power line channels: frequency and time selective

part 1 - response of indoor PLC channels

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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

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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) ...

- **Transmission 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 (?)

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TCE: IEEE Trans. on Consumer Electronics  
TC: IEEE Trans. on Communications  
JCS: International Journal of Communication Systems  
CM: IEEE Communications Magazine  
JSAC: IEEE Journal on Select 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
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   network topology
   channel time variation
   examples of loads short-term variation

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network topology

indoor networks structure

- 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

in Europe 230V @ 50Hz
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

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**devices** with time varying behavior lead to a **time varying channel**
loads high-frequency characteristics

- **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

![Graph showing frequency vs. time and impedance](image)
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   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**
- at the **random scale**: a new channel appears every time an appliance is switched on/off

- traditionally **cyclic scale** has been disregarded
**generic behavioral model**

- **STRUCTURAL MODEL**
- **GENERIC BEHAVIORAL MODEL**

**simplest approximation**

- **LTI CHANNEL MODEL**
- **CYCLIC CHANNEL MODEL**

**non-linear loads assumption**

\[ x(t) \rightarrow T_x[x(t)] \rightarrow y(t) \]

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

\[ n_d(t) = T_n[n_1(t), n_2(t), \ldots, n_i(t)] \]

**LTI system + stationary and impulsive noise**

**LPTV system + cyclostationary and impulsive noise**
channel cyclic model: theoretical framework

- medium: is a **Non Linear System** (contains non-linear elements)
- **alternating current** determines its high frequency behavior

- 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**
channel cyclic model: theoretical framework

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

- **Impulse response:**
  \[ h(t, t - \tau) \leftrightarrow \text{FS} (t) \leftrightarrow h^\alpha(\tau) \leftrightarrow \text{Impulse response} \]

- **Frequency response:**
  \[ H(t, f) \leftrightarrow \text{FS} (t) \leftrightarrow H^\alpha(f) \leftrightarrow \text{Frequency response} \]
channel cyclic model proposal: simplification

slow variation approximation:

\[
x(t) \quad t \\
0 \quad T_0 \\
0 \quad t \approx \sigma \\
0 \quad t \\
0 \quad t \approx q \\
0 \quad t \quad T_0 \\
0 \quad T_0 \\
0 \quad t \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
0 \quad T_0 \\
\]

LPTV system \( \approx \) 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. \[ Y_\sigma(f) \simeq H(t,f)_{t=\sigma} \cdot X_\sigma(f) \]

[ $X_\sigma(t)$: short-time signal applied at $t \approx \sigma$ ]

- 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. \[ S_Y(t,f) \simeq |H(t,f)|^2 \cdot S_X(t,f) \]
calculation of models parameters

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

**Channel response**

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

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

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

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

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

- extrapolation for each of the LTI states in slow variation **cyclic model**

\[
H_\ell(f) = H(t = \ell T_\ell, f); \quad T_\ell = \frac{T_0}{L}
\]
behavioral simulator

3 channel model

cyclic simulator

\[
x(n) \rightarrow h(n,m) \rightarrow y(n) \rightarrow r(n)
\]

white noise

\[
w(n) \rightarrow g(n,m) \rightarrow z(n)
\]

-approximation with intervals of invariance
represents a **decimation** (of factor \( M \) samples):

\[
T_0 = L \cdot M \cdot T_s; \quad T_{\ell} = M \cdot T_s; \quad T_0 = L \cdot T_{\ell}
\]

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

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 )

channel filter

\[
\begin{align*}
h_0(n) \\
h_1(n) \\
h_{L-1}(n)
\end{align*}
\]

\[
\ell = 0, 1, \ldots, L-1
\]

\[
y(n) = \sum_{i} h_{n/M}(i)x(n-i)
\]

filters impulse responses:

\[
h_{\ell}(n) \leftarrow \text{IDFT} \{ H_{\ell}(k) \}
\]

\[
h_{\ell}(n) = h(\ell M + n, \ell M); \quad \ell = 0,1,\ldots,L-1
\]

\[
\]
measuring channel time variation

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

1. **sounding signal**: N tones harmonically related between 0 and \( f_{\text{max}} \)
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)
   \[ x_{\ell}(n) = x(2N\ell + n), \quad 0 \leq n \leq 2N - 1, \quad 0 \leq \ell \leq L - 1 \]
   \[ T_{\ell} = 2NT_s \quad L = \left\lfloor \frac{T_0}{T_{\ell}} \right\rfloor \]
   \( T_0 \) 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
   \[ H_{\ell}(k) \Leftrightarrow H(t,f) \big|_{t=\ell \cdot T_s, f=k \cdot \Delta f} \]
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

3 channel model
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

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

2.64MHz

1.56MHz
measuring channel time variation

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

distance ≈ 25m, tx-rx different branch circuits
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   a reduced set of impedance functions
   examples of generated channels
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some examples of simple impedance functions

- **constant impedance**

\[ Z_1 = 50 \Omega; \quad Z_2 = 5 \Omega \text{ (low impedance);} \quad Z_3 = 150 \Omega \text{ (} \approx Z_0 \text{ transmission line);} \]

\[ Z_4 = 1 \text{k}\Omega; \quad Z_5 = \infty \text{ (open circuit bridged tap)} \]

- **frequency dependent impedance**

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

\[ Z(j\omega) = \frac{R}{1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)} \]

**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:

- \( T_{on} \in [2, 8] \) ms
- \( T_d \in [0, \frac{T_0}{2} - T_{on}] \) ms
- \( T_0 = 20 \) ms

- a **loads database** may be generated from such impedance functions
example of *generated channels*

[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 \([1.5,2.5,4,6] \text{ mm}^2\), etc

- some **tentative values**:

<table>
<thead>
<tr>
<th>scenario type</th>
<th>area (sq. meters)</th>
<th>mean n.circuits</th>
<th>mean section length</th>
<th>mean n.outlets</th>
</tr>
</thead>
<tbody>
<tr>
<td>small</td>
<td>60</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>medium</td>
<td>100</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>large</td>
<td>200</td>
<td>10</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>
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 time variant impedance:

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

the phase response varies in many different ways with two states
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- **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