Power Line Communications

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Outline

PLC – what frequency bands

Status of PLC Standards

The Channel – Noise, fading, and dopplers

PLC is like wireless, but…

Communication Theory opportunities

What PLCs

- Narrowband PLCs (NB-PLCs), aka Distribution Line Carrier
  - Worldwide common band 10-148.5 kHz
    - EU (CENELEC): 3-148.5 kHz
    - USA (FCC): 10-490 kHz
    - JAPAN (ARIB): 10-450 kHz
    - China (EPRI): 3-500 kHz
  - PSD decreases with frequency (linear in dB)
  - Single carrier systems deliver ~5 kbps
  - Multicarrier systems can deliver 100-1,000 kbps
- Broadband PLCs (BB-PLCs)
  - Bandwidth: 1.8-250 MHz
    - Some countries: 1.8-30 MHz only for indoor use, no outdoor PLCs
  - PSD mask constant until 30 MHz, then goes down 30 dB
  - All available solutions are multicarrier (use up to 30 MHz, ~200 Mbps)
  - New ITU/IEEE standards optionally up to 50/100 MHz (~500 Mbps)

IEEE/ITU Standardization

IEEE P1901

- Focuses on MAC/PHY, started in June 2005
- Scope: broadband over power lines for in-home, access and coexistence
- Sponsor ballot passed in April 2010, 81% approval (requires 75%)
- Two PHY/MACs:
  - Windowed OFDM (2048 carriers), Turbo Code ➔ Based on HomePlug AV
  - Wavelet OFDM (512 carriers), RS/CC and LDPC ➔ based on Panasonic HD-PLC
  - Coexistence mechanism (ISP) ➔ Panasonic proposal

Galli, Logvinov, "Recent Developments in the Standardization of PLCs within the IEEE," *IEEE Comms Mag.*, July 2008.

ITU-T G.9960 (G.hn)

- Focuses on MAC/PHY, started in May 2006
- Scope: broadband over all in-home wires (phone, PLC, coax)
- PHY approved in October 2009, MAC should be approved in June 2010
- Single PHY: scalable Windowed-OFDM (2048 carriers for PLCs), QC-LDPC code

Oksman, Galli, "G.hn: The New ITU Home Networking Standard," IEEE Comms Mag., Oct. 2009.

IEEE/ITU Standardization

ITU-T G.cx (G.9972)

- PLC coexistence (ISP) in the HF band, started in 2008
- Same mechanism included in IEEE 1901
- Consented in Oct. 2009, expected approval in June 2010

Galli, Kurobe, Ohura, "The Inter-PHY Protocol (IPP): A Simple Co-Existence Protocol," IEEE Int. Symp. on Power Line Comms (ISPLC), March 2009.

IEEE P1901.2

- Focuses on MAC/PHY, starting next week
- Scope: Smart Grid applications, operations over LV/MV and DC

ITU-T G.hnem

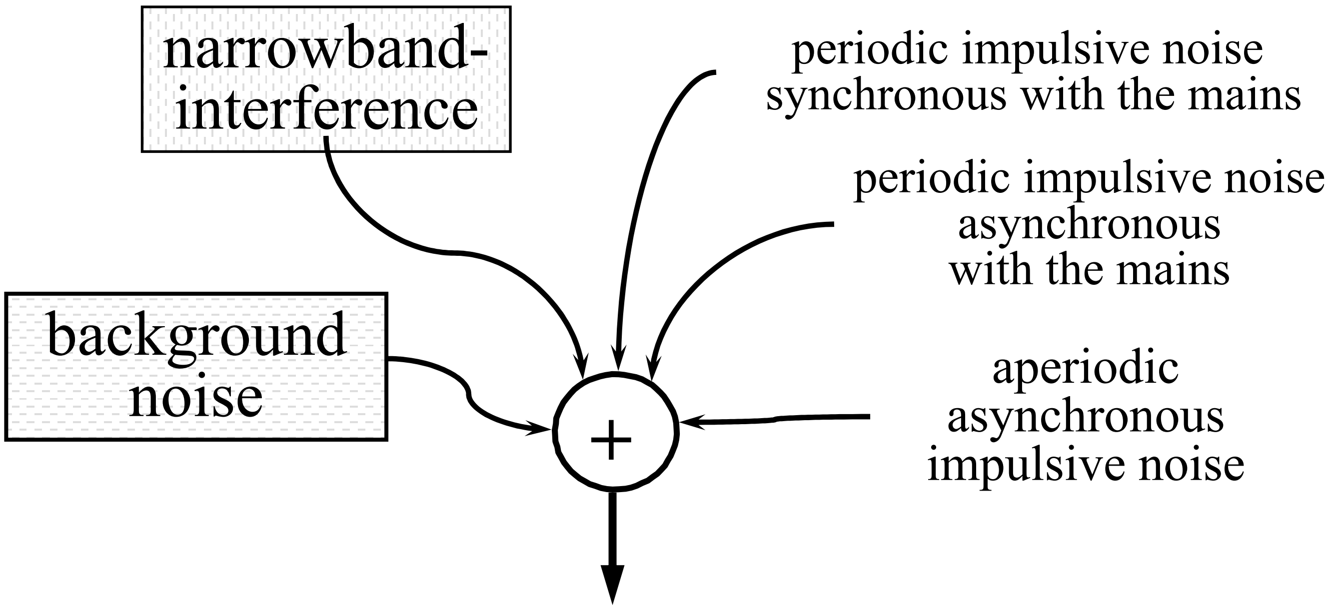
- Focuses on MAC/PHY, started in Jan 2010
- Scope: in-home energy management, LV only

Why Certain Choices at the PHY?

- **Standards are not optimal and they are the result of compromises, but here it seems that there is very little agreement on what is best:**
  - IEEE P1901
    - OFDM and Turbo Codes
    - Wavelet-OFDM and RS-CC/Convolutional LDPC
  - ITU-T G.hn
    - Scalable OFDM and Block LDPC

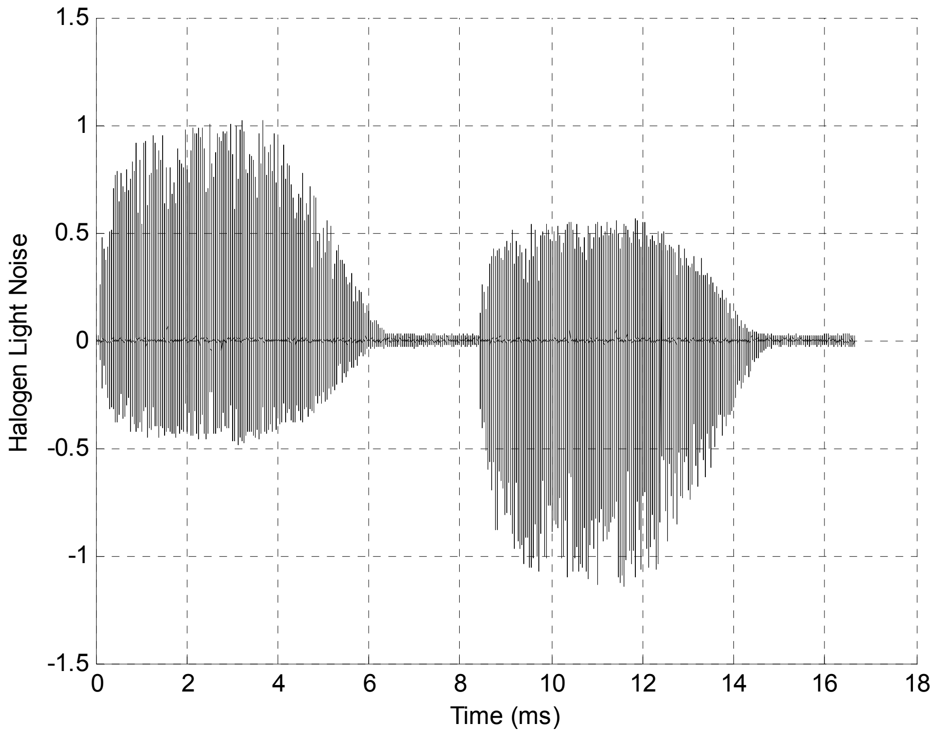
- **What are the reasons for this diversity?**
  - Competitive environment, vendors rush to market with what they have
  - R&D done mostly in industry, very few academic contributions:
    - Vendors stick with their solution
    - Lack of methodological approach, few fundamental results
  - **There is no commonly agreed upon channel model!!**

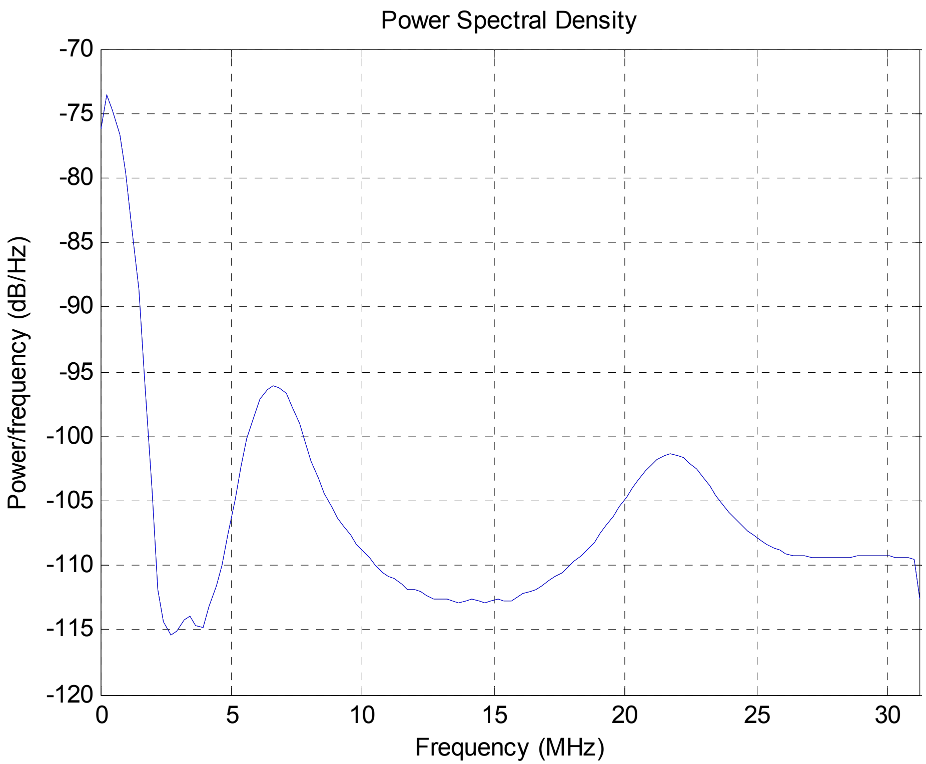
The Noise Environment



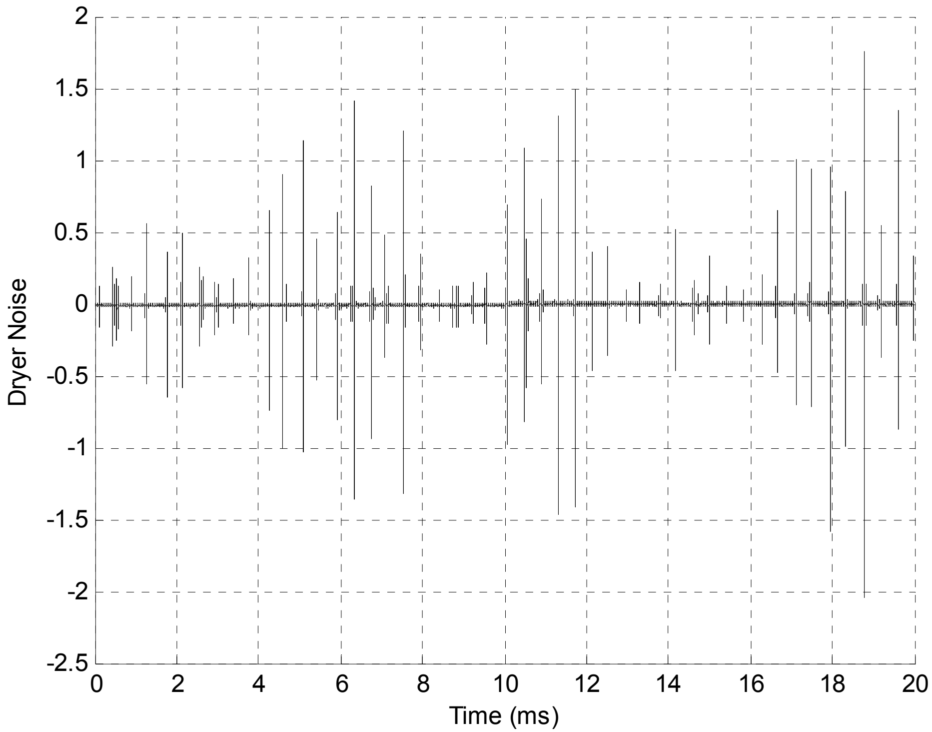
- Colored background noise, significantly higher at low frequencies
- Narrow-band interference, e.g. broadcast radio stations
- Periodic synchronous impulse noise, by rectifiers within DC power supplies and appliances.
- Periodic asynchronous impulse noise, by switching of appliance power supplies
- Aperiodic asynchronous impulse noise caused by switching transients, which occur all over a power supply network at irregular intervals

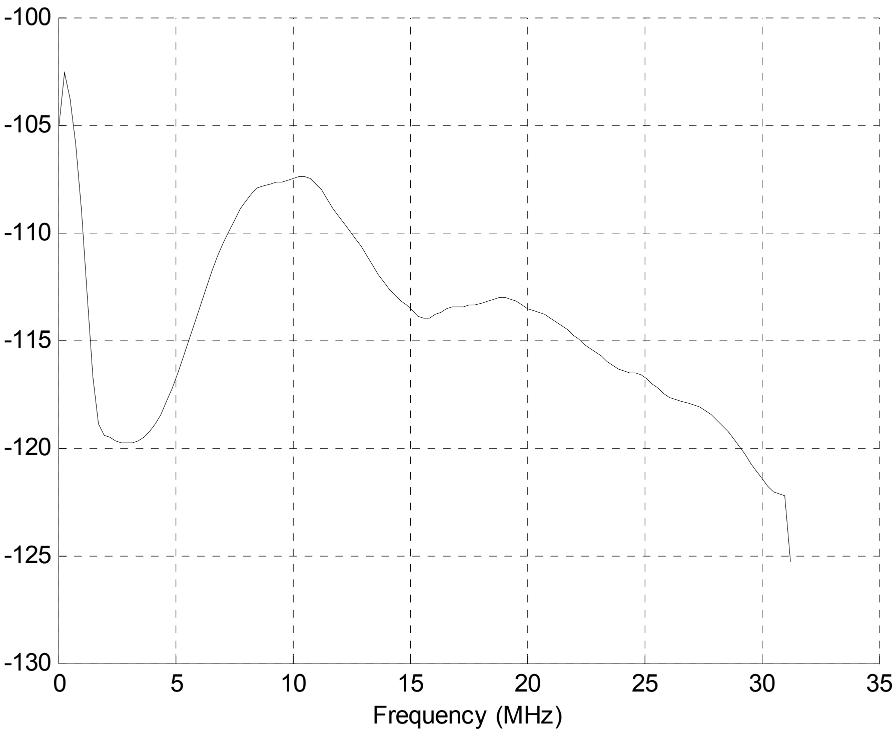
Halogen Light Noise





Dryer Noise


2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Dryer Noise
0
2
4
6
8
10
12
14
16
18
20
Time (ms)


-100
-105
-110
-115
-120
-125
-130
0
5
10
15
20
25
30
35
Frequency (MHz)

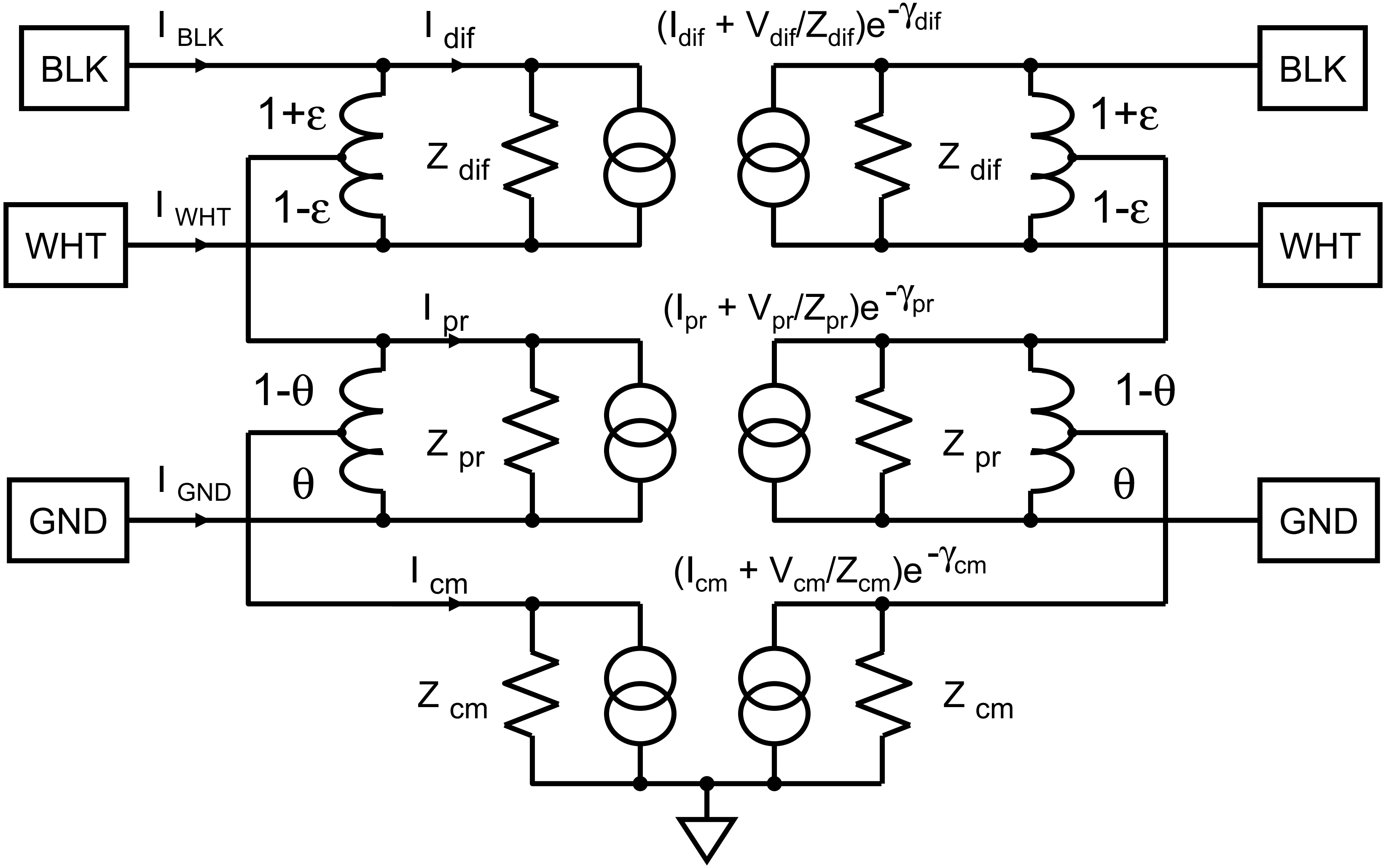
Channel Modeling

- **Two-Conductor TL Case (Hooijen - ISPLC'98)**
  - Straightforward approach, follows TPC/coax modeling
  - Insufficient when more than 2 wires present

- **Multipath Model (Dostert & Zimmermann - TCOM'02)**
  - The multipath nature arises from the presence of several branches and impedance mismatches that cause reflections
  - Not limited to PLC, see [Galli & Waring, JSAC'02] for phone channels
  - Phenomenological approach, does not factor in wiring and grounding practices

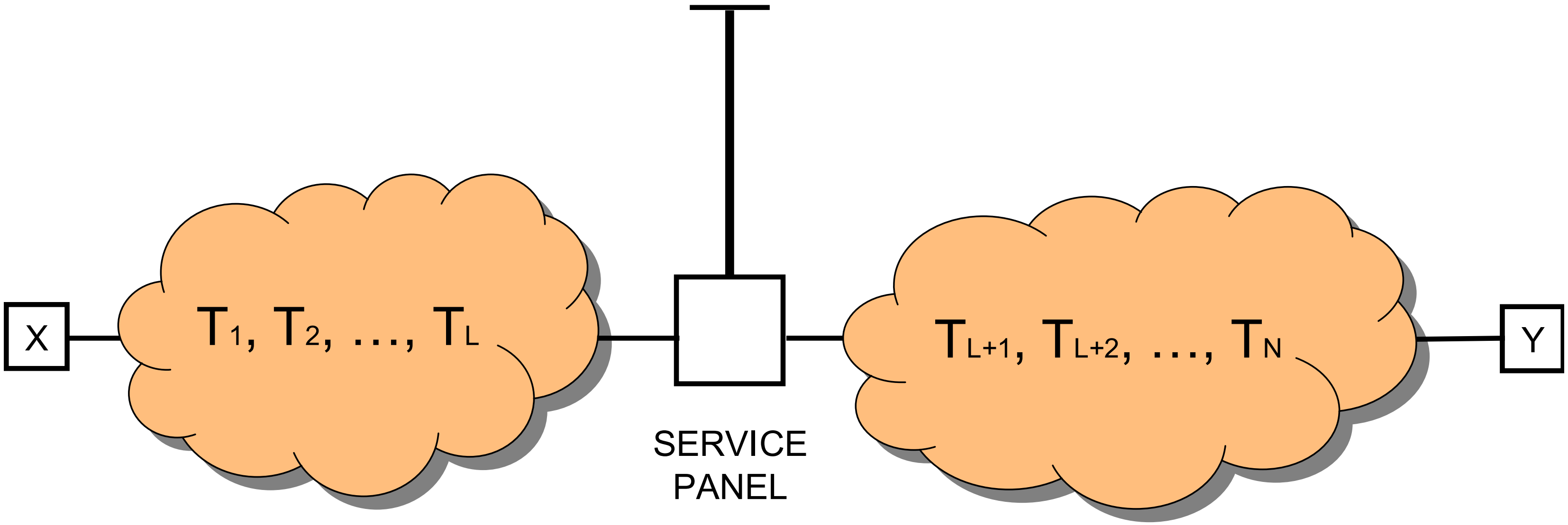
- **Multi-Conductor TL Case (Galli & Banwell – TPWRD'05, JSAC'06)**
  - Takes grounding explicitly into account via modal decomposition
  - Raises level of abstraction and treats grounded and ungrounded links under the same formalism
  - Allows unveiling interesting properties
    - Channel isotropy regardless of topology
    - Correlation of resonant modes

Grounding as an MTL Problem



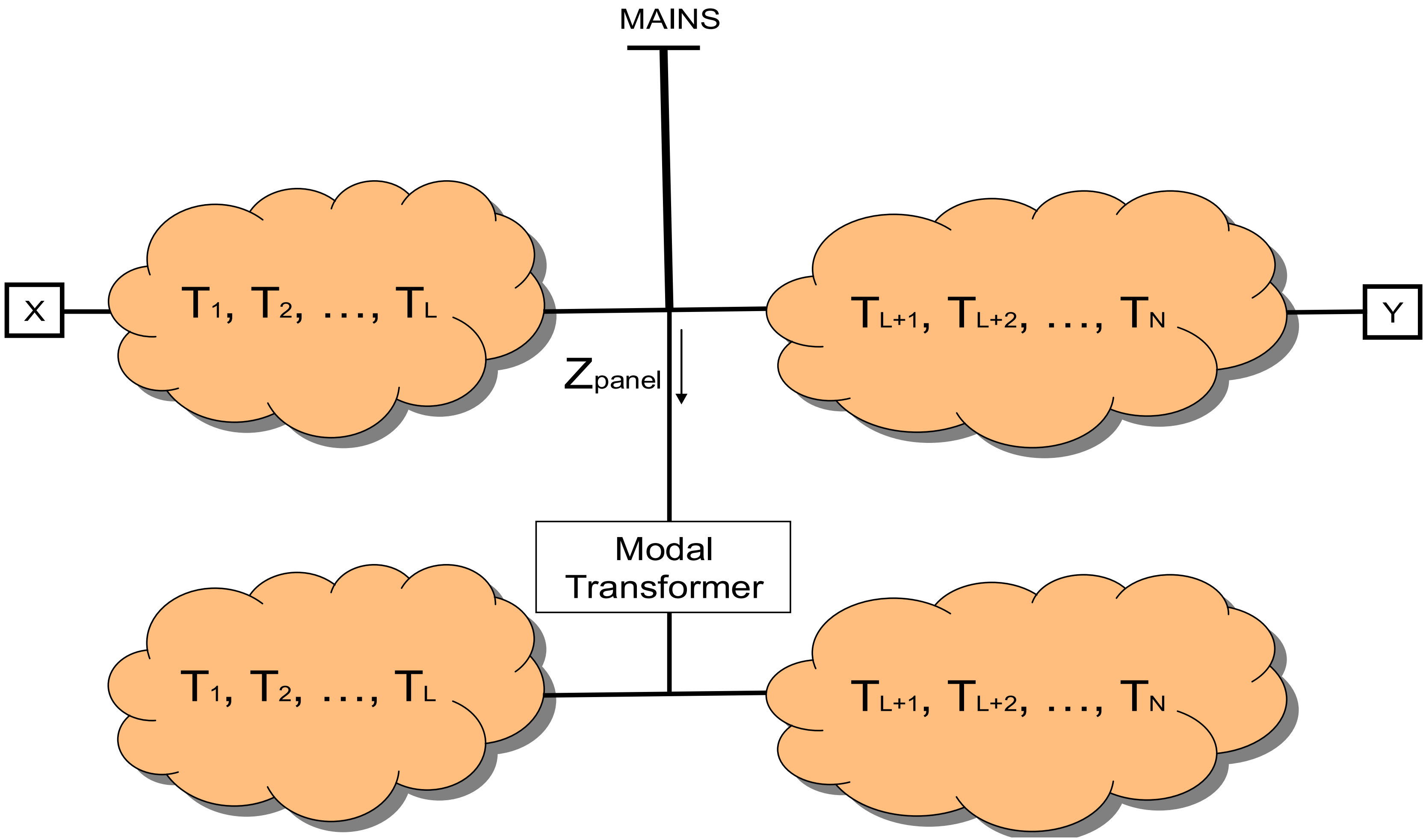
T. Banwell, S. Galli, "A Novel Approach to the Modeling of the Indoor Power Line Channel - Part I: Circuit Analysis and Companion Model," ***IEEE Transactions on Power Delivery*****, Apr. 2005.**

Ungrounded link



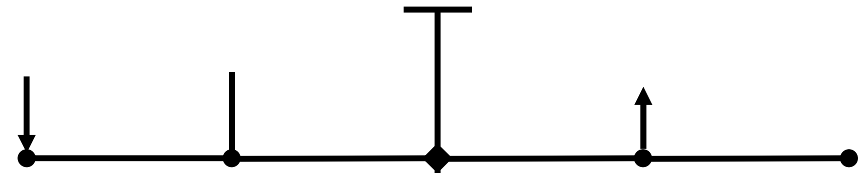
$$T_{XY} = \begin{vmatrix} A_{XY} & B_{XY} \\ C_{XY} & D_{XY} \end{vmatrix} = T_1 \cdot T_2 \cdot \ldots\ldots\ldots \cdot T_L \cdot T^{(Mains)} T^{(Panel)} T_{L+1} \cdots \cdot T_N$$

Grounded link

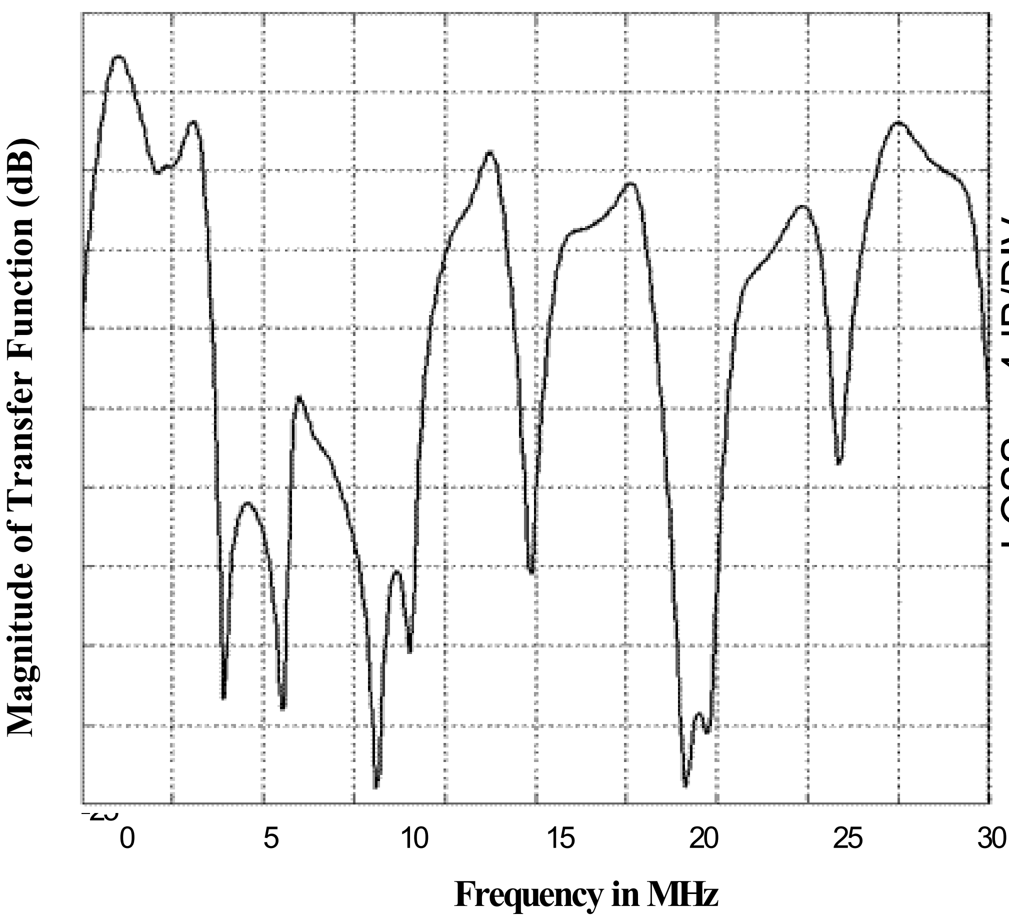


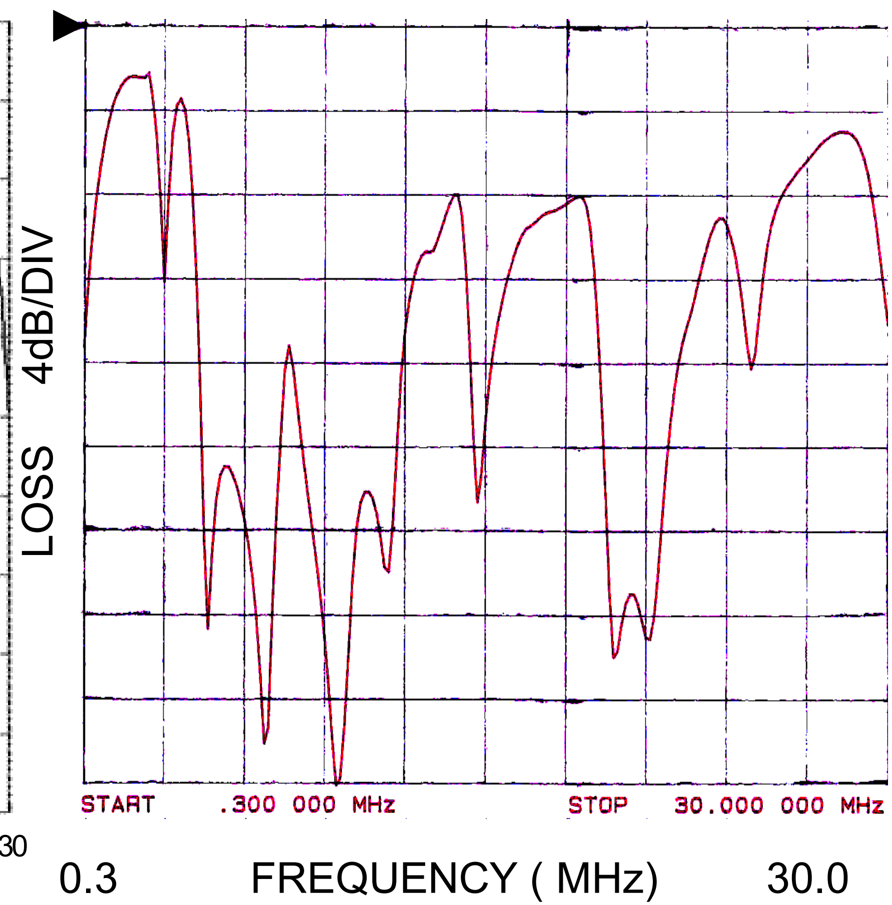
S. Galli, T. Banwell, "A Deterministic Frequency-Domain Model for the Indoor Power Line Transfer Function," *IEEE Journal on Selected Areas in Communications*, July 2006.

MTL Model for Grounded links



MTL Model





Channel Modeling: From Deterministic to Statistical Models

- TL-based channels differ from other stochastic channels because their transfer function can be accurately and deterministically calculated once the link topology is known

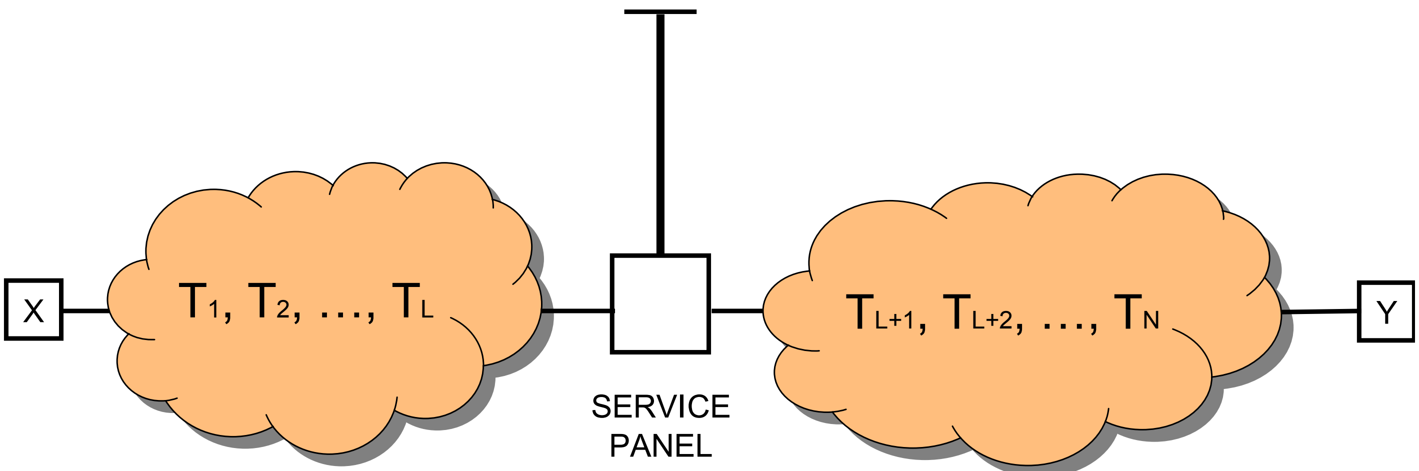
- However, the variability of link topologies and wiring practices gives rise to a stochastic aspect of TL-based channels

- The statistical modeling of this TL-based stochastic aspect is still a seldom investigated open problem (not only in PLCs but for any TL-based channel)

- Statistical results became available only in the last year
  - ➢ Necessary for deployment and coverage studies
  - ➢ Necessary for a communication theory approach

Lognormality of Channel Gains

- Sections of cable, bridged taps, mains breaker box, grounding can be modeled as two-port networks (ABCD matrices)
- The ABCD matrix of the overall link is calculated exploiting the chain rule: the overall ABCD matrix is equal to the product of the individual ABCD matrices
- Gain at one frequency depends on ABCD matrix elements, and each element is the result of many multiplicative terms



$$T_{XY} = \begin{vmatrix} A_{XY} & B_{XY} \\ C_{XY} & D_{XY} \end{vmatrix} = T_1 \cdot T_2 \cdot \ldots\ldots \cdot T_L \cdot T^{(Mains)} T^{(Panel)} T_{L+1} \ldots \cdot T_N$$

Lognormality of Channel Gains

- **Amplitude and shape of a signal are a function of:**
  - reflection coefficients $\rho(f)$ of all impedance discontinuities
  - transmission coefficients $\tau(f)=[1+\rho(f)]$ of all impedance discontinuities
  - low-pass behavior of the channel in the absence of multipath
- **Path amplitudes are a function of a cascade of several random propagation effects (product of reflection/transmission coefficients)**

$$H(f) = \sum_{i=0}^{N_{path}-1} g_i(f) e^{-\alpha(f) v_p \vartheta_i} e^{-j2\pi f \vartheta_i}$$

Direct path $(i = 0)$:

$$\begin{cases} d_0 = L_{XA} + L_{AC} + L_{CY} \\ g_0 = (1+\rho_{A1})(1+\rho_C) \end{cases}$$

Secondary paths of Type 1 $(i > 0)$:

$$\begin{cases} d_i = L_{XA} + 2iL_{AB} + L_{AC} + L_{CY} \\ g_i = (1+\rho_{A1})(1+\rho_{A2})(\rho_B\rho_{A2})^{i-1}\rho_B(1+\rho_C) \end{cases}$$

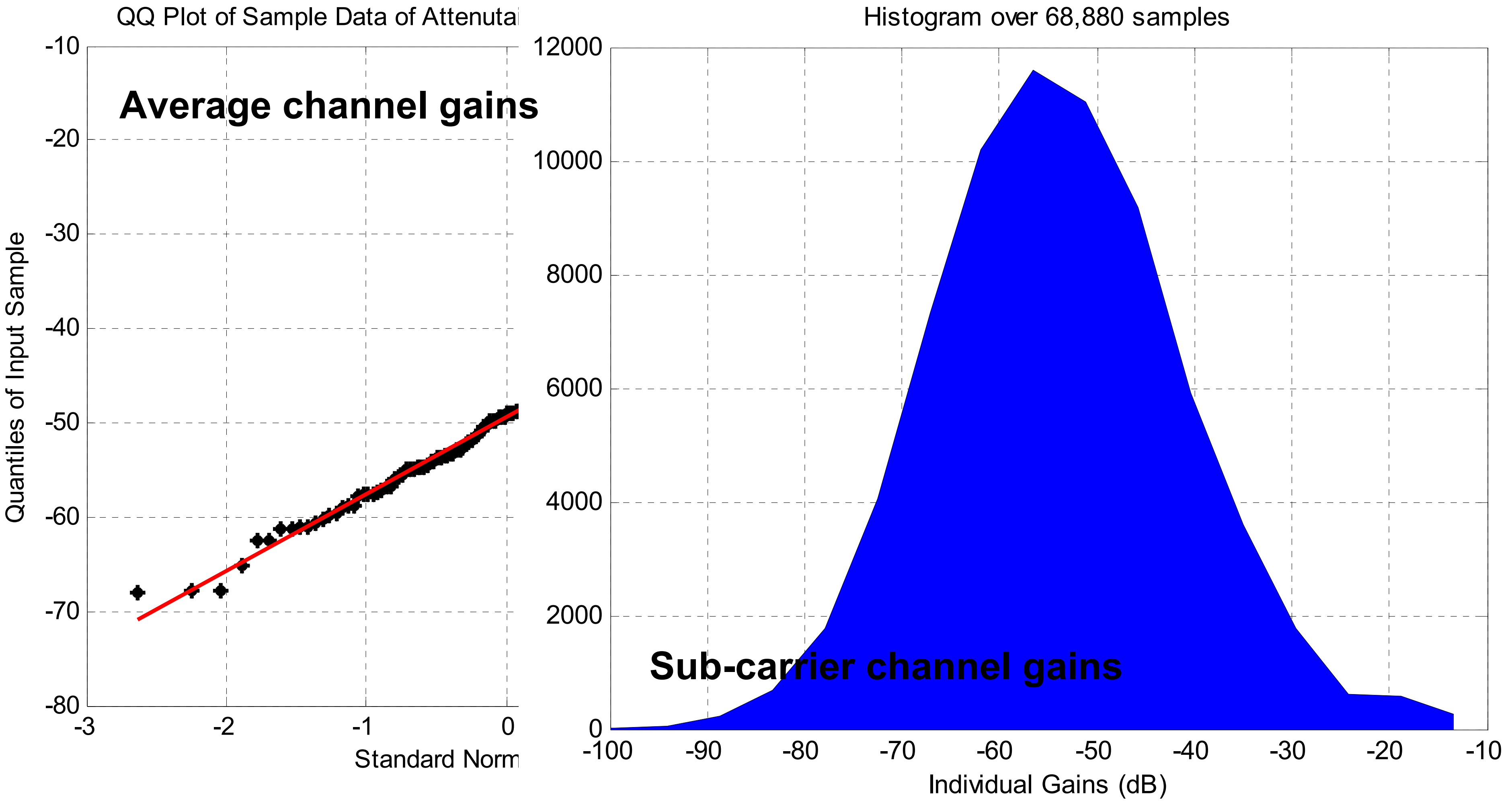
Secondary paths of Type 2 $(j > 0)$:

$$\begin{cases} d_i = L_{XA} + (2j+1)L_{AC} + L_{CY} \\ g_i = (1+\rho_{A1})(\rho_C\rho_{A3})^j(1+\rho_C) \end{cases}$$

Secondary paths of Type 3 $(i,j > 0)$:

$$\begin{cases} d_i = L_{XA} + 2iL_{AB} + (2j+1)L_{AC} + L_{CY} \\ g_i = (1+\rho_{A1})(\rho_B\rho_{A2})^{i-1} \\ \quad\quad \times\rho_B(1+\rho_{A2})(\rho_C\rho_{A3})^j(1+\rho_C) \end{cases}$$

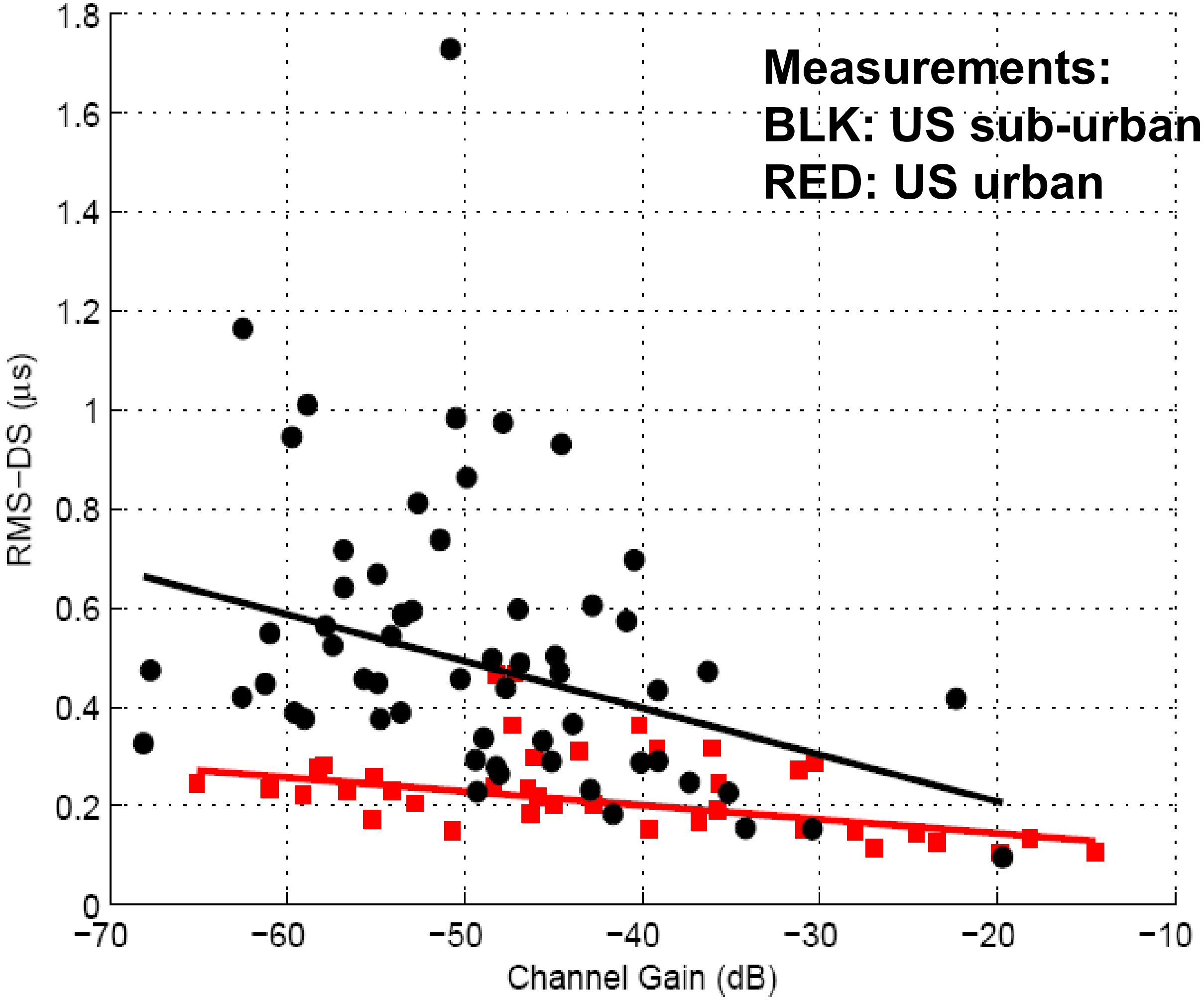
Lognormality – Empirical confirmation



S. Galli, "A Simplified Model for the Indoor Power Line Channel," *IEEE Int. Symp. on Power Line Comms (ISPLC)*, Mar. 2009.

Panasonic ideas for life

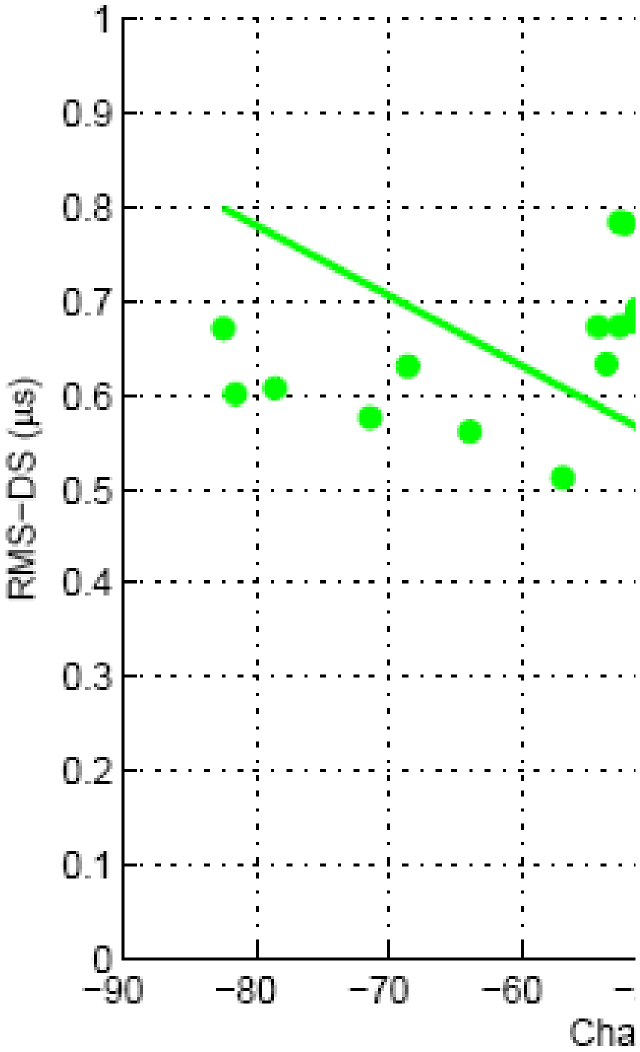
Channel Gain and RMS-DS are Correlated Lognormal RVs

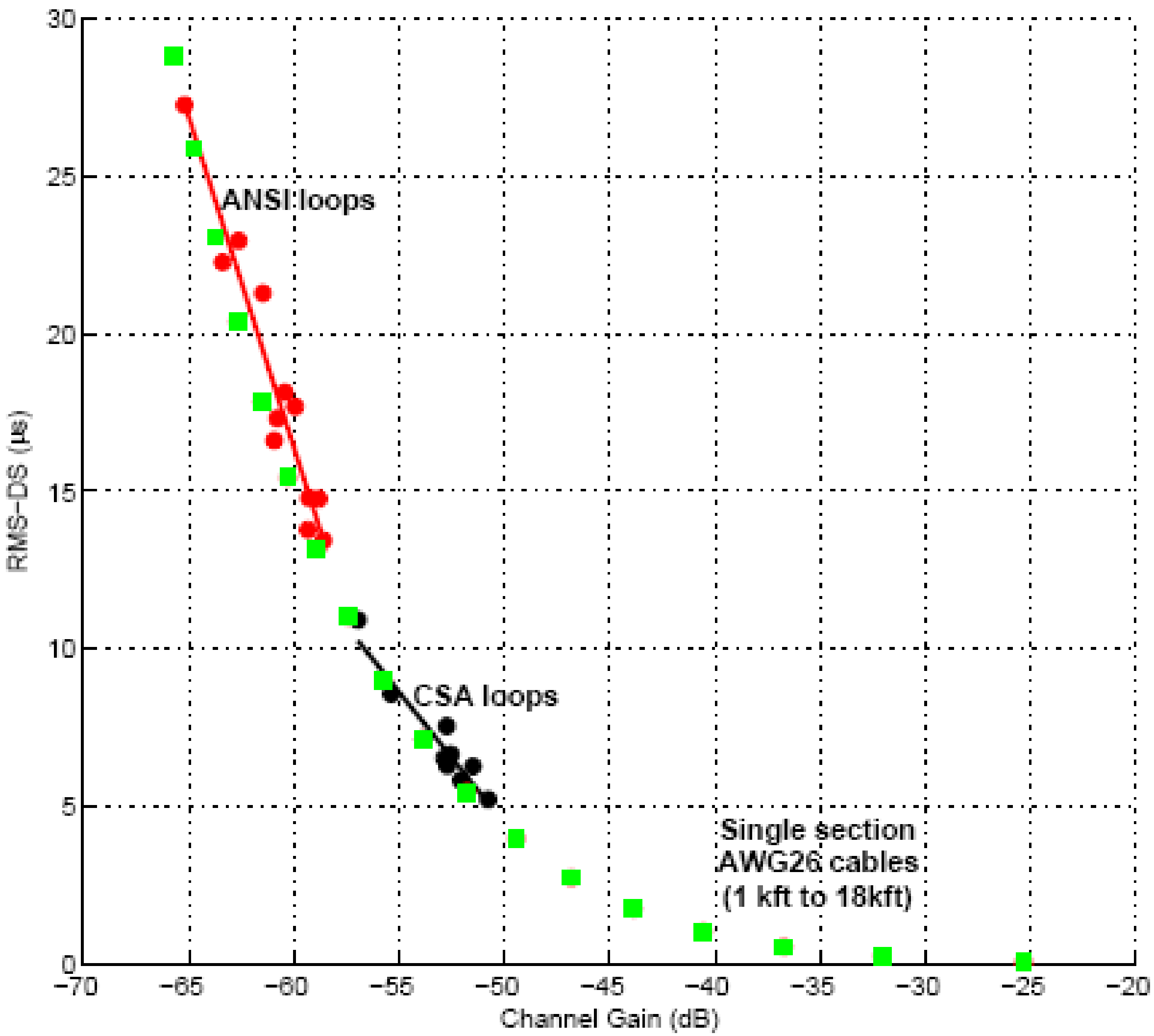


Gain excursion: ~50 dB
RMS-DS: <2 us!!

S. Galli, "A Novel Approach to the Statistical Modeling of the Power Line Channel and Other Communications Channels," submitted to TCOM, 2009.

… and not only in PLCs





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Observations on the Correlation Between Channel Gain and RMS-DS

- The existence of this correlation should caution us from using channel models where a unitary power normalization is carried out:
  - Normalizing channel gain without changing the RMS-DS is a methodological mistake as those two quantities are correlated
- For fixed TX power, severe ISI is encountered only in highly attenuated channels and equalization results should be correctly interpreted:
  - Equalizer performance on channels with mild (severe) ISI is only relevant at high (low) SNR
- The correlation observed in wired channels, can also be observed in indoor/outdoor wireless channels and…
  - Many cellular and WiFi channel models have normalized power
  - MIMO channel matrices are often normalized
    - In MIMO, rich multipath scattering necessary for achieving high multiplexing gains is typically found in highly attenuated channels which are naturally characterized by low capacity - interpretation of results requires again grain of salt

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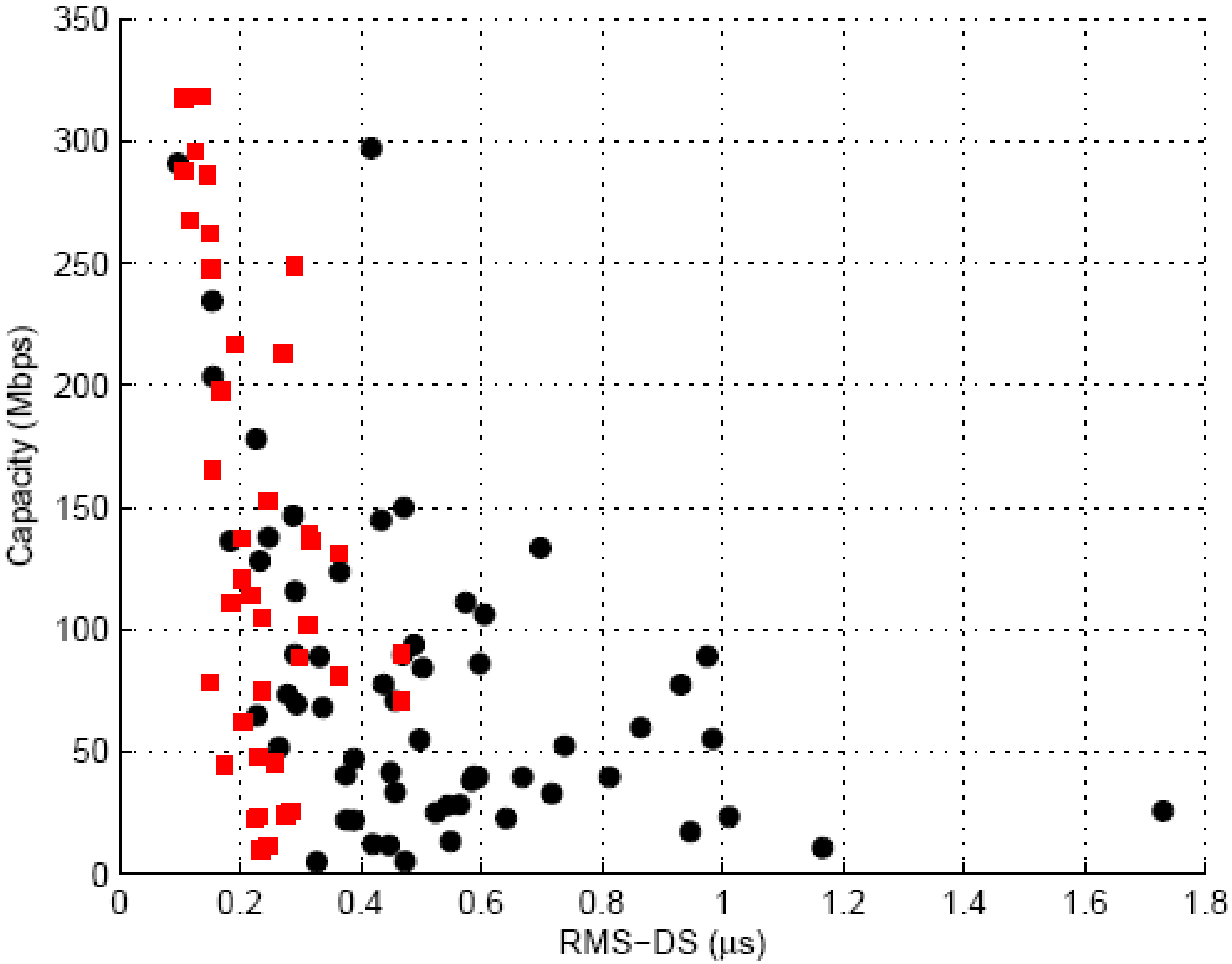
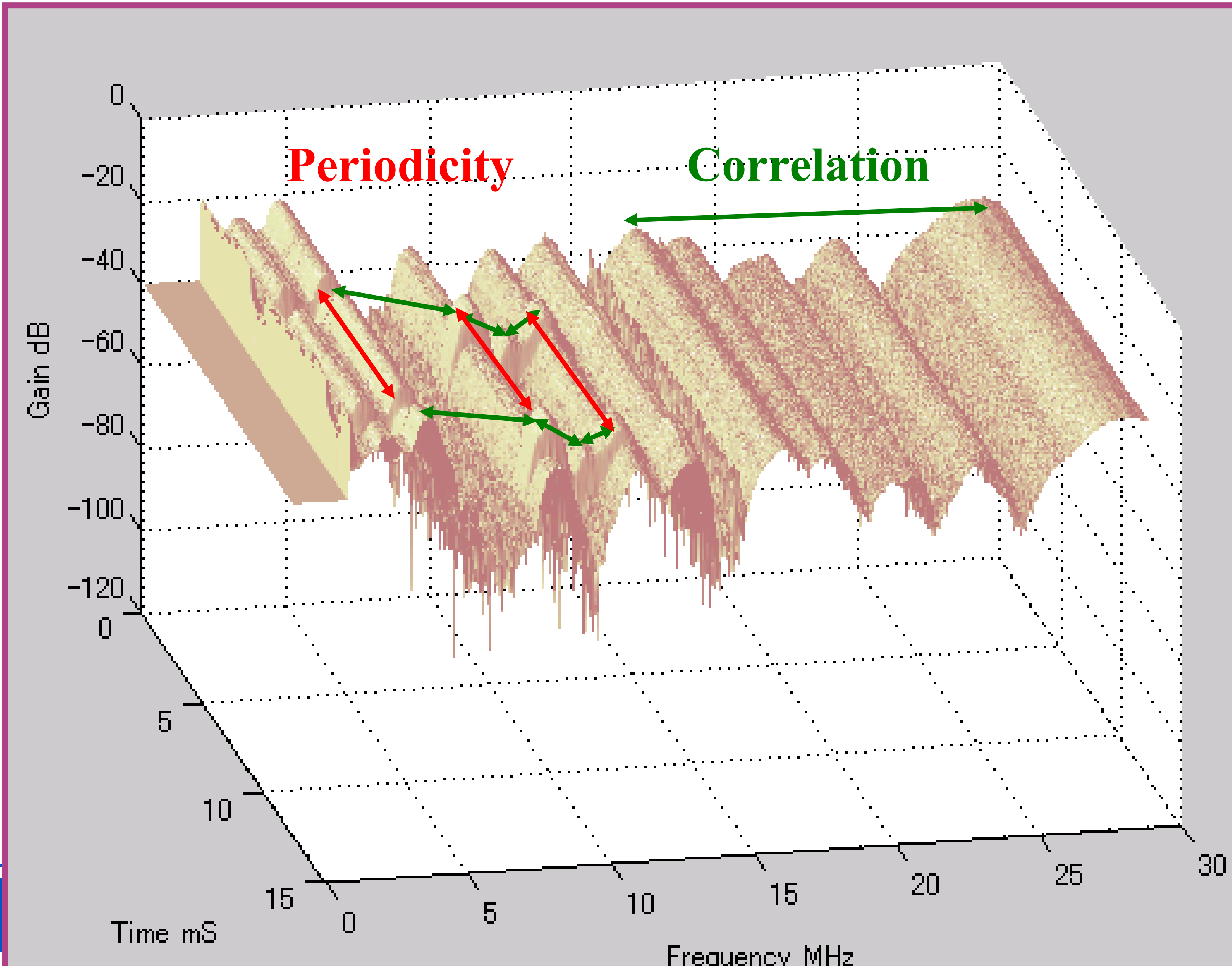
Capacity vs RMS-DS: Indoor PLC Measured Channels

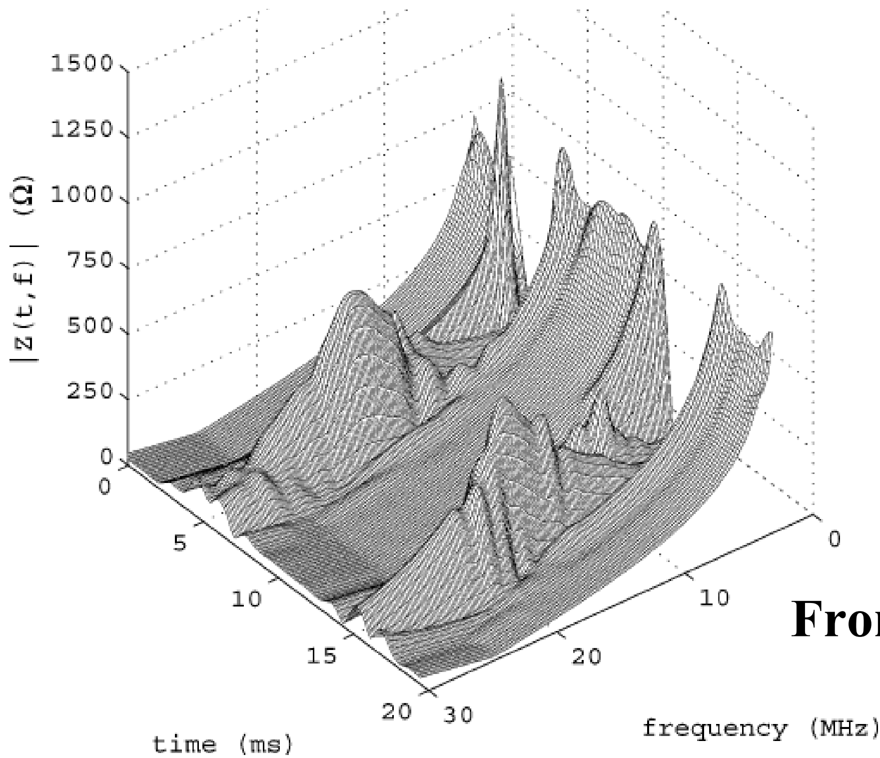


Time Variability



Channel Time Variability

- Electrical devices plugged in outlets (loads) contain non-linear elements that, relative to the small and rapidly changing communication signals, appear as a resistance biased by the AC voltage
- The AC signal swings the devices over different regions of their non-linear I/V curve and this induces a periodically tine varying change of their resistance



From Canete, JSAC'06

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Channel Time Variability is Periodic

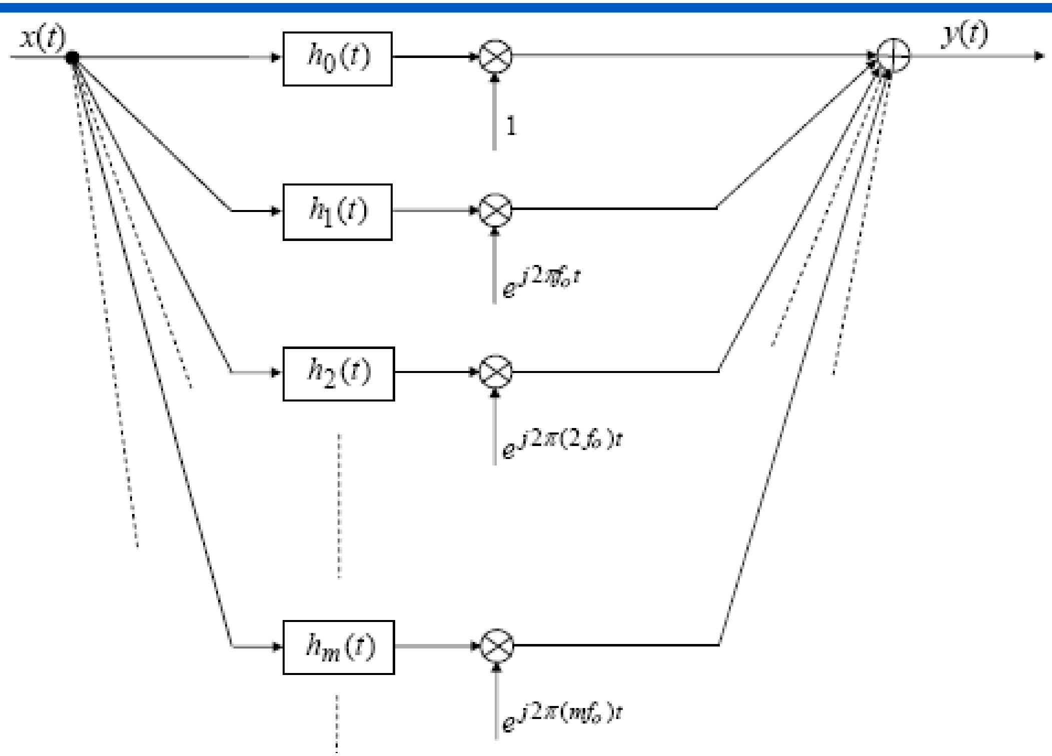
- The overall impedance appears as a shunt impedance across the "hot" and "return" wires and, since its time variability is due to the periodic AC mains waveform, the channel is naturally periodic
- [Canete, JSAC'06] reports median Doppler spread of 100 Hz, a 90%-percentile of 400 Hz, and Doppler components up to 1, 750 Hz (channel is underspread)
  - Observed components are quantized at multiples of 50Hz

$$h(t,\tau) = \sum_{m=-\infty}^{+\infty} h_m(\tau) e^{j\frac{2\pi m}{T_0}t} \qquad h(t+kT_0,\xi) = h(t,\xi), \forall k \in \mathbb{Z}$$

$$y(t) = \sum_{m=-\infty}^{+\infty} e^{j\frac{2\pi m}{T_0}t} \int_{-\infty}^{\infty} h_m(\tau)x(t-\tau)d\tau = \sum_{m=-\infty}^{+\infty} e^{j\frac{2\pi m}{T_0}t} \{h_m(\tau) * x(t-\tau)\}$$

The LPTV power line channel can be modeled as a bank of LTI filters followed by a Doppler (Zadeh, 1950)

Channel Time Variability is Periodic



We then need to bridge comms/DSP methodologies with circuits and systems analysis and solve two open problems:

A) Find a discrete time representation for TL channels

B) Estimate the harmonic functions $h_m(t)$

S. Galli, A. Scaglione, "Discrete-Time Block Models for Transmission Lines: Static and Doubly Selective Cases," submitted to TCOM, 2009.

PLCs are like wireless comms, *but…*

- **PLCs are like wireless comms:**
  - Fading channel, but it is only lognormal
  - Time varying channel, but slowly and periodically time varying (LPTV)
  - Channel is stochastic, but there is more embedded determinism
  - Channel is noisy, but noise is colored and impulsive (periodic and aperiodic)
  - Allows MIMO, but very low order (number of wires -1)
  - Broadcast medium, but mere distance is not the only variable for SNR and less usable bandwidth is available
  - Interference limited, but also when very few (non-interoperable) users present
  - Master (BS) Slave (MU) architecture, but Master coverage areas overlap, and Slaves don't move, can talk to each other, and are not power constrained

- **In addition:**
  - Power cables radiate, EMC regulations impose PSD masks
  - There is a distributed clock, PLC stations can synchronize

Areas of Investigation: In-Home A/V Applications

- **Main problem has always been to maximize single link throughput, but:**
  - Transmit power capped by regulation
  - Adding bandwidth allows only marginal improvements because attenuation is proportional to frequency
- **MIMO is being investigated**
  - Still unclear how much gain possible due to correlation of channel paths
  - However, distributed MIMO would not require synchronization overhead… there is a distributed clock
- **Relaying is a very little investigated topic but probably not much gain possible due to the fact that channels in a home are correlated**
- **Available solutions and new standards do not perform any kind of interference management between PLC nodes**
  - PLC channel is interference limited (node scalability, neighboring networks)
  - Only managed case is non-interoperable neighboring networks (coexistence)
- **Synergistic cooperation of PLCs with wireless can increase coverage and throughput of (hybrid) home networks**
  - Use PLC to bridge APs (products available today are just dumb repeaters)
  - Use PLC to assist wireless relaying [Kuhn, JSAC'06]
  - Use PLC to do beamforming

Areas of Investigation: Smart Grid

- **For the MV: substation connectivity, fault detection, island detection, PQ monitoring, etc. ➔ PLC combines sensing and comms functions**
- **For the LV: Metering, vehicle-to-grid (PHEV), DR, DSM, HEMS**
- **Broadband PLCs not suited for Smart Grid outside the home:**
  - Most Smart Grid applications do not require high data rate
  - HF band has high path loss (~150 dB/km on LV, and ~60 dB/km on MV)
  - HF band not available everywhere in the world
  - Require coupler to by-pass MV/LV transformer
- **Narrowband PLCs much better suited for Smart Grid:**
  - Path loss is ~1-2 dB/km
  - Ease of upgrade, can be implemented as a soft modem
  - Band of operation available worldwide
  - Requires PHY/MAC design targeted for low power, low bandwidth, low complexity terminals ➔ new design paradigm, similar to wireless M2M
- **A basic issue in Smart Grid is scalability:**
  - PLC cooperative schemes proven experimentally for NB-PLCs [Bumiller, 2010]
- **The power grid is the information source of the Smart Grid, but for PLCs it also becomes the actual physical network over which data travels**
  - Study of the grid as a graph becomes an interesting topic (HV is a small world networks, but MV/LV is not) ➔ from single link analysis to network PLC issues

Conclusions

- PLCs is still a quasi virgin territory from a communication theory point of view
- Last couple of years has seen several results that can finally pave the way for a communication theoretic investigation
  - ➢ Better understanding of PLC determinism
  - ➢ Statistical channel models
  - ➢ Bridge between comms/DSP methodologies and circuits and systems ones:
    - o Discrete time equivalent model for TL-based communications channels formalism allows addressing both the LTI and the LTV/LPTV cases
    - o Model allows design of precoders and bit loading methods that are tailored to better cope with the LPTV channel
- PLCs have many problems similar to wireless, some things are worse (smaller bandwidth, noise, etc.), but other things are better (LPTV, distributed clock, determinism, etc.)…. creativity needed in adapting wireless schemes
- PLCs have not experienced yet mass market adoption, but Smart Grid may have pivotal role in fostering the success of PLCs
  - ➢ But comms is not enough, combining with distributed control is key
- While wireless R&D funding is shrinking…. Smart Grid R&D funding is growing fast!!