two terms Gaussian**

- Sum of two Gaussian PDFs weighted by a Bernoulli process with occurrence probability \( P \)

\[ p_{\eta}(v) = (1 - P) N(0, \sigma_b^2) + PN(0, K \sigma_b^2) \]

- **Middleton Class A**

- Weighted sum of Gaussian PDFs

\[ p_{\eta}(v) = \sum_{k=0}^{\infty} \frac{e^{-A^k}}{k!} \frac{1}{\sqrt{2\pi\sigma_k^2}} \exp\left(-\frac{v^2}{2\sigma_k^2}\right) \sigma_k^2 = \left(1 + \frac{1}{\Gamma}\left(k/A + \Gamma\right)\right)\sigma_b^2 \]
Physical Layer Techniques

Single Carrier Modulation (FSK)
Multi Carrier Modulation
Adaptation
Performance Increase
Single Carrier Modulation: FSK

- **Binary FSK**
  
  "1" \( \iff \sqrt{\frac{2E_s}{T}} \cos(2\pi f_H t) \)

  "0" \( \iff \sqrt{\frac{2E_s}{T}} \cos(2\pi f_L t) \)

  - Modulation index: \( h = (f_H - f_L)T \)
  - Normalized cross-correlation: \( \rho = \text{sinc} \left(2h\right) \)
  - Symbol error probability in AWGN power spectral density \( N_0 \):
    \[
    P_e = Q \left( \sqrt{\frac{E_s(1 - \rho)}{N_0}} \right)
    \]

- **M-ary FSK**
  
  "i-th symbol" \( \iff \sqrt{\frac{2E_s}{T}} \cos(2\pi f_i t), \quad i = 0,1,\ldots,M - 1 \)
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

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**REF.** A. J. Han Vinck and J. Haring, "Coding and Modulation for Power-Line Communications," *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
M tones (sub-channels)

Rectangular sub-channel pulse (window) of duration $N > M$ samples

Cyclic prefix (CP) of length $\mu=N-M$ 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

![Notching Mask](image)

- Example of spectrum mask up to 30 MHz in HPAV
- 917 tones out of 1536
- 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.

Example of spectrum mask up to 30 MHz in HPAV.
Use a root-raised-cosine window (or other), to fulfill the mask with a higher number of active tones
- It is a filter bank system with a prototype pulse equal to the window

- If no symbol overlapping exists, we obtain windowed OFDM

- It introduces a transmission rate penalty. Overhead $\beta = \mu + \alpha = N - M$

- The transmission rate is

$$R = \frac{M}{NT} = \frac{M}{(M + \mu + \alpha)T}$$
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

FMT Basics

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


Efficient Realization

- **Synthesis**
  - $M$ point IDFT and Cyclic extension to $M_2 = \text{l.c.m.}(M,N) = L_1 M = L_2 N$
  - **Pulses**: PP components of order $N$, i.e., $g^{(i)}(nN) = g(i + nN)$ $i = 0, ..., N - 1$
  - Sample with period $L_2$

- **Analysis**
  - Dual operations

- **Complexity**: $M \log_2 M + L_{g,h}$ (pulse length) operations/sample

---

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
What Can We Gain with Increased Bandwidth?

- 4096 Tones in 100 MHz, fixed CP=5.57 us, PSD noise -110 dBm/Hz
- PSD signal: -50 dBm/Hz + HPAV notching 0-30 MHz, -50/-80 dBm/Hz 30-87.5 MHz
What Can We Gain with Increased Bandwidth?

- 4096 Tones in 100 MHz, fixed CP=5.57 us, PSD noise -110 dBm/Hz
- PSD signal: -50 dBm/Hz + HPAV notching 0-30 MHz, -50/-80 dBm/Hz 30-87.5 MHz
We can adapt the pulse shape and the overhead $\beta = N-M$ such that capacity is maximized

$$R(\beta) = \frac{1}{(M + \beta)T} \sum_{k \in K_{oN}} \log_2 \left( 1 + \frac{\text{SINR}^{(k)}(\beta)}{\Gamma} \right) \quad [\text{bit} / \text{s}]$$

For example, in CP-OFDM we adapt the CP to the channel response

Example of Performance: System Parameters

- Number of carriers: \( M = \{256, 512, 1024, 2048, 4096\} \)
- SNR Gap for \( P_e = 10^{-2} \): \( \Gamma = 3.4 \) dB
- PSD of the transmitted signal: -50 dBm/Hz (in 0-100 MHz)
- PSD of the Gaussian background noise: -140 dBm/Hz
- Test channel response of class 5
- Average SNR at the receiver: 44, 24 or 4 dB
- Pulse-Shaped OFDM: Raised-cosine window
- FMT: Truncated root-raised-cosine pulse
  - Single tap equalization
  - Fractionally spaced sub-channel equalization

Achievable Rate as a Function of N. of Tones

Masked 2-100 MHz

Masked 2-28 MHz

Target notching mask below 30 MHz: HPAV

FMT outperforms PS-OFDM
Rate scales approx. linearly with bandwidth up to 100 MHz
FMT vs. 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
- Achievable rate can be used as a design metric to choose properly the number of carriers and the equalization method in the system
  - Adaptation of the parameters is beneficial
- The achievable rate increases significantly using 100 MHz band (depending, however, on the transmitted PSD beyond 30 MHz)
Physical Layer Techniques

Possible Capacity Increases from Extended Bandwidth and MIMO
Inferring the Capacity Increase

- Used power Spectral Density of the Transmitted Signal and Noise Model

- *Real capacity* of PLC channels is unknown since the channel is not just Gaussian and disturbances are not fully characterized yet

---

*Wipli Lab*  
Tutorial Advances in PLC – EUSIPCO 2012

A. Tonello  
90
Inferring the Capacity Increase (In-Home Case)

- Capacity can be improved with MIMO and/or Bandwidth Increase

- With MIMO (2 – 100 MHz)

- With extended bandwidth (SISO)


Physical Layer Techniques

Other Modulation Schemes: Impulsive UWB
Impulsive UWB: I-UWB

- **For low data rate**: Impulsive UWB

  - Gaussian monocycle $D=50-200$ ns, $T_f=2$ us, $R = 0.5$ Mpulses/s.
  - Symbol energy is spread in frequency by the monocycle (*frequency diversity*)
  - The *monocycle* is spread in time via a binary code (*time diversity*)
  - Coexistence with broadband systems is possible due to the low PSD and high processing gain

Comparison of I-UWB with NB-OFDM

I-PLC may be suitable also for outdoor communications
- Same transmitted power: higher data rates with I-UWB than NB-OFDM
- Same data rate: very low transmitted PSD with I-UWB

G3 Bandwidth = 54.7 kHz, PRIME Bandwidth = 46.9 kHz (here, only G3 because they perform similarly)

Cooperative Algorithms

Relaying and Flooding
Relay and Flooding Techniques

- Relaying (well studied in the wireless context)
  - Decode and Forward
  - Amplify and Forward
  - Opportunistic Protocols
- Flooding


Direct Transmission

- The source (S) transmits its data to the destination (D) during all the time slot whose duration is $T_f$
- The relay is silent

$C_{x,y}$: Capacity of the link (x,y)
• During the first part of the time slot the source (S) transmits its data to both the destination (D) and the relay (R)
• The relay is silent

\[ C_{x,y} \]: Capacity of the link \((x,y)\)
During the second part of the time slot the relay transmits its data to the destination (D) using an independent codebook.

The source is silent.
Amplify & Forward (1/2)

- During the first part of the time slot the source (S) transmits its data to both the destination (D) and the relay (R)
- The relay is silent

\[ C_{x,y} \] Capacity of the link (x,y)
• During the second part of the time slot the relay amplifies and forwards the data received from the source (S) to the destination (D)
• The source is silent
Opportunistic DF (ODF): Capacity Improvements

- ODF uses the relay whenever it allows for capacity improvements w.r.t. the direct transmission. Its capacity is:

\[ C_{ODF}(t) = \max\{ C_{DT}, C_{DF}(t) \} \]

where

\[ C_{DF}(t) = \min\{ tC_{S,R}, tC_{S,D} + (1-t)C_{R,D} \} \]

\[ C_{DT} = C_{S,D} \]

\[ t^* = \arg\max_{t\in[0,1]} \{ C_{DF}(t) \} \]
Opportunistic AF (OAF): Capacity Improvements

- OAF uses the relay whenever it allows for capacity improvements w.r.t. the direct transmission. Its capacity is:

\[ C_{OAF} = \max \{ C_{DT}, C_{AF} \} \]

where

\[ C_{DT} = \frac{1}{MT} \sum_{k \in K_{ON}} \log_2 \left(1 + P_{S, DT}^{(k)} \eta_{SD}^{(k)} \right) \]

\[ C_{AF} = \frac{1}{2MT} \sum_{k \in K_{ON}} \log_2 \left(1 + \frac{P_{S, AF}^{(k)} \eta_{SR}^{(k)} P_{R, AF}^{(k)} \eta_{RD}^{(k)}}{1 + P_{S, AF}^{(k)} \eta_{SR}^{(k)} + P_{R, AF}^{(k)} \eta_{RD}^{(k)} + P_{S, AF}^{(k)} \eta_{SD}^{(k)}} \right) \]

\[ \eta_{XY}^{(k)} = \left| G_{ch,XY}^{(k)} \right|^2 \]

\[ \eta_{XY} = \frac{P_{noise,Y}^{(k)}}{P_{XY}^{(k)}} \]
Application of Relay in Home Networks

Source Derivation Box (SDB)

The relay is located in the derivation box that feeds the source node.
Main Panel Single Sub-Topology (MPS)

The relay is located immediately after the CB of the main panel.
Numerical Results: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Area</td>
<td>U(100 - 300) m²</td>
</tr>
<tr>
<td>Cluster Area</td>
<td>U(15 - 45) m²</td>
</tr>
<tr>
<td>Average Outlet / Area</td>
<td>0.5 outlets / m²</td>
</tr>
<tr>
<td>Probability of Open loads</td>
<td>0.3</td>
</tr>
<tr>
<td>Sample Frequency (1/T)</td>
<td>37.5 MHz</td>
</tr>
<tr>
<td>M</td>
<td>1536</td>
</tr>
<tr>
<td>1/(MT)</td>
<td>24.414 kHz</td>
</tr>
<tr>
<td>Considered Band</td>
<td>(1-28) MHz</td>
</tr>
<tr>
<td>Transmitted PSD limit</td>
<td>-50 dBm/Hz</td>
</tr>
<tr>
<td>Noise PSD</td>
<td>(-110) dBm/Hz</td>
</tr>
</tbody>
</table>
Numerical Results: Capacity Improvements

CCDF of capacity using ODF and OAF with the relay located according to the considered configurations. For the DT configuration, no relay is connected to the network.

Flooding for Large Scale Networks

- Multi-hop communication protocol
- Suitable for command and control applications with large number of nodes, e.g., lightning systems
- Network nodes forward the received packets altruistically

- A sends a broadcast packet that is received by B, C, and G
- Nodes B, C, G forward the packet that will be now received also by D, E, F

Flooding: Considerations

- **Pros**
  - No routing overhead
  - Robust against network changes
  - Shortest path always used

- **Cons**
  - Redundant transmissions
  - Loop cycles
  - Waste of energy for many retransmissions

- **Improvements**
  - In highly populated networks, only a subset of nodes are allowed to retransmit
  - Counters for packets (number of retransmissions)
  - MAC protocol based on hybrid TDMA-CSMA/CA
    - The master broadcasts a network-wide TDMA frame
    - Within each TDMA frame there are contention free and contention based time slots
Media Access Techniques
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
Media Access Techniques

Scheduling in Linear Periodically Time Variant (LPTV) Channels
The Central Coordinator (CCo) manages the channel access in a TDMA fashion.

We consider the **downlink** case.

The CCo sends training sequences to the users that estimate the periodic time variant SINR experienced in a mains cycle.

We want to compute the optimal slot duration, scheduling, and bit loading.

The optimal time slot scheduling and duration can be found maximizing the aggregate rate (AR)

\[
AR(N_{ITS}) = \max_{\alpha} \sum_{u=1}^{N_U} \sum_{s=0}^{N_{TS}-1} \alpha^{(u,s)} R_s^{(u)}(N_{ITS})
\]

subject to \(\sum_{u=1}^{N_U} \alpha^{(u,s)} = 1\)
\(s = 0, \ldots, N_{TS} - 1\), and
\[
\sum_{s=0}^{N_{TS}-1} \alpha^{(u,s)} R_s^{(u)}(N_{ITS}) \geq \frac{P^{(u)}}{100} \sum_{s=0}^{N_{TS}-1} R_s^{(u)}(N_{ITS})
\]
\(u = 1, \ldots, N_U\)

\(\alpha^{(u,s)}\): binary coefficient equal to one if slot \(s\) is assigned to user \(u\), zero otherwise

\(P^{(u)}\): weighting factor.
Systems, Standards and MAC Details

Summary of Systems and Standards
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
### Narrow Band PLC Systems and Standards

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK</td>
<td>S-FSK</td>
<td>PPM</td>
<td>Spread Spectrum</td>
<td>PPM</td>
<td>DCSK differential code shift keying</td>
<td>BPSK</td>
<td>OFDM DBPSK DQPSK DBPSK</td>
<td>OFDM QPSK 16-QAM</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Bit-rate</td>
<td>2.4 kbps</td>
<td>1.2 kbps</td>
<td>50 or 60 bps</td>
<td>8.5 kbps</td>
<td>240 bps</td>
<td>0.6 to 7.5 kbps</td>
<td>Up to 4800 bps</td>
<td>34 to 240 kbps</td>
<td>128 kbps</td>
<td>up to 1 Mbps</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>ND</td>
<td>CSMA</td>
<td>CSMA/CD</td>
<td>CSMA/CD</td>
<td>-</td>
<td>CSMA/CA</td>
<td>-</td>
<td>CSMA/CA</td>
<td>CSMA/CA TDMA</td>
<td>CSMA/CA</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Home Automation**
- **Command and Control**
- **Automatic Meter Reading**

- **Single carrier**
  - Low data rate:
  - Some kbits/s

- **Multicarrier**
  - Data rate:
  - Hundred of kbits/s
## Broadband PLC Systems and Standards

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HomePlug</td>
<td>HomePlug</td>
<td>High Definition</td>
<td>IEEE</td>
<td>ITU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consortium</td>
<td>Consortium</td>
<td>PLC Alliance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Multicarrier data rate:
Over 200 Mbits/s

<table>
<thead>
<tr>
<th>Modulation &amp; Coding</th>
<th>OFDM (1536 tones)</th>
<th>Wavelet OFDM (512 tones)</th>
<th>OFDM (HPAV) (3072 tones)</th>
<th>OFDM (up to 4096 tones)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bit-loading Up to 1024-QAM</td>
<td>Bit-loading Up to 16-PAM</td>
<td>Bit-loading Up to 4096-QAM</td>
<td>Bit-loading Up to 4096-QAM</td>
</tr>
<tr>
<td></td>
<td>Convolutional, Turbo codes</td>
<td>QPSK</td>
<td>RS, Convolutional, LDPC</td>
<td>LDPC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bit-rate</th>
<th>200 Mbit/s</th>
<th>3.8-9.8 Mbit/s</th>
<th>190 Mbit/s</th>
<th>540 Mbit/s</th>
<th>&gt;200 Mbps Up to 1Gbps</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>MAC</th>
<th>TDMA-CSMA/CA</th>
<th>CSMA/CA</th>
<th>TDMA-CSMA/CA</th>
<th>TDMA-CSMA/CA</th>
<th>TDMA-CSMA/CA</th>
</tr>
</thead>
</table>
Systems, Standards and MAC Details

Status of Standardization
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: Pulse shaped 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. hnm: ratified in Dec. 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
Systems, Standards and MAC Details

MAC in Narrowband Systems
MAC in NB-PLC

- We consider, as examples, the MAC specified in the NB-PLC systems:
  - PRIME (power line intelligent metering)
  - G3-PLC (for meter reading)
  - ITU G.hnem

- G3-PLC and PRIME have been used as baseline for standardization in the working group IEEE P1901.2 and also in ITU G.hnem
The subnetwork is a tree with two kind of nodes

- **Service Node**
  - Can be either a *leaf* or in a *branch* point
  - In *Terminal state* it can send its own data
  - In *Switch state* it forwards data

- **Base Node**
  - It is the *root* of the tree
  - It assigns the network identifier to the **Service Nodes**
  - It manages the channel allocation in contention free periods

Each node has a MAC address (48 bits)

---

**REF.** PRIME Alliance Technical Working Group, “*Draft Standard for PoweRline Intelligent Metering Evolution,*” R1.3E.
At the first step, only the Base node has an address
S=(Sub Net ID, Local Net (node) ID)

Nodes B, C, D ask for addresses to the Base node A

A assigns the address

E, F are not visible from A but are visible from B.

B asks A to have a switch node identifier too

B becomes a switch node

B assigns the network ID to E and F
PRIME: MAC Frame and Channel Access

<table>
<thead>
<tr>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Beacon reserved to the Switch Node
- Beacon reserved to the Base Node

- Each Beacon contains information on the SCP and CFP
- SCP: based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)
  - The nodes contend to occupy the channel
  - Priority mechanisms are provided
- CFP: based on TDMA where the slot are assigned by the Base Node
- In both SCP and CFP, the packets go always through the Base Node
- It is possible to establish direct connections for “peer to peer” communication
G3-PLC MAC

- Based on the contention access scheme of IEEE 802.15.4 (ZigBee)
- Two types of devices:
  - **Private Area Network (PAN) Coordinator** (typically, the concentrator)
    - It performs device discovery
  - **Reduced Function Devices (RFD)**
    - Represented by meters
- Distributed access procedure (peer to peer communication is possible)
- Two priority levels are possible: high and low priority
- 64 bit address (extended address) used to join the network by the node
- The address is reduced to 16 bit (short PAN address) once the node joins


**REF.** IEEE 802.15.4 Working Group, “Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs),” 2006.
G3-PLC MAC: Network Architecture

- The PAN Coordinator defines the network ID
- Each RFD node asks the PAN Coordinator for a beacon with the ID to join the network
- The PAN Coordinator has the complete list of the network nodes
- Other PANs can be established
G3-PLC MAC: Channel Access

- The channel access is based on CSMA/CA
- Communication **from the coordinator to the devices** is done under a polling procedure *initiated* by the device who asks the coordinator to transmit pending data
- Communication **from the devices to the coordinator** is done using CSMA/CA. The coordinator receiver is always on
- Note that the network devices are not synchronized at all (**unslotted scheme**)
ITU-T G.hnem MAC

- Similar to the G3-PLC MAC
  - Based on IEEE 802.15.4 (CSMA/CA)
- Four priority levels are offered
  - The fourth is reserved for emergency signals
- The network is split in domains (LV networks)
  - Each domain is managed by a Domain Manager (DM) that acts as a data concentrator
  - DMs can be connected to the utility head-end through DSL or wireless
  - Inter-domain bridges are provided for communication between nodes belonging to different domains
  - More DMs are managed by a Global Master (GM) to reduce inter-domain interference

Systems, Standards and MAC Details

MAC in Broadband Systems
We consider the MAC specified in the BB-PLC systems:

- IEEE P1901
- ITU G.HN
IEEE P1901 MAC

- Two kind of nodes
  - Local Administrator (BSS): first node that joins the network
    - Network setup, synchronization, coordination
  - Station “slave” (SS)
- Nodes are identified by MAC addresses
- Multiple BSS can be located in the same network
- Channel Access
  - CSMA/CA for best effort traffic
    - 7 levels of priority are provided
  - TDMA for QoS
- Two PHY layers coexist thanks to the inter PHY protocol (IPP)

Beacons are sent by the BSS 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 BSS to stations (TDMA).
ITU-T G.hn MAC

- Two kind of nodes
  - **Domain Manager (DM):** first node that joins the network
    - Network setup, synchronization, coordination
  - **Station “slave” (SS)**

- Nodes are identified by MAC addresses

- Channel Access
  - CSMA/CA for best effort traffic
    - 4 levels of priority are provided
  - TDMA for QoS

ITU-T G.hn: MAC Frame and Channel Access

- Medium Access Plan (MAP)
  - Describes TXOP and STXOP of next cycle/cycles
- Transmission Opportunities (TXOP)
  - Contention free TDMA access scheduled by the DM
- Shared Transmission Opportunities (STXOP)
  - Contention based access (CSMA/CA)
  - STXOP is divided into time slots
  - Only some nodes can contend for a certain time slot

AC line 50/60Hz
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)
  - Smart metering is probably the killer application in the short 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
- PLC network synchronization
- Routing with PLC technology
References
Useful Information Source

- **PLC DocSearch** ([http://www.isplc.org/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](http://www.comsoc.org/best-readings))
  - a collection of selected books, articles, and papers on PLC.

  - a good gateway to PLC research world
References from WiPlI Lab 1

**Channel Characterization and Modeling**


**Multicarrier Modulation and Resource Allocation**

References from WiPli Lab 2


Ultra Wide Band


References from WiPli Lab 3


Other: Smart Grid, Smart Home, In-Vehicle


Other References 1

**PLC, Smart Grids, and Broad Coverage**

**Channel Modeling**
Other References 2

Noise Modeling

Physical Layer
Other References 3

MAC, Resource Allocation and Cooperative Schemes

PLC Standards
10) OPERA Specification – Part 1: Technology, v1.0, 31/01/06, WP SWG
17) IEC, CISPR//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.
Short Bio of the Speaker
www.diegm.uniud.it/tonello

- 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.
- Founder and CEO of WiTiKee s.r.l.


IEEE positions: Vice Chair of IEEE TC-PLC, Chair of Awards and Nominations Committee of TC-PLC, Steering Committee Member of IEEE ISPLC.

Editorial positions: Associate editor of IEEE Trans. on Vehicular Technology, Editor IEEE Trans. on Comm., Member of the Editorial Board of ISRN Communications and Networking.

Conference positions: Chair of WSPLC 2009, Chair of IEEE ISPLC 2011, TPC co-chair IEEE ISPLC 2007, and several others.