Universidad de Málaga

Dpt. Ingeniería de Comunicaciones

keynote

power line channels: frequency and time selective

part 1 - **response** of **indoor PLC** channels

ISPLC 2007

Pisa, 27 march

Francisco Javier Cañete

outline

1 introduction

2 some features of indoor PLC channels

3 analysis of channel modeling

4 reference channel models for testing

5 conclusions

1 introduction

state of the art in PLC channel modeling

review of different approaches

2 some features of indoor PLC channels

3 analysis of channel modeling

4 reference channel models for testing

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state of the art in PLC channel modeling

[focusing only in channel response at 'high' frequency]

- **Channel characterization**: Phillips (ISPLC'98), Liu (TCE'99)...

- **Multipath models:** Phillips (ISPLC'99), Dostert-Zimmermann (ISPLC'99, TC'02), Degardin et al. (JCS'03), Papaleonidopoulos et al. (TCE'03) **...**

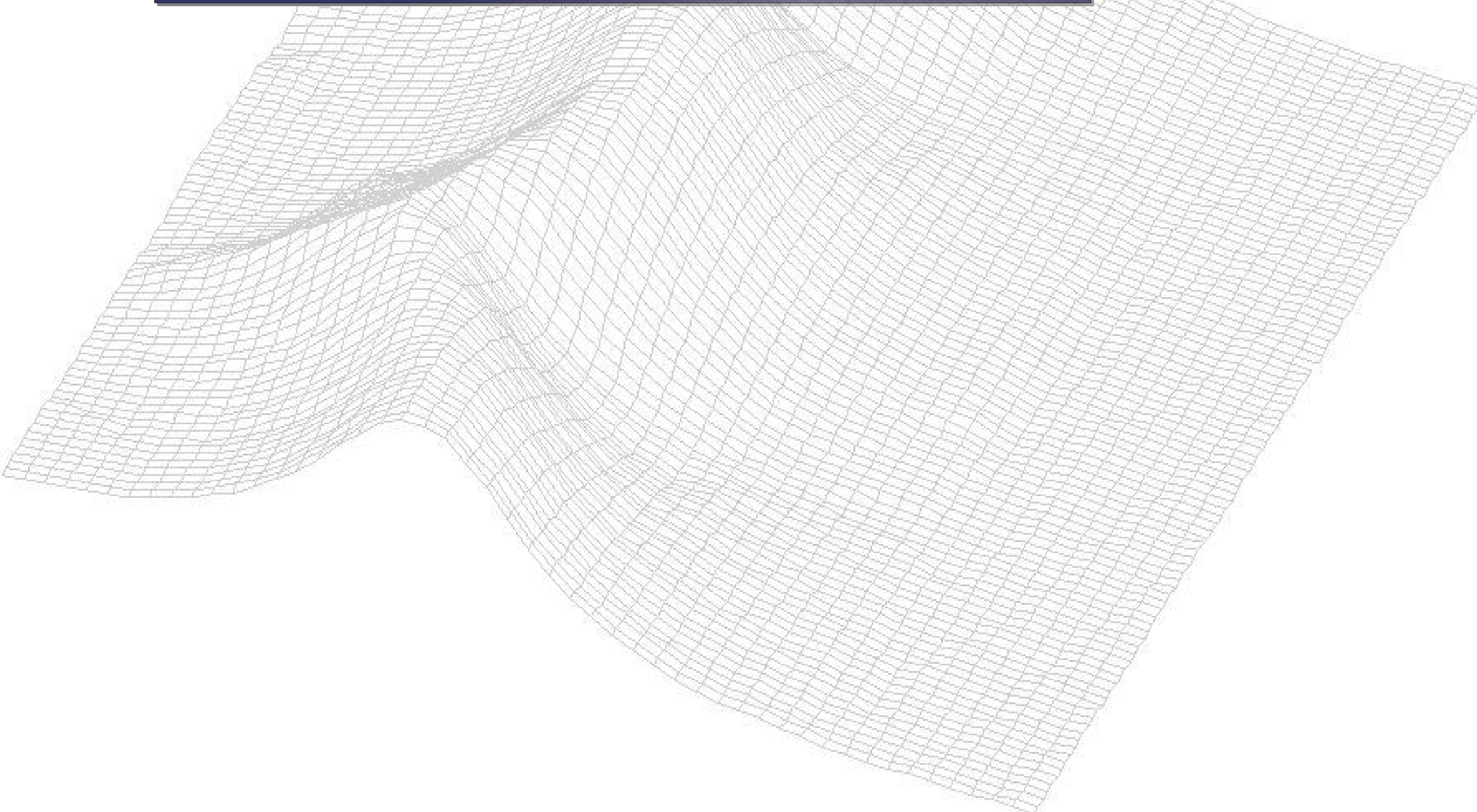
- **Transmision lines models:** Cañete et al. (ISPLC'00-05, TCE'02, CM'03, JSAC'06), Galli-Banwell (ISPLC'01, TPD'05, JSAC'06), Esmailian et al. (ISPLC'02, JCS'03), Sartenaer-Delogne (ISPLC'01, JSAC'06) ...

- **Channel model standards**: Opera 2005, IEEE P1901 (?)

TCE: IEEE Trans. on Consumer Electronics
TC: IEEE Trans. on Communications
JCS: International Journal of Communication Systems
CM: IEEE Communications Magazine
JSAC: IEEE Jounal on Selected Areas in Communications
TPD: IEEE Trans. on Power Delivery

review of different approaches

- **behavioral** or **structural** definition?
- **stochastic** or **deterministic** modeling?
- **LTI** or **LTV** channel?



review of different approaches

- **behavioral** or **structural** definition?
- **stochastic** or **deterministic** modeling?
- **LTI** or **LTV** channel?

structural modeling: bottom-up strategy (like in ADSL)

- from network characteristics to behavioral channel model
- physical parameter estimation is more intuitive
- model adaptation to power grid features worldwide is easier

behavioral modeling: top-down strategy (like in wireless)

- statistical characterization of the system
- parameter estimation must be based on extensive measurements
- even more extensive to cover power networks worldwide
- indoor power lines, large number of taps for FIR-like models
- It is not straightforward to define reference channels for testing

review of different approaches

- **deterministic** models are extremely difficult:

  usually the network layout is unknown (uncertainty of some meters is inadmissible)

  is not sensible to characterize every load behavior

- maybe the best **choice: structural** modeling but using **statistical values** for the physical parameters

  even just take expected values, selected from the common sense

- State-of-the-art **PLC modems** are versatile

  able to adapt to channels with particular features

  e.g. to have a notch at an exact frequency may be not relevant

1 introduction

2 some features of indoor PLC channels

- network topology
- channel time variation
- examples of loads short-term variation

3 analysis of channel modeling

4 reference channel models for testing

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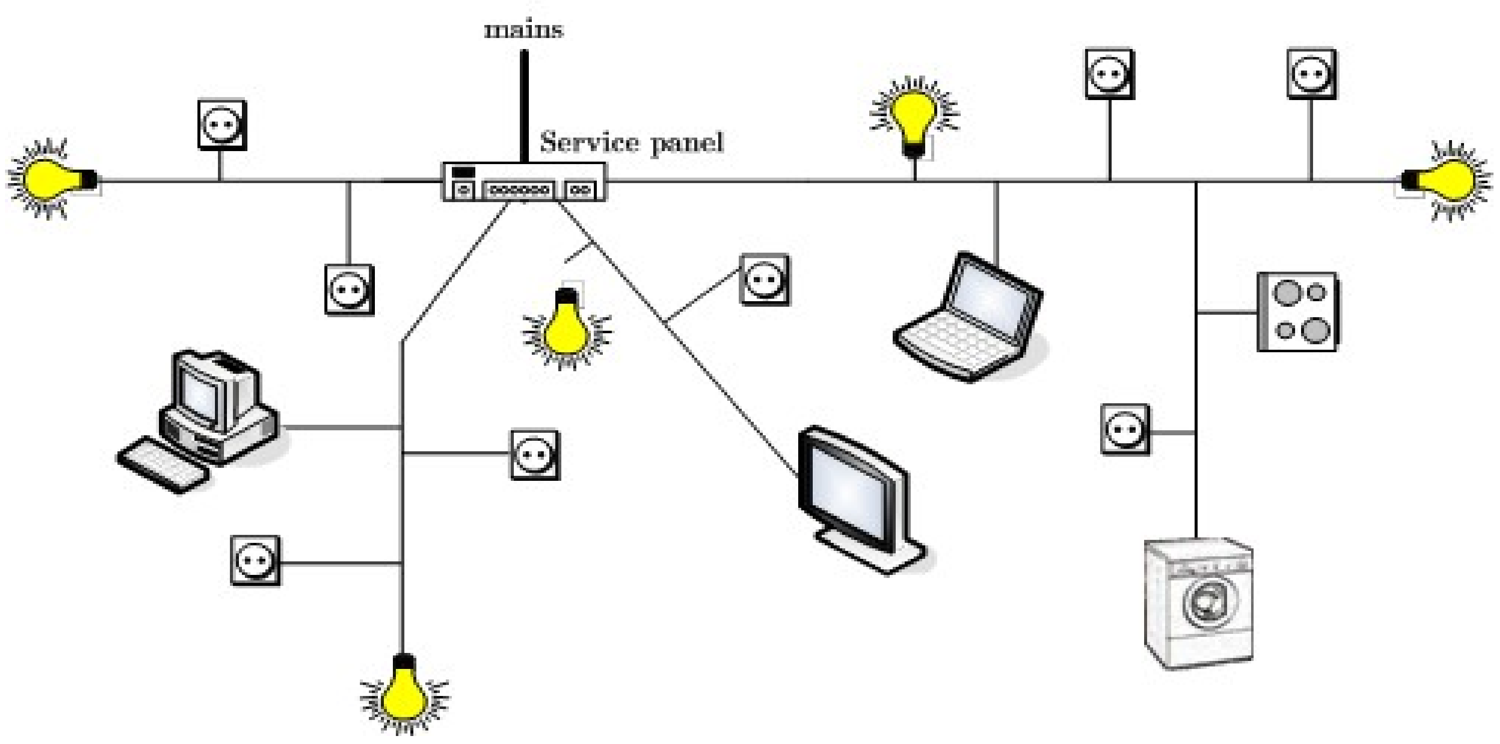
indoor networks structure

in Europe 230V @ 50Hz

- multiple branch circuits (line, neutral... and protection)
- usually differential transmission between line and neutral
- grounding practices causes mode coupling

wiring

- layout with a tree-like topology
- impedance mismatch » **multipath propagation**



channel time variation

indoor channels response is time-varying in different ways:

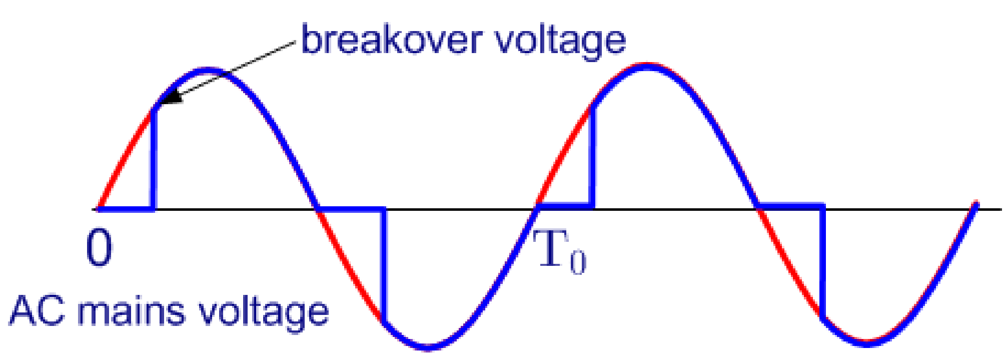
- **long-term variation**: due to the connection and disconnection of loads (changing both impedance value and generated noise)

  infrequent and random transitions, stable channel in between

  dynamics related to human behavior at homes or offices

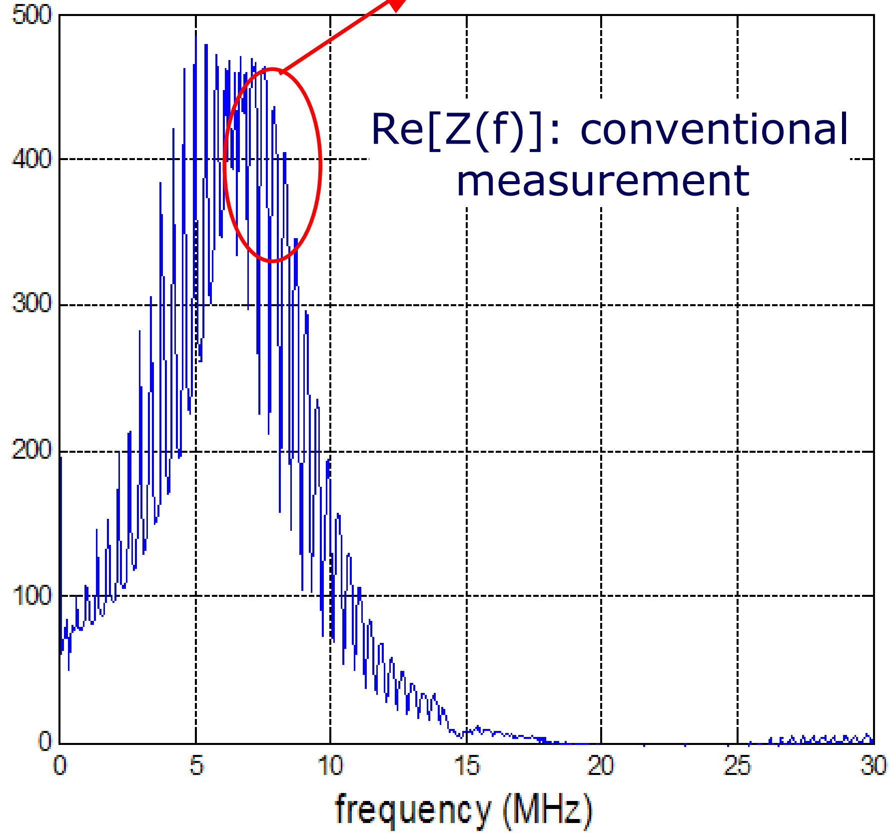
- **short-term variation**: due to non-linear devices typical in appliances power circuits (e.g. SCR)

  results in periodical changes in the high-frequency behavior of the loads

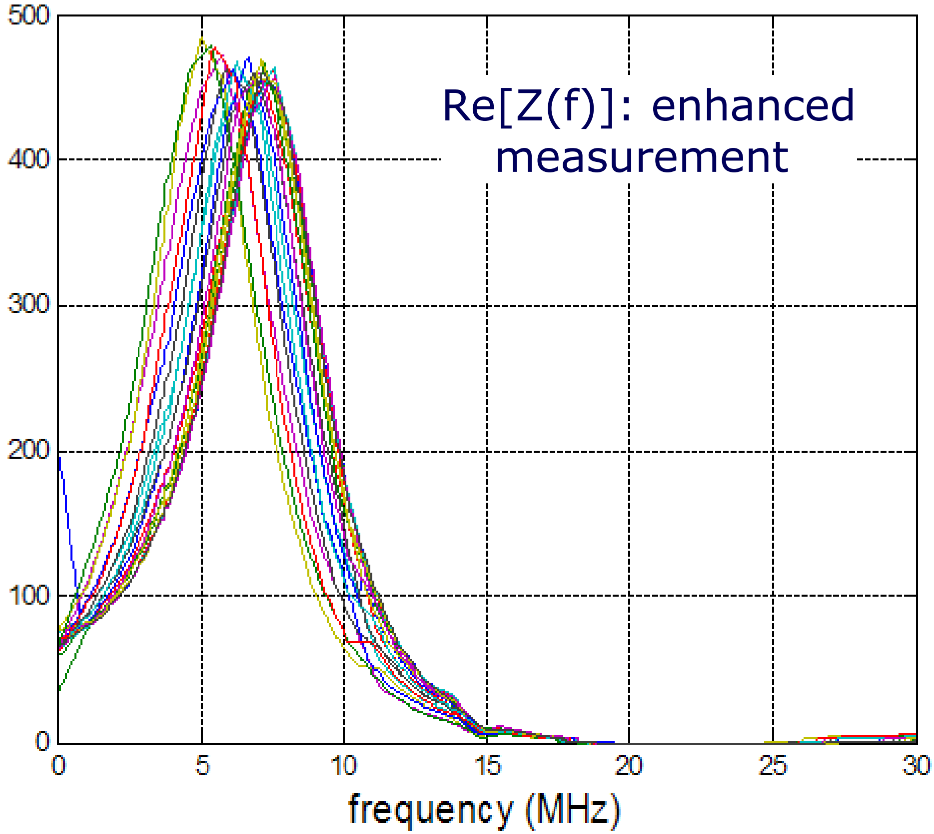


Analysis of **devices** behavior at high-frequency

mains voltage periodicity affects devices behavior



Coffee machine



devices with time varying behavior lead to a **time varying channel**

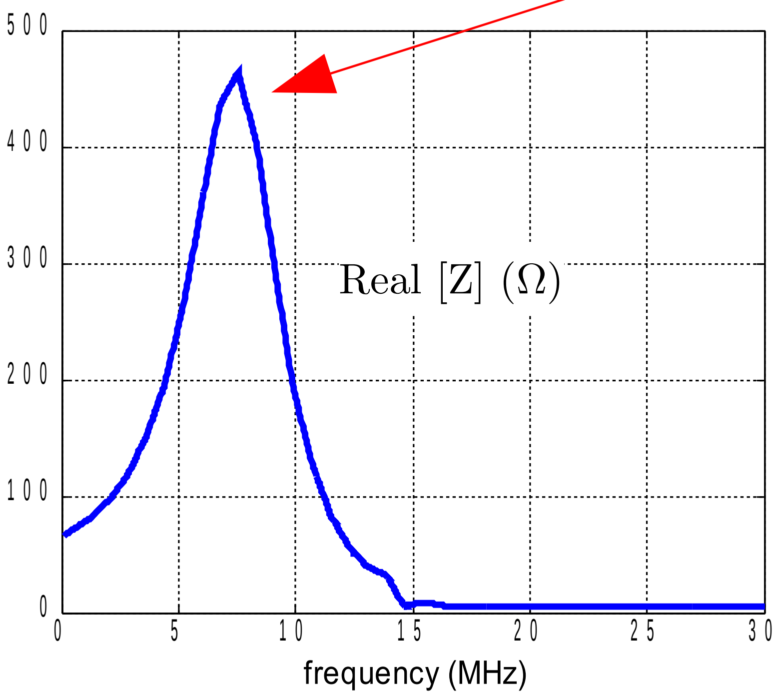
- time varying impedance value

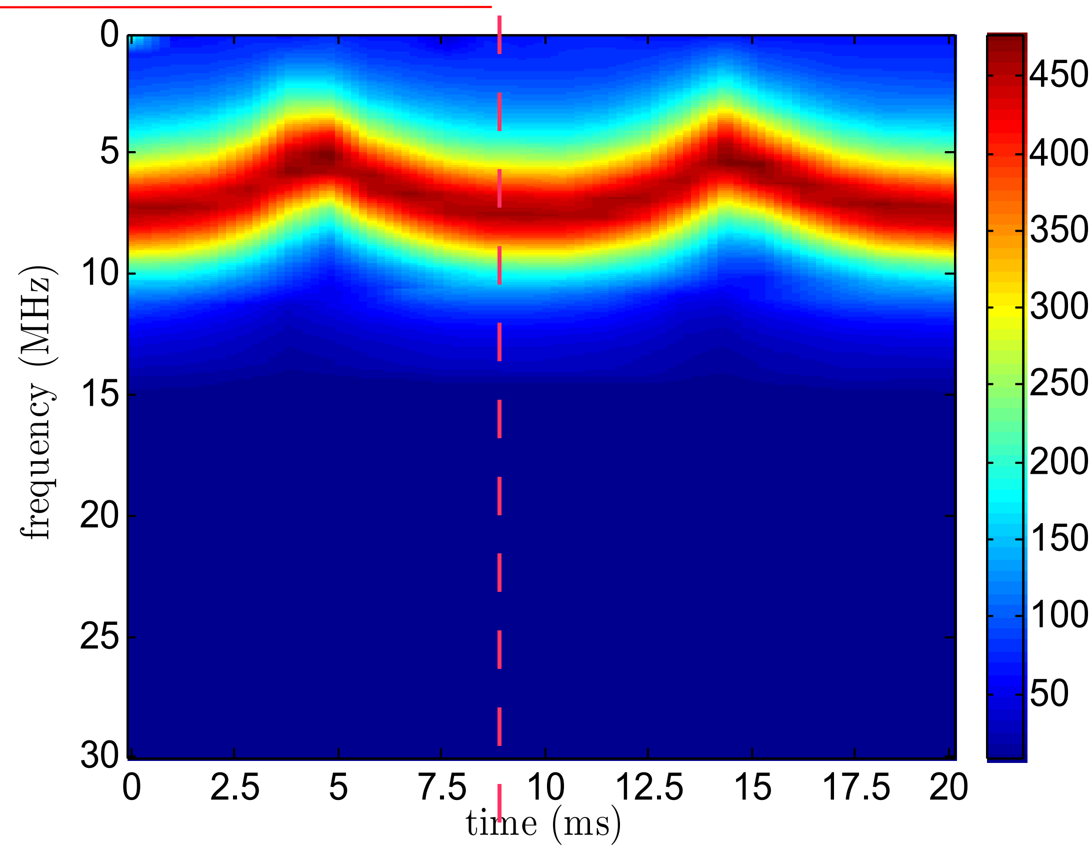
- **Network analyzer** frequency sweep must be **synchronized** with 50/60Hz and triggered with **mains** voltage
- Additional **processing**:

  from a vector in frequency to a matrix in **time-frequency plane**

  two type of devices:
  - CLASS 1: "continuous" impedance
  - CLASS 2: "switched" impedance

-example CLASS 1: coffee machine





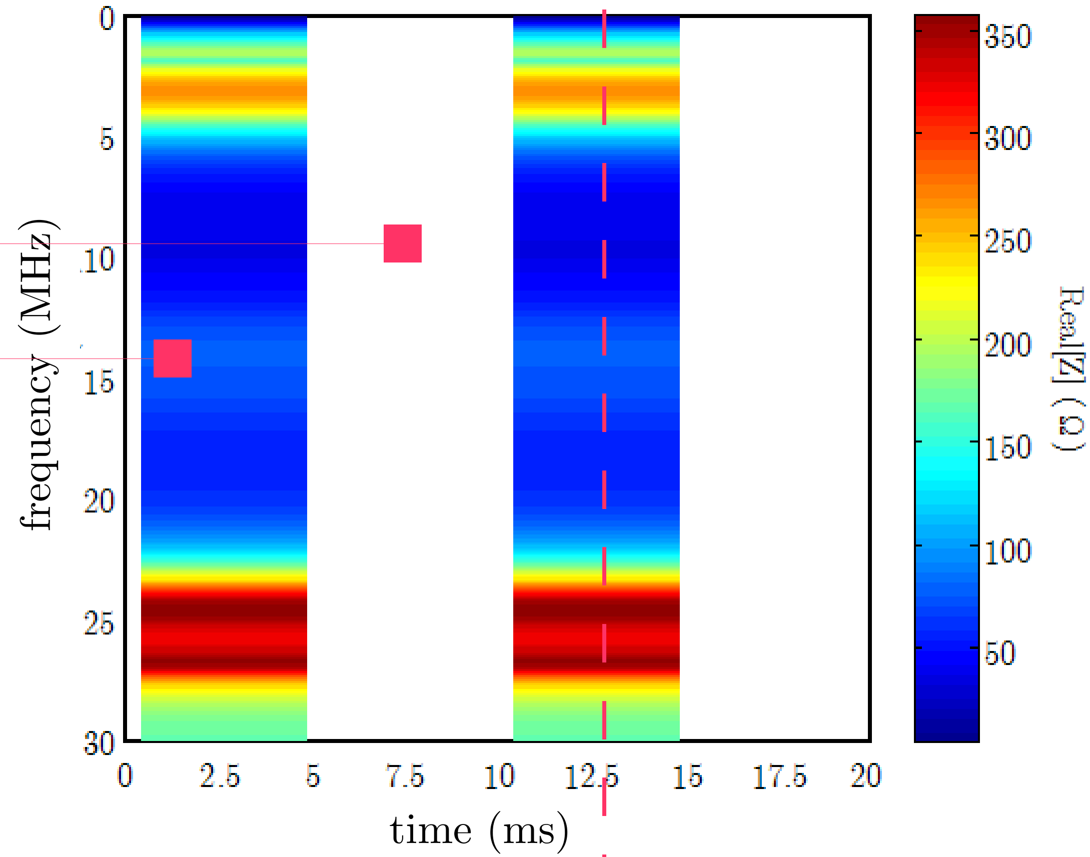
loads high-frequency characteristics

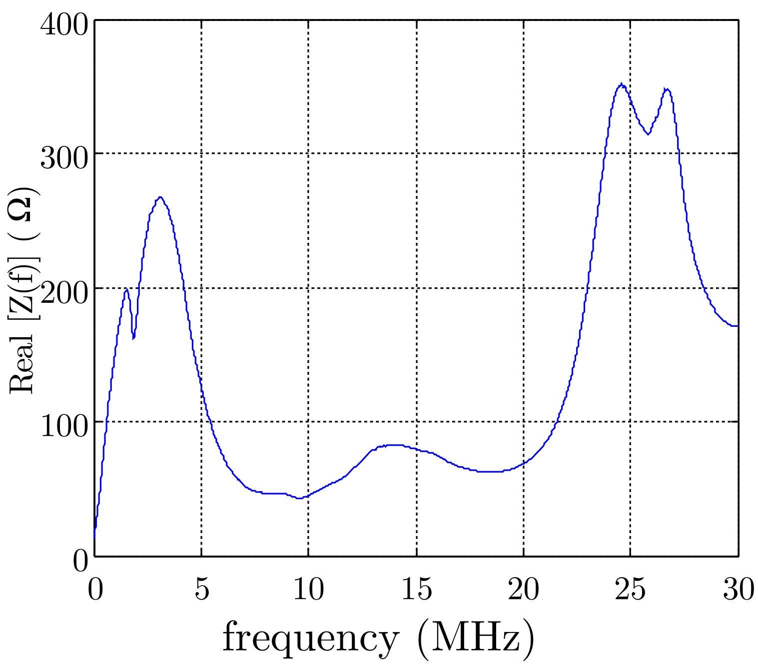
- time varying impedance value

-**example** CLASS 2:
low energy lamp

state of “high” impedance

state of “low” impedance





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3 analysis of channel modeling

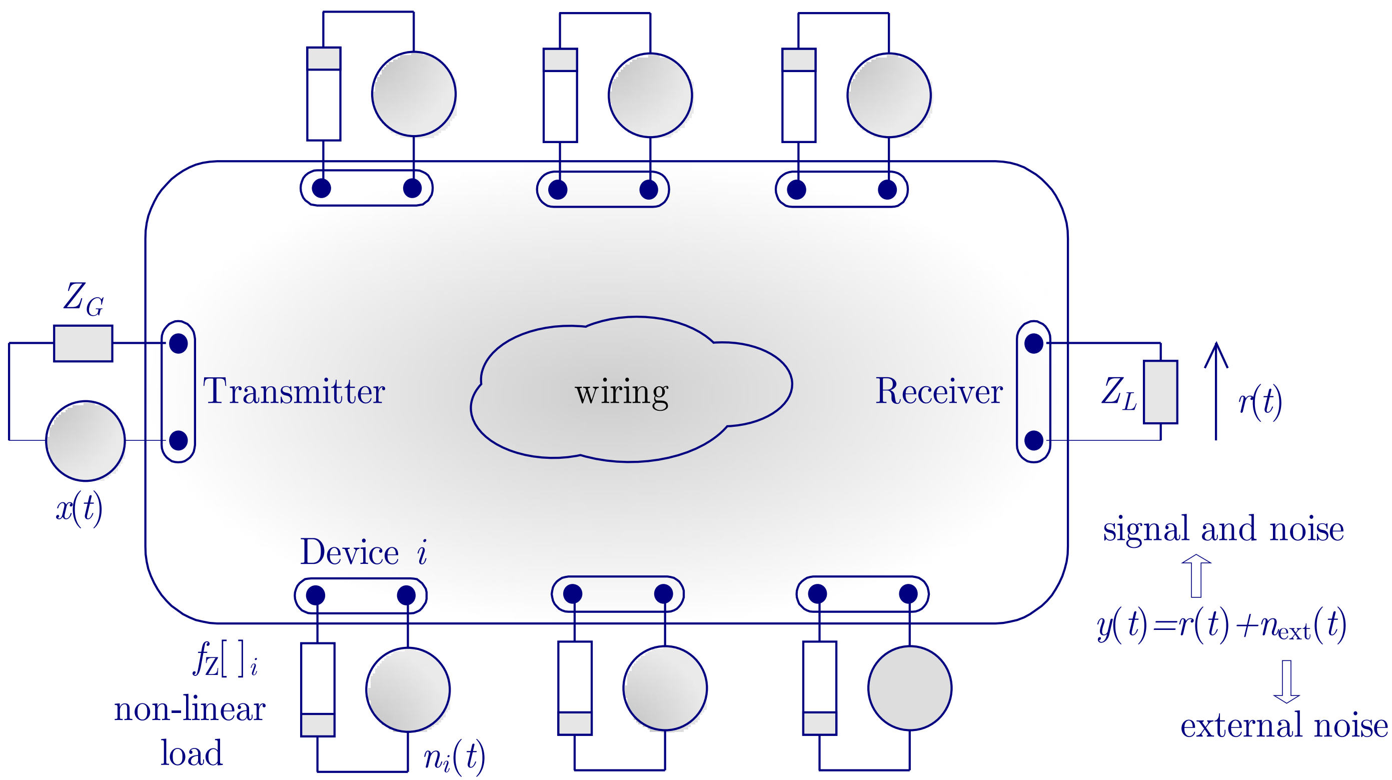
- structural modeling
- definition of time scales
- channel cyclic model
- measuring channel time variation

4 reference channel models for testing

5 conclusions

structural modeling

- **functional description** of the network elements:



wiring: two-wires transmission lines is enough

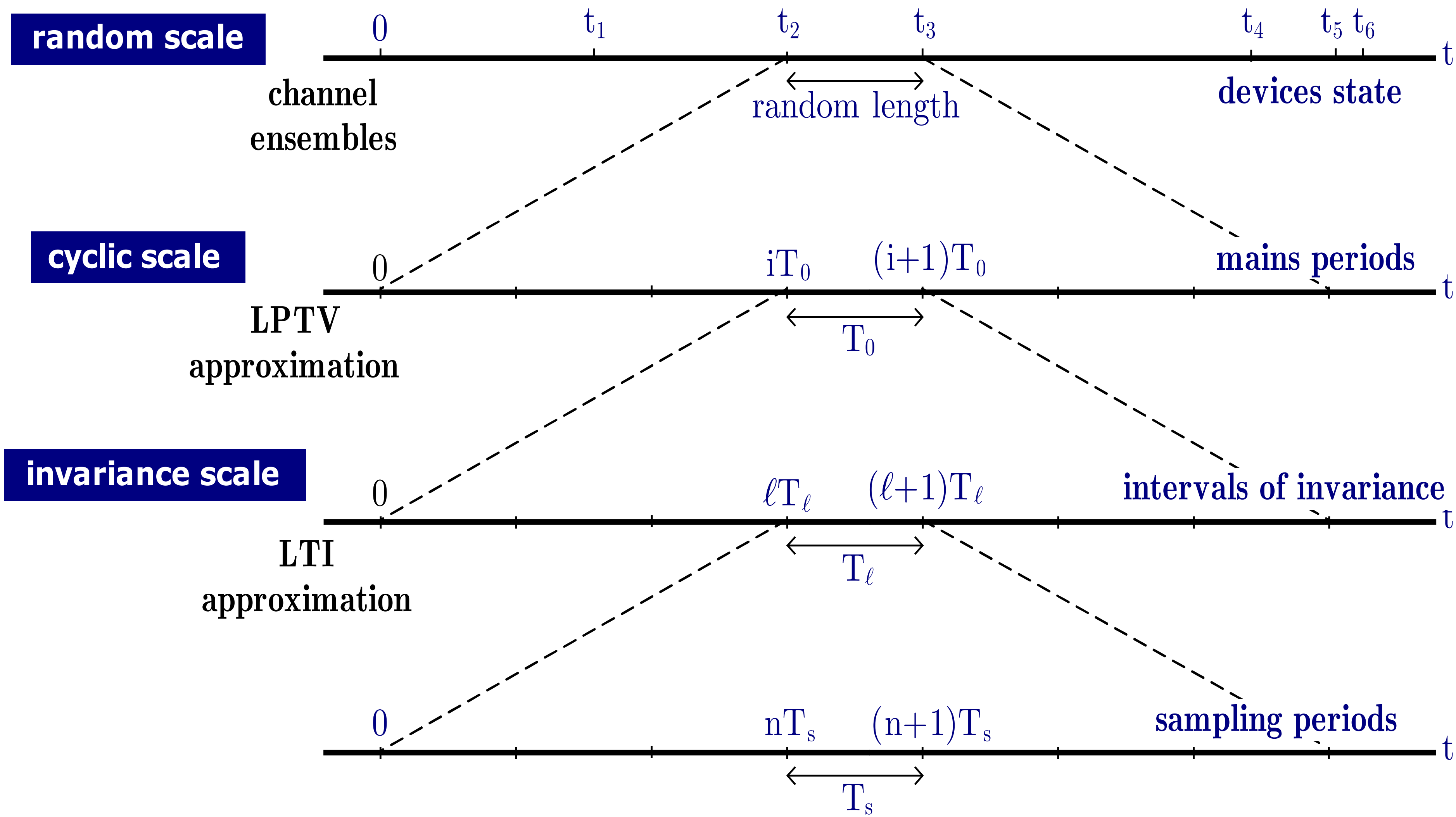
devices: load + noise generator (long-term random switching)

transmitter and receiver: one-port network loads

external noise: additive at the receiver

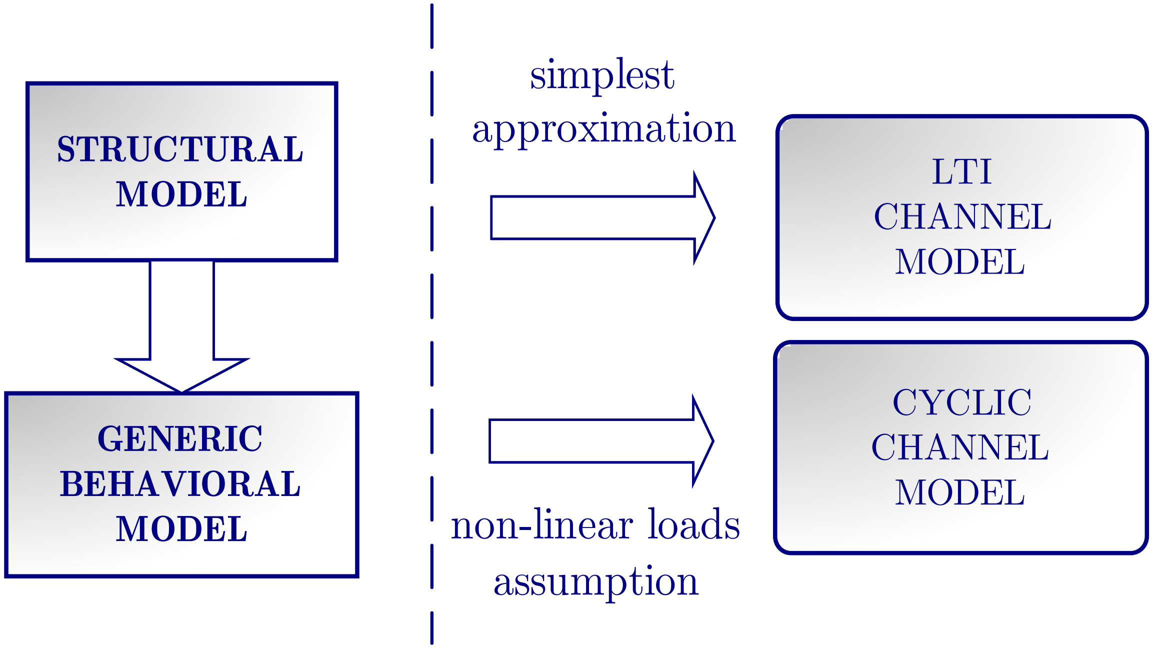
strategy: approximate definition of physical **parameters**, just to obtain **reasonable scenarios**

channel variation: time scales



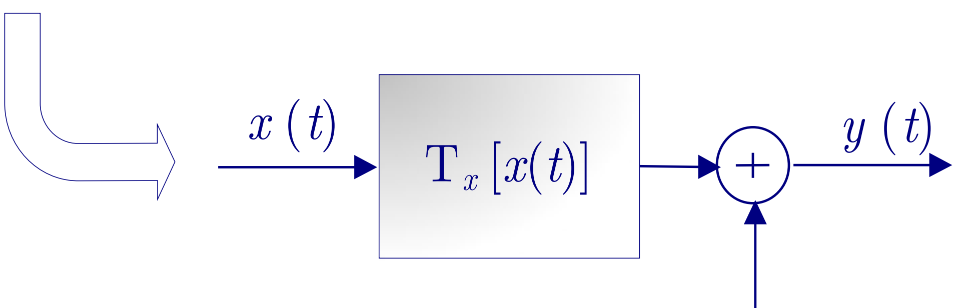
- at the **random scale**: a new channel appear every time an appliance is switched on/off
- traditionally **cyclic scale** has been disregarded

generic behavioral model



LTI system + stationary and impulsive noise

LPTV system + cyclostationary and impulsive noise



$$n_d(t) = \mathrm{T_n}[n_1(t), n_2(t), \ldots\ n_i(t)]$$

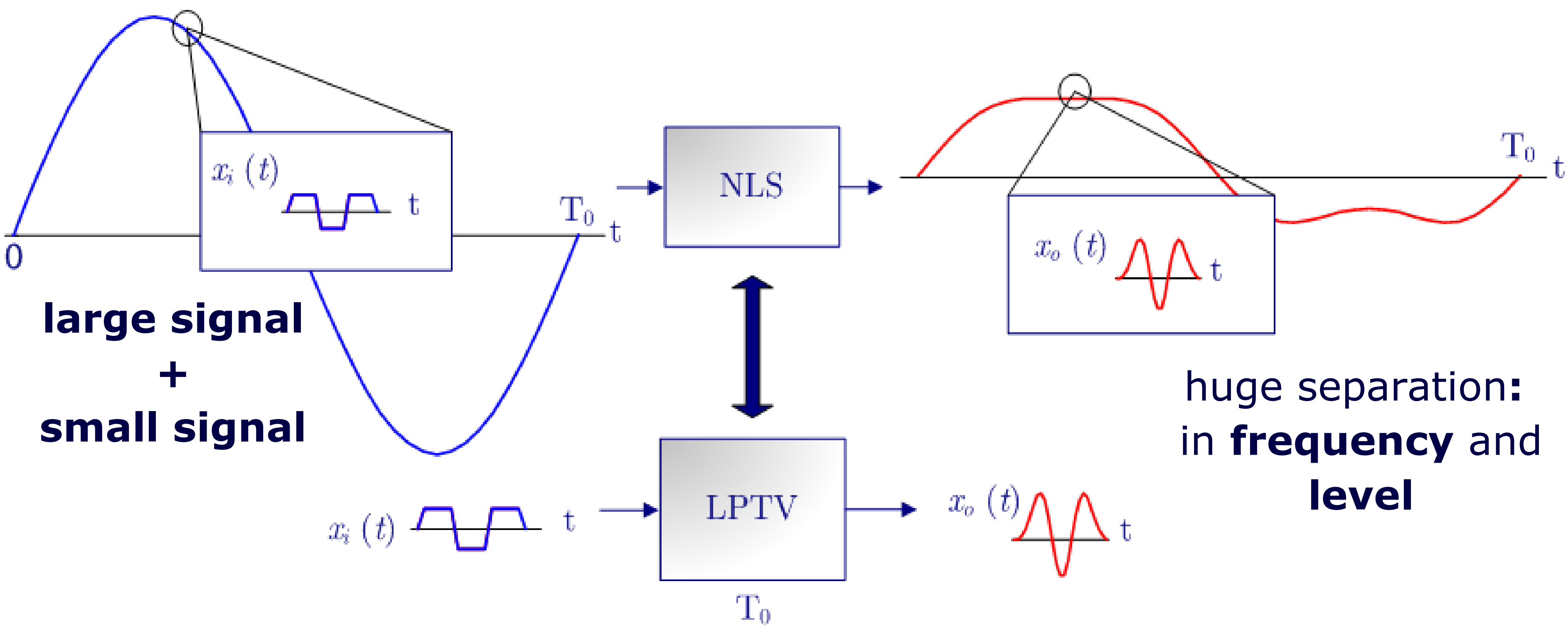
$$n\ (t) = n_d(t) + n_{ext}(t)$$

channel cyclic model: theoretical framework

-medium: is a **Non Linear System** (contains non-linear elements)

-**alternating current** determines its high frequency behavior

large signal
+
small signal



huge separation**:**
in **frequency** and
level

- **high pass filtering**: suppresses many non-linear terms (frequencies near 50Hz of large signal)
- **remaining non-linear terms**, depend exclusively on **large signal** value, which is **periodic in time**

NLS can be seen as an **LPTV system**

LPTV systems properties

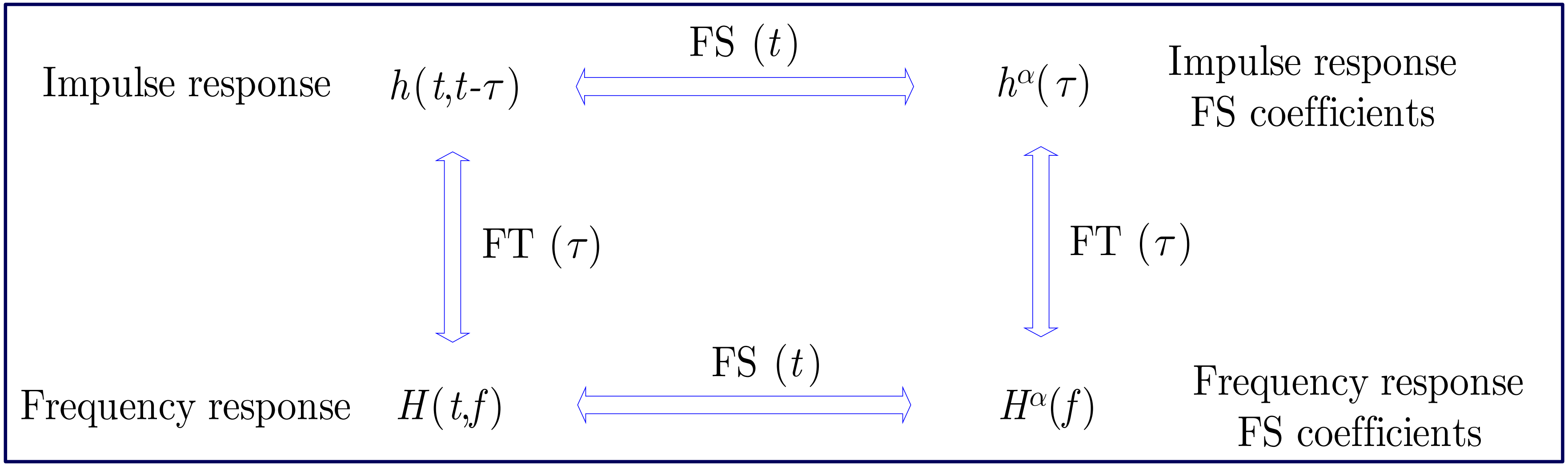
Impulse response: $$y(t)=\int_0^{\infty} h(t,t-\tau)x(t-\tau)d\tau$$

Frequency response: $$H(t,f)=\int_{-\infty}^{\infty} h(t,t-\tau)e^{-j2\pi f\tau}d\tau$$

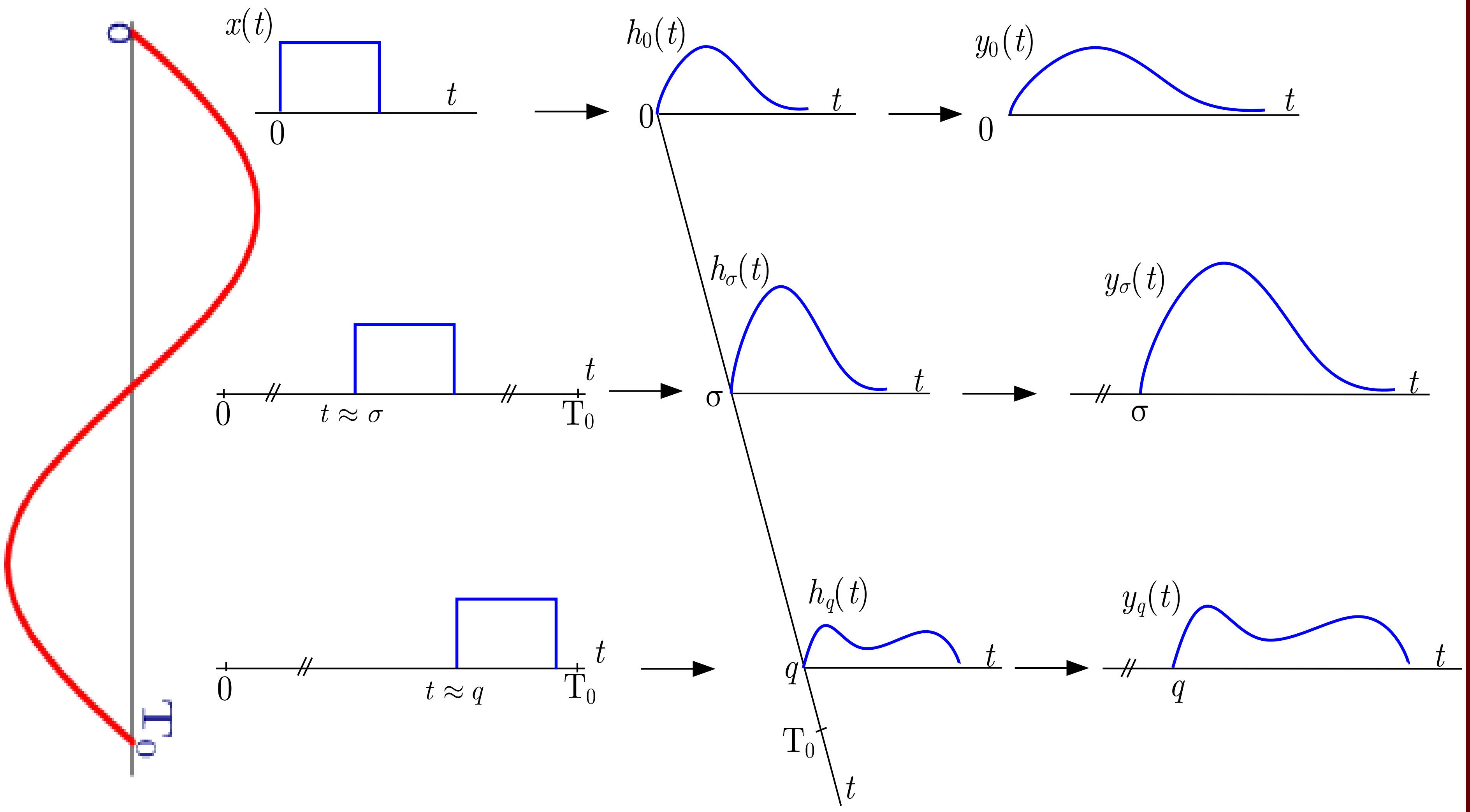
periodicity: $$H(t,f)=H(t-nT_0,f)\quad \forall n\in\mathbb{Z}$$

Frequency response Fourier Series coefficients: $$H^{\alpha}(f)=\frac{1}{T_0}\int_{T_0/2}^{T_0/2} H(t,f)e^{-j2\pi\alpha t/T_0}dt$$

relations



slow variation approximation:



LPTV system ≈ a collection of **LTI** systems synchronized with mains

channel cyclic model proposal: simplification

slow variation approximation restrictions:

- underspread, channel delay spread < channel coherence time (T_C)
- “short-time” input signal (in relation to T_C)

approximation for the **devices**:

a collection of states with **linear load** and **stationary** noise synchronized with mains.

result:

- LPTV **filtering** of **deterministic signals**

$$Y(f) = \sum_{\alpha=-\infty}^{+\infty} H^{\alpha}\left(f - \frac{\alpha}{T_0}\right) X\left(f - \frac{\alpha}{T_0}\right)$$

approx. $$Y_\sigma(f) \simeq H(t,f)\big|_{t=\sigma} \cdot X_\sigma(f)$$ [$X_\sigma(t)$: short-time signal applied at t≈σ]

- LPTV **filtering** of **random signals**

$$S_Y^{\alpha}(f) = \sum_{\beta=-\infty}^{+\infty} \sum_{\gamma=-\infty}^{+\infty} \left[H^{\beta}\left(f - \frac{\alpha+\beta}{T_0}\right)\right]^* H^{\gamma}\left(f - \frac{\gamma}{T_0}\right) S_X^{\alpha+\beta-\gamma}\left(f - \frac{\gamma}{T_0}\right)$$

approx. $$S_Y(t,f) \simeq \left|H(t,f)\right|^2 \cdot S_X(t,f)$$

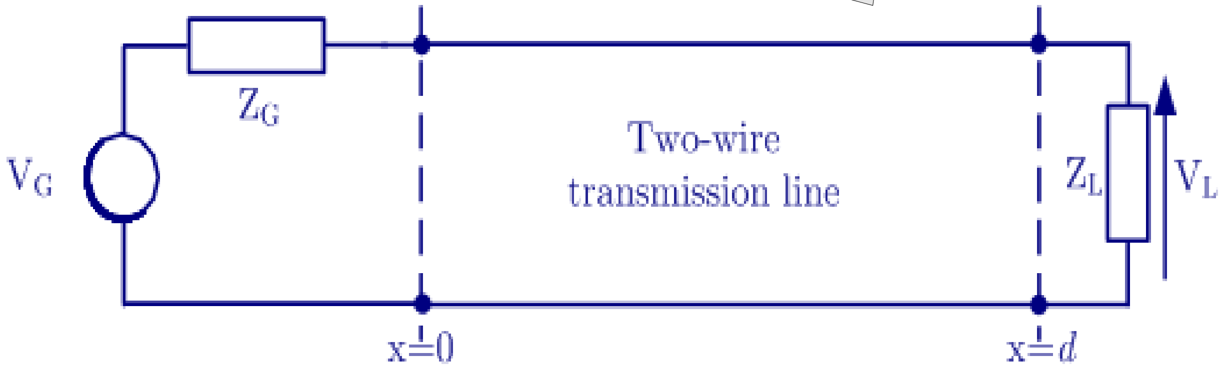
calculation of **models parameters**

-based on the **structural model**, both **behavioral models** share the same idea

grounding practices can be included by means of an additional stub

Channel response

power line = structure with several **transmission lines**



$$\begin{bmatrix} V_G \\ I_G \end{bmatrix} = \begin{bmatrix} 1 & Z_G \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_L \\ I_L \end{bmatrix}$$

$$\begin{bmatrix} V_G \\ I_G \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} V_L \\ I_L \end{bmatrix}$$

- assumption, sinusoidal steady state (matches **LTI model**)

LTI channel response

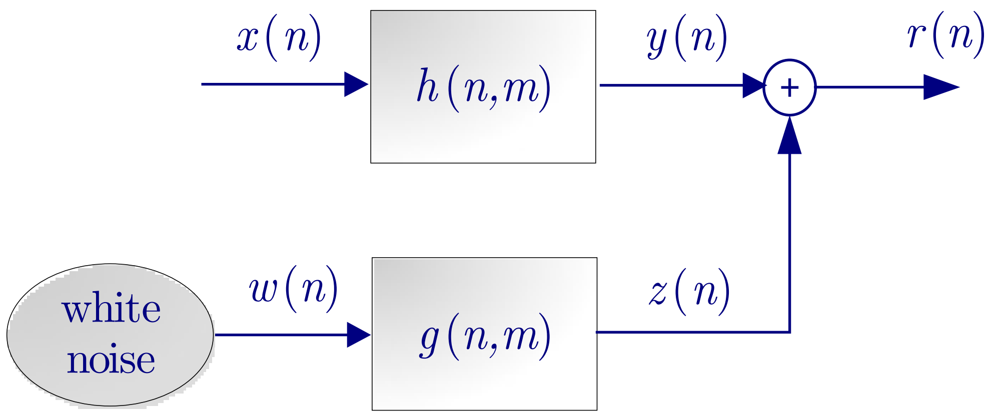
$$H(f) = \frac{V_L}{V_G} = \frac{1}{A' + B'/Z_L}$$

- <u>extrapolation</u> for each of the LTI states in slow variation **cyclic model**

LTI channel response for each of the L intervals of invariance

$$H_\ell(f) = H(t = \ell T_\ell, f); \;\; T_\ell = \frac{T_0}{L}$$

cyclic simulator



both filters LPTV

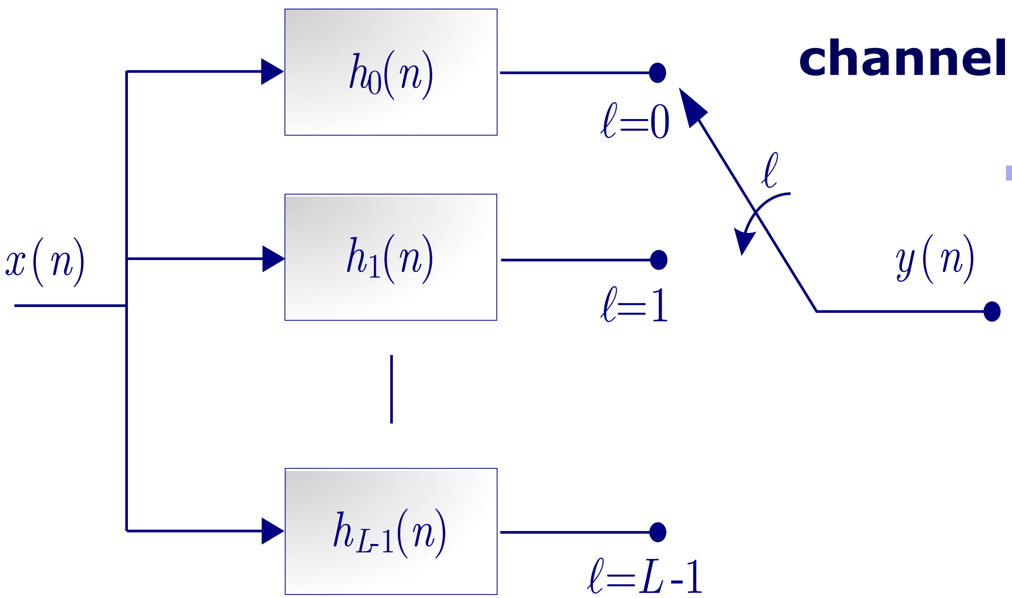
$$y(n) = \sum_i h(n, n-i)x(n-i)$$

response periodic,
with a period of $L \cdot M$ samples

(T_S = sampling period)

-approximation with intervals of invariance
represents a **decimation** (of factor M samples): $T_0 = L \cdot M \cdot T_S;\ T_\ell = M \cdot T_S;\ T_0 = L \cdot T_\ell$

- using a zero-order hold **interpolation**:



channel filter

$$y(n) = \sum_i h_{\left\lfloor \frac{n}{M} \right\rfloor}(i)x(n-i)$$

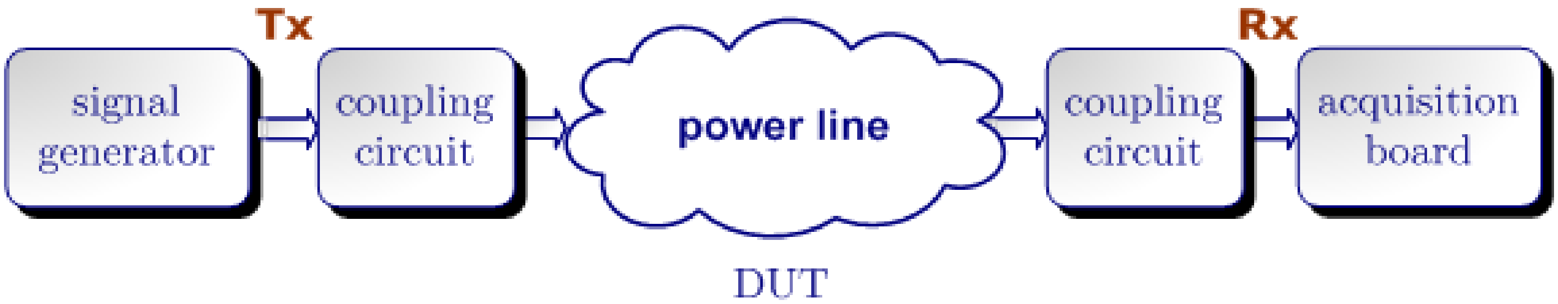
filters impulse responses:

$$h_\ell(n) \leftarrow \mathrm{IDFT}\left\{H_\ell(k)\right\}$$

$$h_\ell(n) = h(\ell M + n, \ell M);\quad \ell = 0,1,\ldots,L-1$$

measuring channel time variation

set-up to measure channel **frequency response**:



- measurement **procedure**:

1. sounding signal: N tones harmonically related between 0 y f_{max}

2. tones received with a **periodical variation** (due to channel filtering) and with noise

3. arrangement in time of the capture signal (compensate for mains jitter)

$$x_\ell(n) = x(2N\ell + n), \quad 0 \le n \le 2N-1, \quad 0 \le \ell \le L-1$$

$$T_\ell = 2NT_s \qquad L = \lfloor T_0 / T_\ell \rfloor$$

T_0 divided into L intervals of invariance

4. averaging synchronized with mains cycle

-reduces noise in the estimate to unveil periodical variations

5. estimation of **frequency response** in every interval of invariance

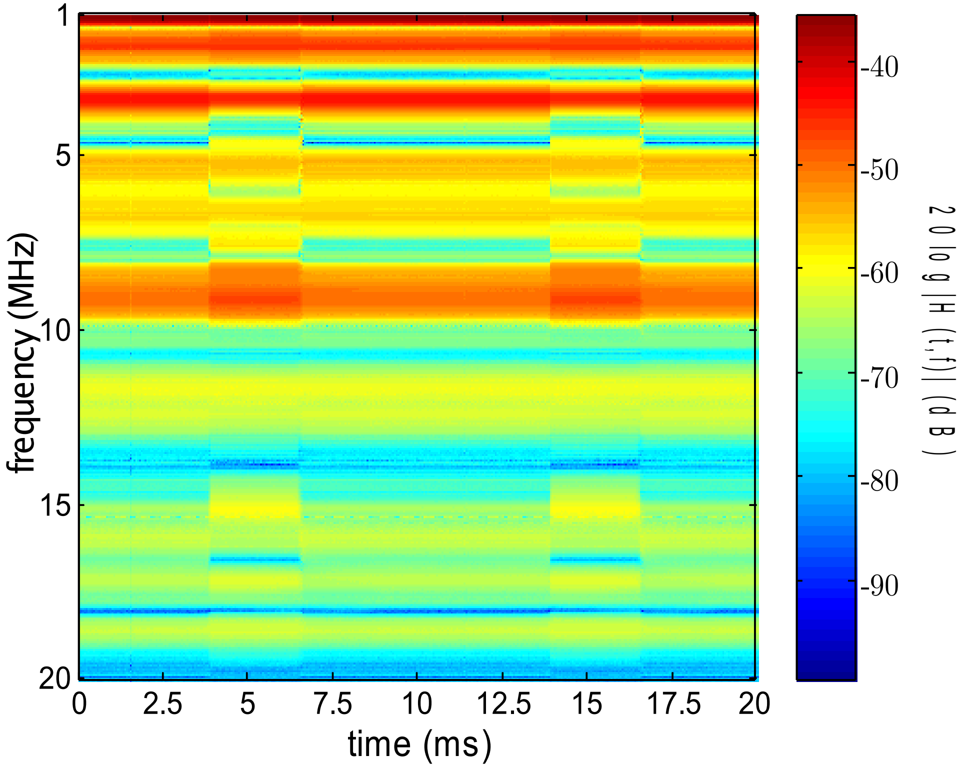
$$H_\ell(k) \Leftrightarrow H(t,f)\big|_{t=\ell\cdot T_\ell, f=k\cdot\Delta f}$$

measuring channel time variation

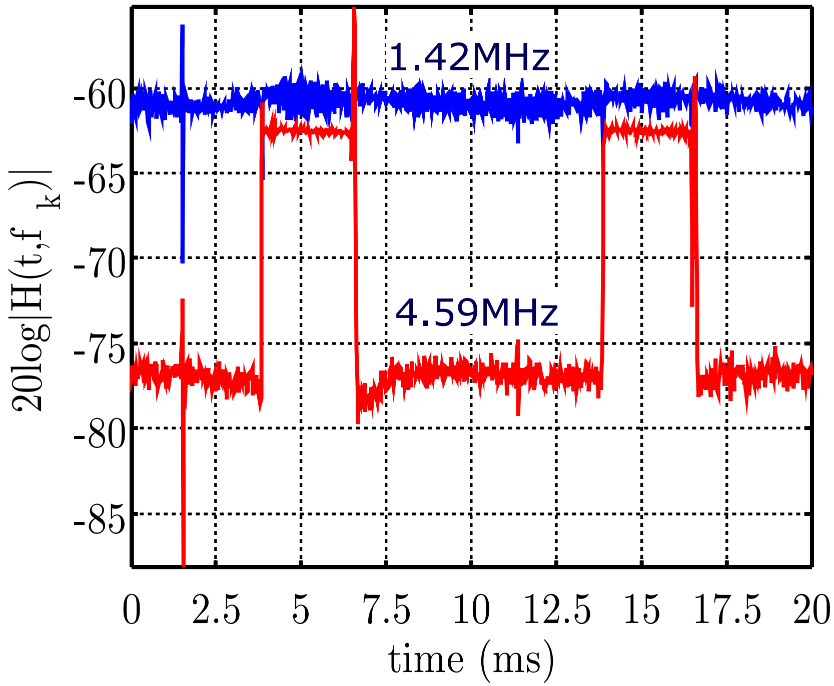
- **An example** of frequency response in a detached house

  (approx. 300m², 10 branch circuits)

distance ≈40m, tx-rx in different circuits



evolution of amplitude response along mains cycle



measuring channel time variation

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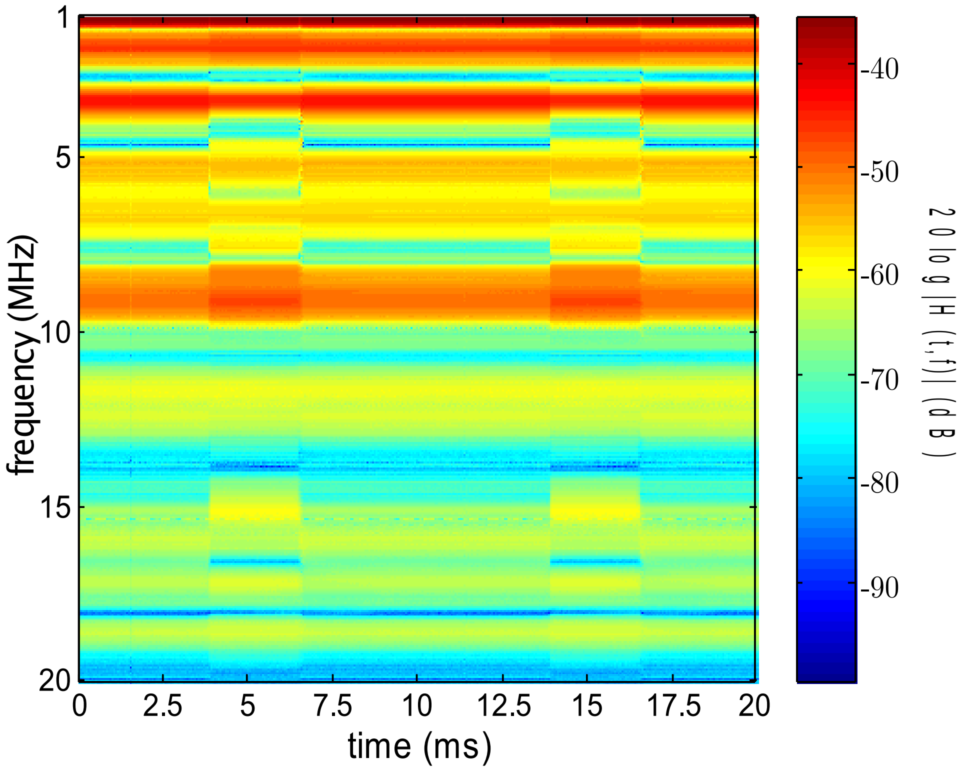

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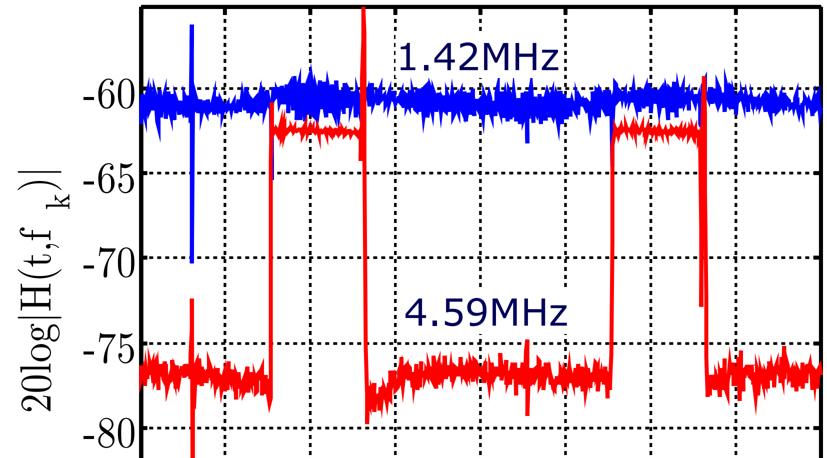
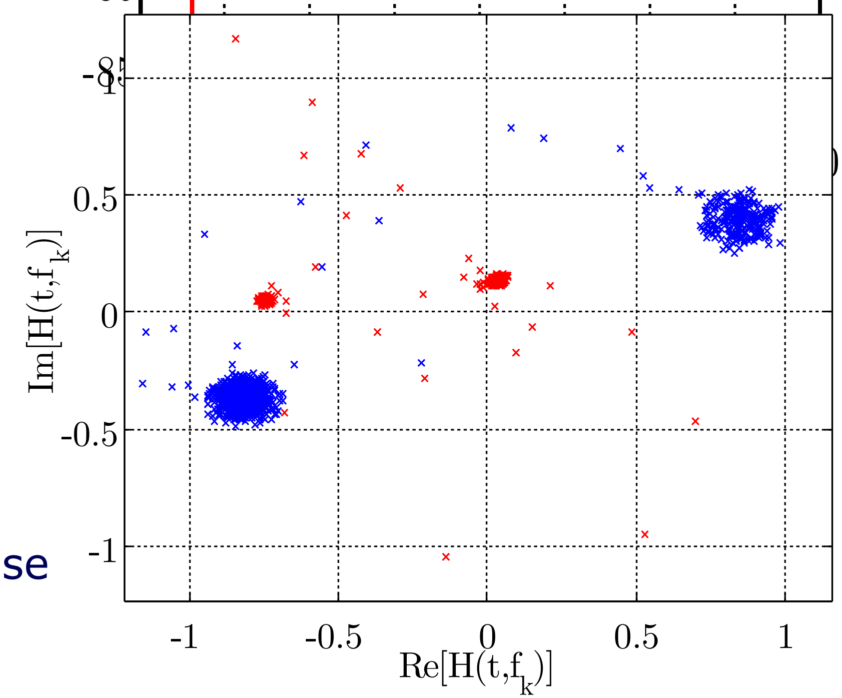


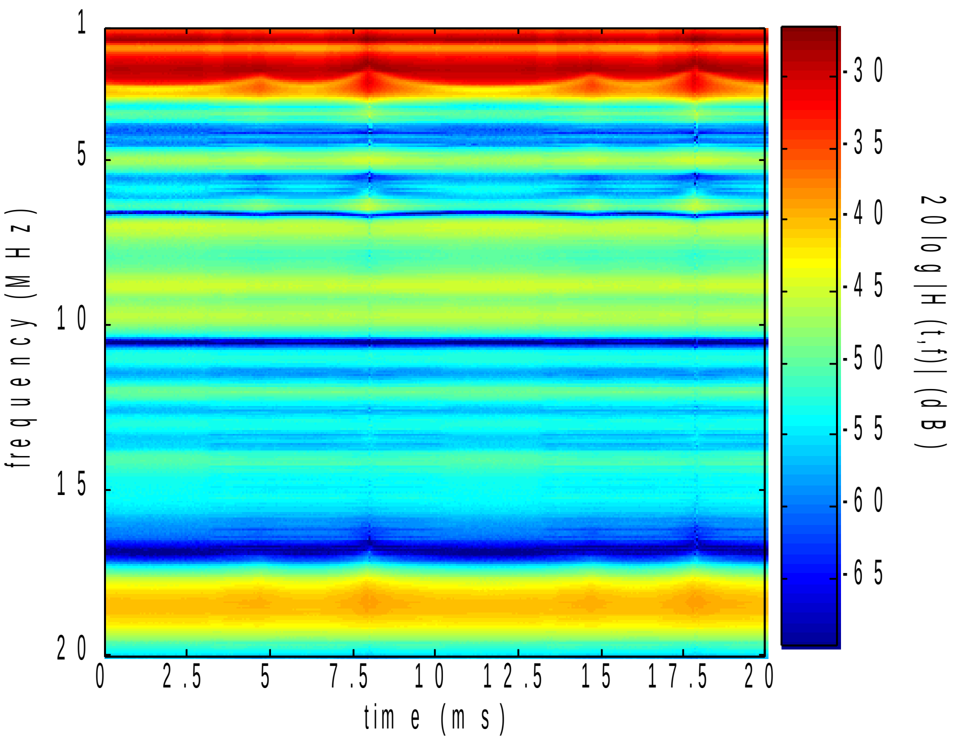


evolution of the response in the complex plane

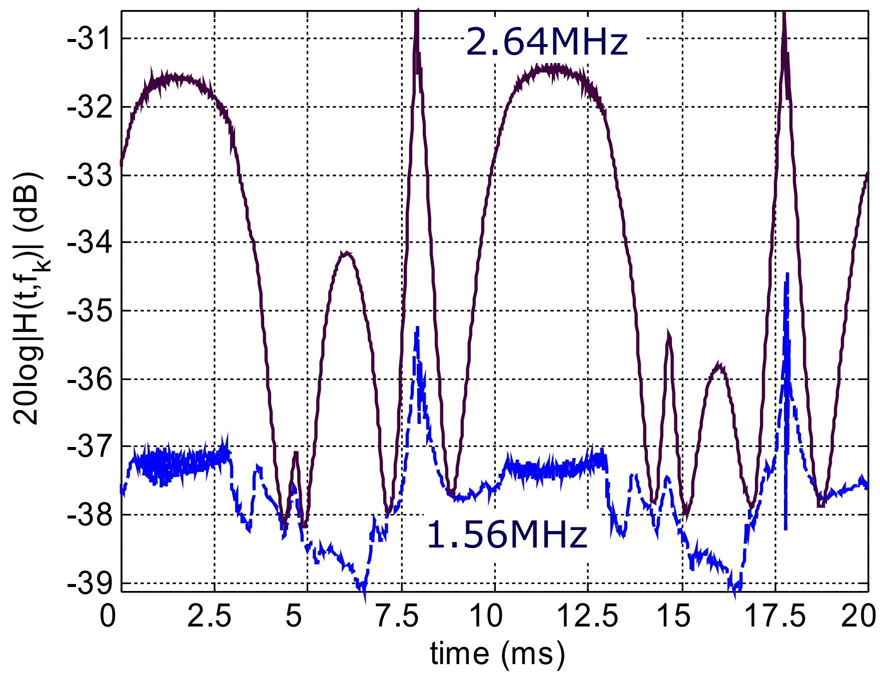
measuring channel time variation

- analysis of a channel response from an apartment
  (aprox. 80m², 4 branch circuits)

distance≈25m, tx-rx different branch circuits



evolution of amplitude response along mains cycle

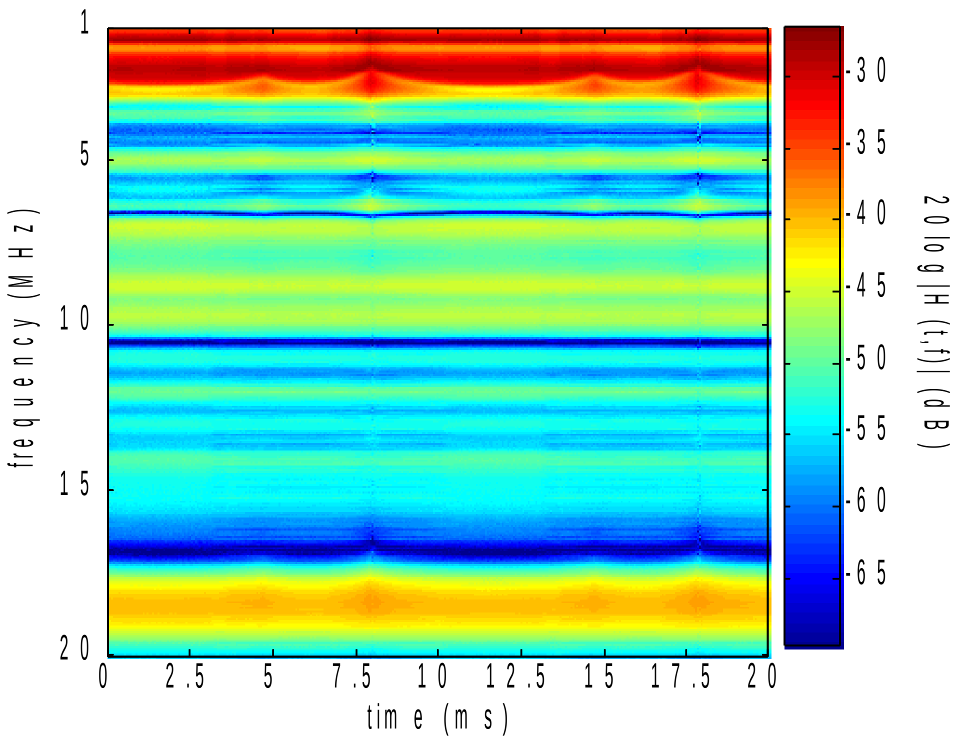


measuring channel time variation

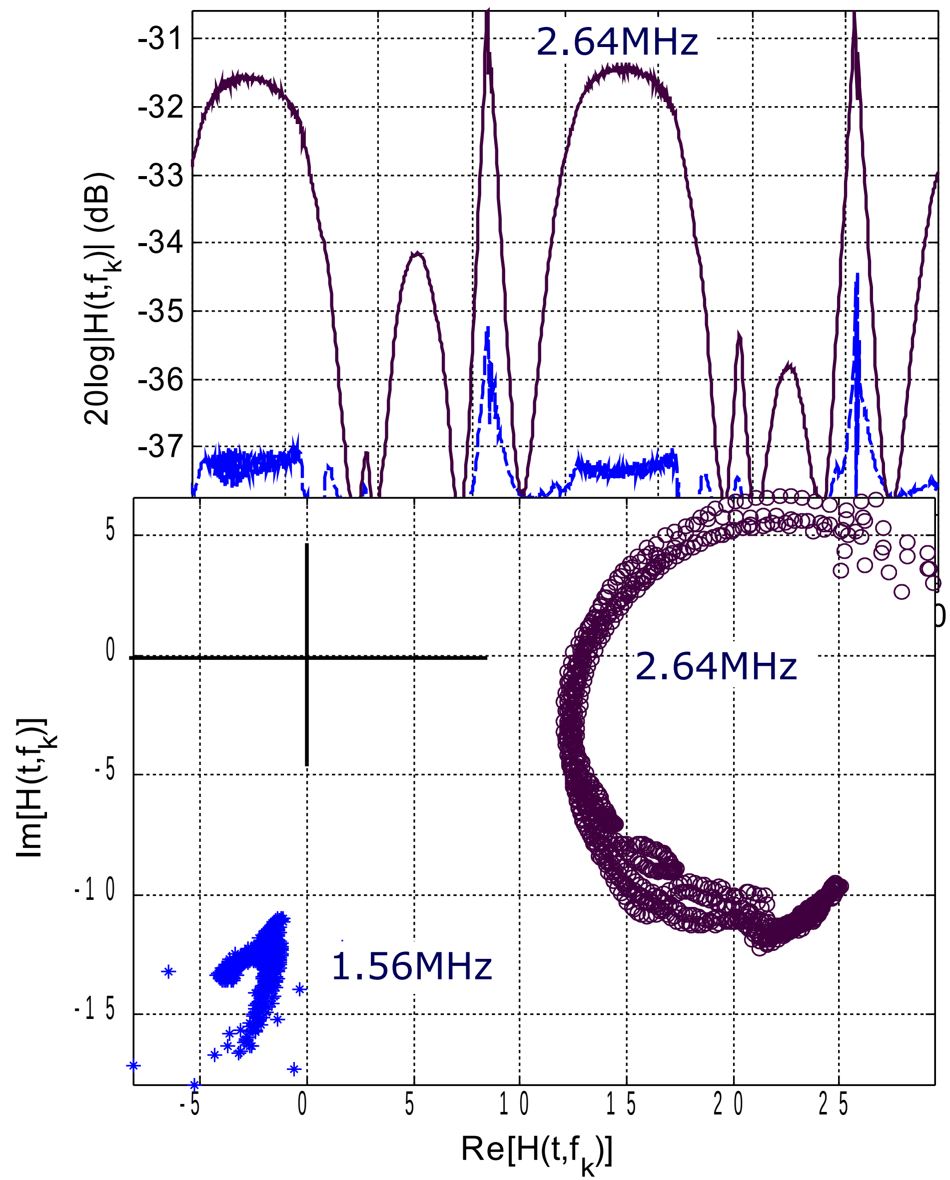
- analysis of a channel response from an apartment

  (aprox. 80m^2, 4 branch circuits)

distance≈25m, tx-rx different branch circuits



evolution of amplitude response along mains cycle



response evolution in the complex plane

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a reduced set of impedance functions

examples of generated channels

5 conclusions

some examples of **simple impedance functions**

- constant impedance

Z_1=50Ω; Z_2=5Ω (low impedance); Z_3=150Ω (≈Z_0 transmission line);

Z_4=1kΩ; Z_5=∞ (open circuit bridged tap)

- frequency dependent impedance

$$[\omega = 2\pi f]$$

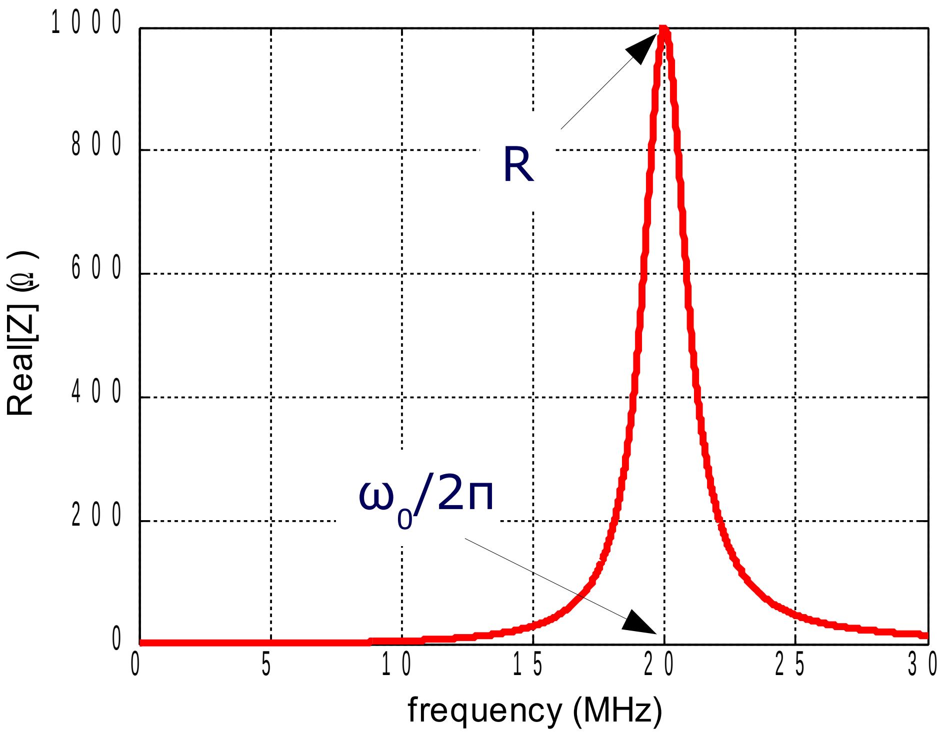
$$Z(j\omega) = \frac{R}{1 + jQ(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})}$$

parameters:

$$\omega_0 \in [2, 28] \cdot 2\pi \text{ Mrad/s}$$

$$R \in [200, 1800]\ \Omega$$

$$Q \in [5, 25]$$



→ uniformly distributed?

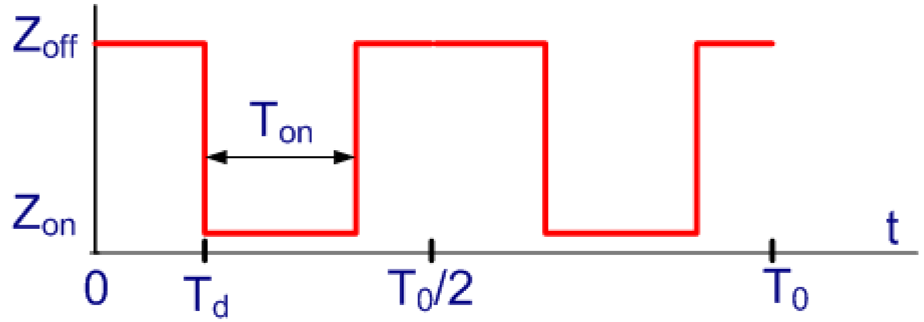
impedance functions

- variant impedance: $Z(t,f)$

just a "not-best case"

$$Z_{on} = Z(j\omega)$$

$$Z_{off} \approx \infty$$



parameters:

$$\mathrm{T_{on}} \in [2,8]\ \mathrm{ms}$$

$$\mathrm{T_d} \in [0, \frac{T_0}{2} - \mathrm{T_{on}}]\ \mathrm{ms}$$

$$T_0 = 20\ \mathrm{ms}$$

→ uniformly distributed?

- a loads data base may be generated from such impedance functions

[not really new idea, see e.g. Esmailian JCS'03]

- typical **scenarios** should be defined: small, medium, large

- **physical parameters**, give some estimated values:

  - number of branch circuits
  - length of sections
  - number of outlets per branch circuit

- transmission line parameters (R,L,G,C): **data** from **cables** manufacturers; e.g. PVC, wire section [1.5,2.5,4,6] mm^2, etc

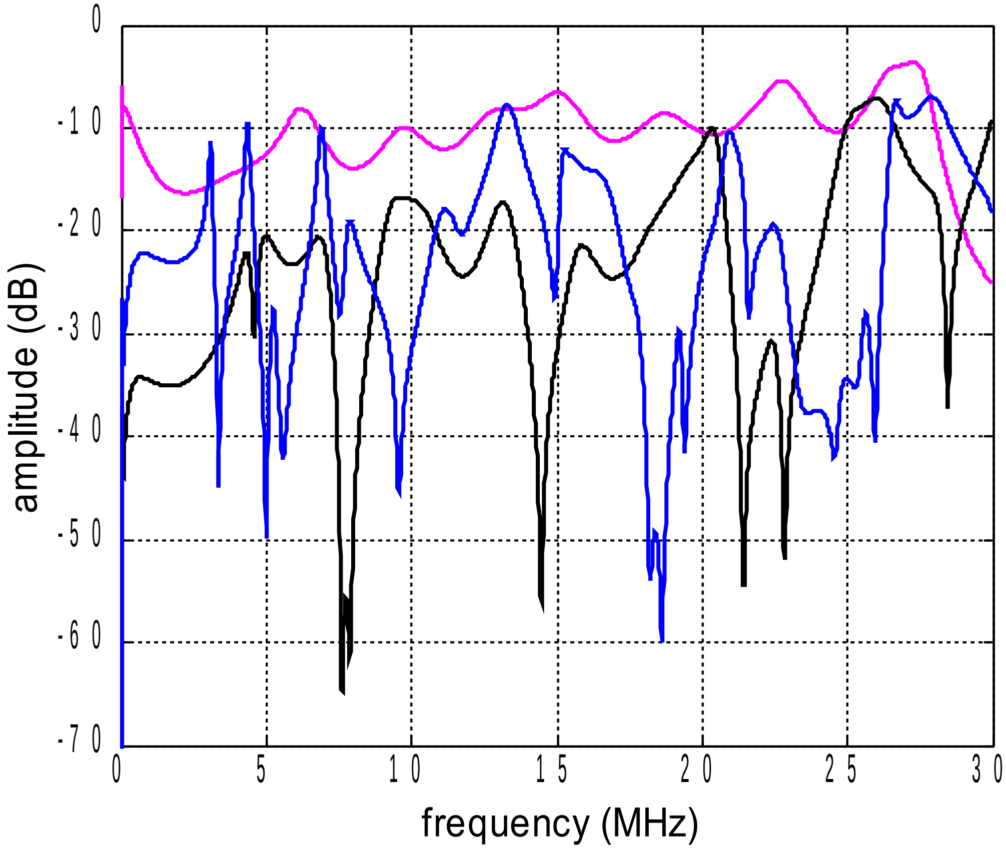
- some tentative values:

scenario type	area (sq. meters)	mean n.circuits	mean section length	mean n.outlets
small	60	4	5	5
medium	100	6	7	6
large	200	10	10	7

example of **generated channels**

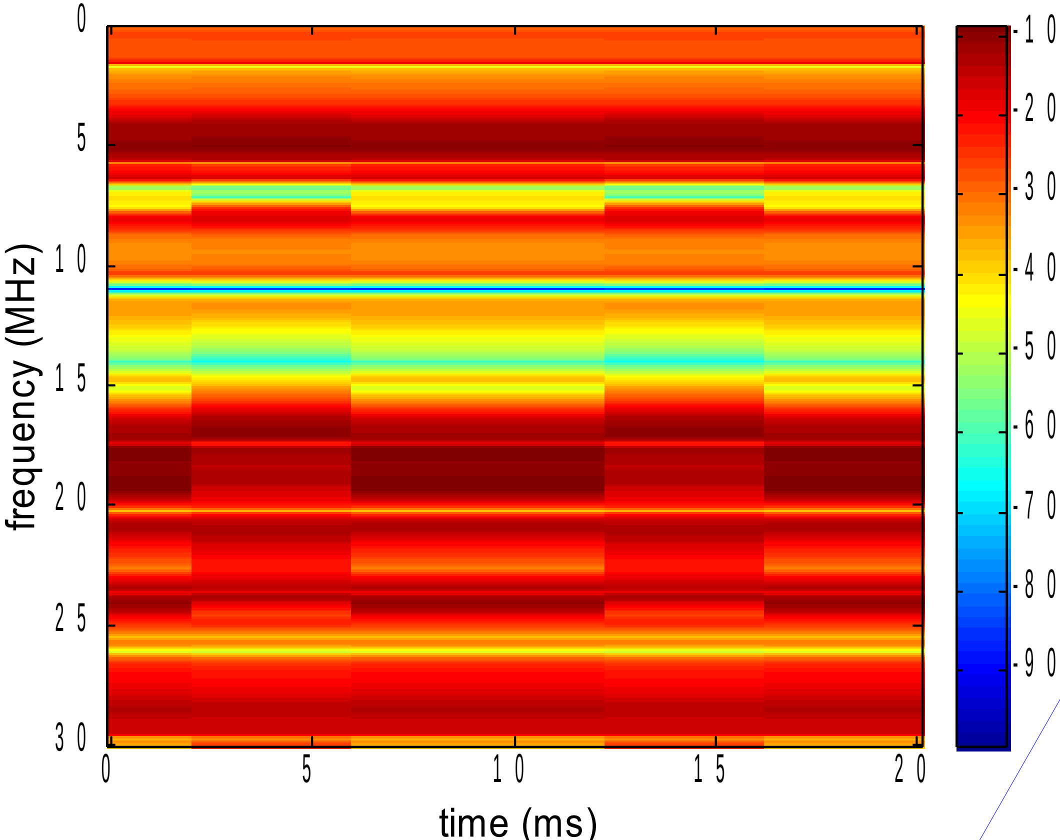
-some frequency response results:

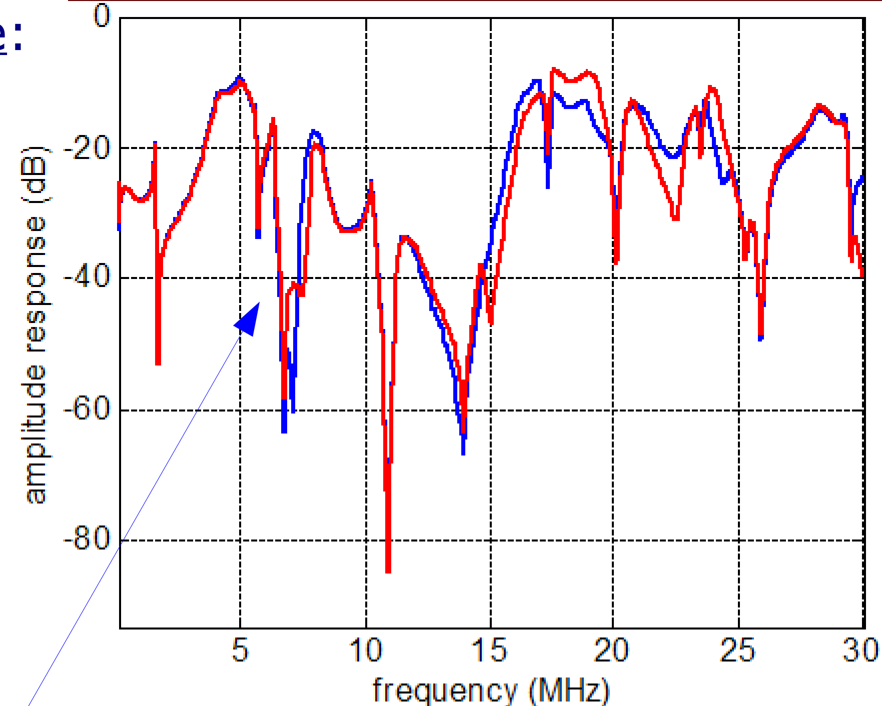
using only frequency variant impedances

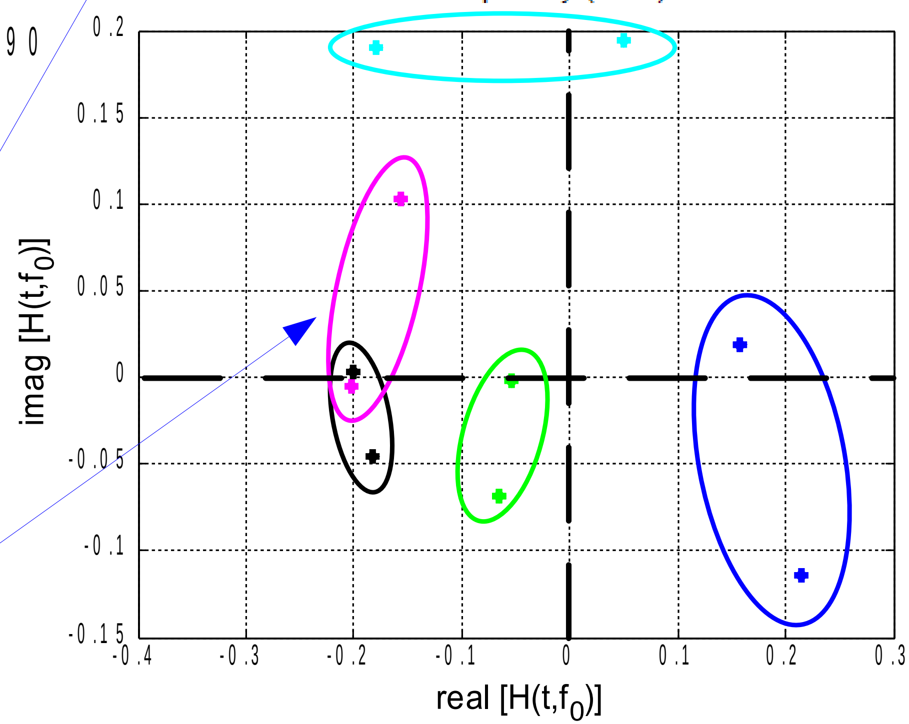


three different channels randomly generated (for a small scenario) example of **generated channels**

- and using also a <u>time variant impedance</u>:







two states of amplitude response shape vs frequency (varying during mains cycle)

the phase response varies in many different ways with two states

1 introduction

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5 conclusions

- **structural modeling** based on transmission lines
  - two-wire lines can be enough
  - electrical devices behavior makes the channel time-varying
- **cyclic channel model** for indoor PLC channels behavior
  - short-time periodical variations influence the performance of PLC transmission systems
  - channel parameters synchronized with mains voltage
  - measurement systems designed according to these periodical properties
- a **set** of **reference channel models** is required
  - helpful to test PLC transmission systems
  - can be created from simple impedance functions and wiring topologies