LPTV-Aware Bit Loading and Channel Estimation in Broadband PLC for Smart Grid

Department of Electrical Engineering and Computer Science

Muharrem Ali Tunc
tunc@ku.edu

Outline of the Dissertation

Chapter 1	**Introduction and Motivation**
Chapter 2	**System Model**
Chapter 3	**Bit and Power Allocation**
Chapter 4	**Channel Estimation**
Chapter 5	**Conclusion**

External Contributions

Chapter 1 Introduction and Motivation

Chapter 2 System Model

Chapter 3 **Bit and Power Allocation**

Chapter 4 Channel Estimation

Chapter 5 Conclusion

Tunc M. A., Perrins E., Lampe L., "The Effect of LPTV Channel Adaptation on the Performance of Broadband PLC for Smart Grid," in *IEEE SmartGridComm*, October 2011.

Tunc M. A., Perrins E., Lampe L., "Reduced Complexity LPTV-Aware Bit Loading for Channel Adaptation in Broadband PLC," in *IEEE ISPLC, International Symposium on Power Line Communications and its Applications*, March 2012.

Tunc M. A., Perrins E., Lampe L., "Optimal LPTV-Aware Bit Loading in Broadband PLC," accepted for publication at *IEEE Transactions on Communications*, December 2013.

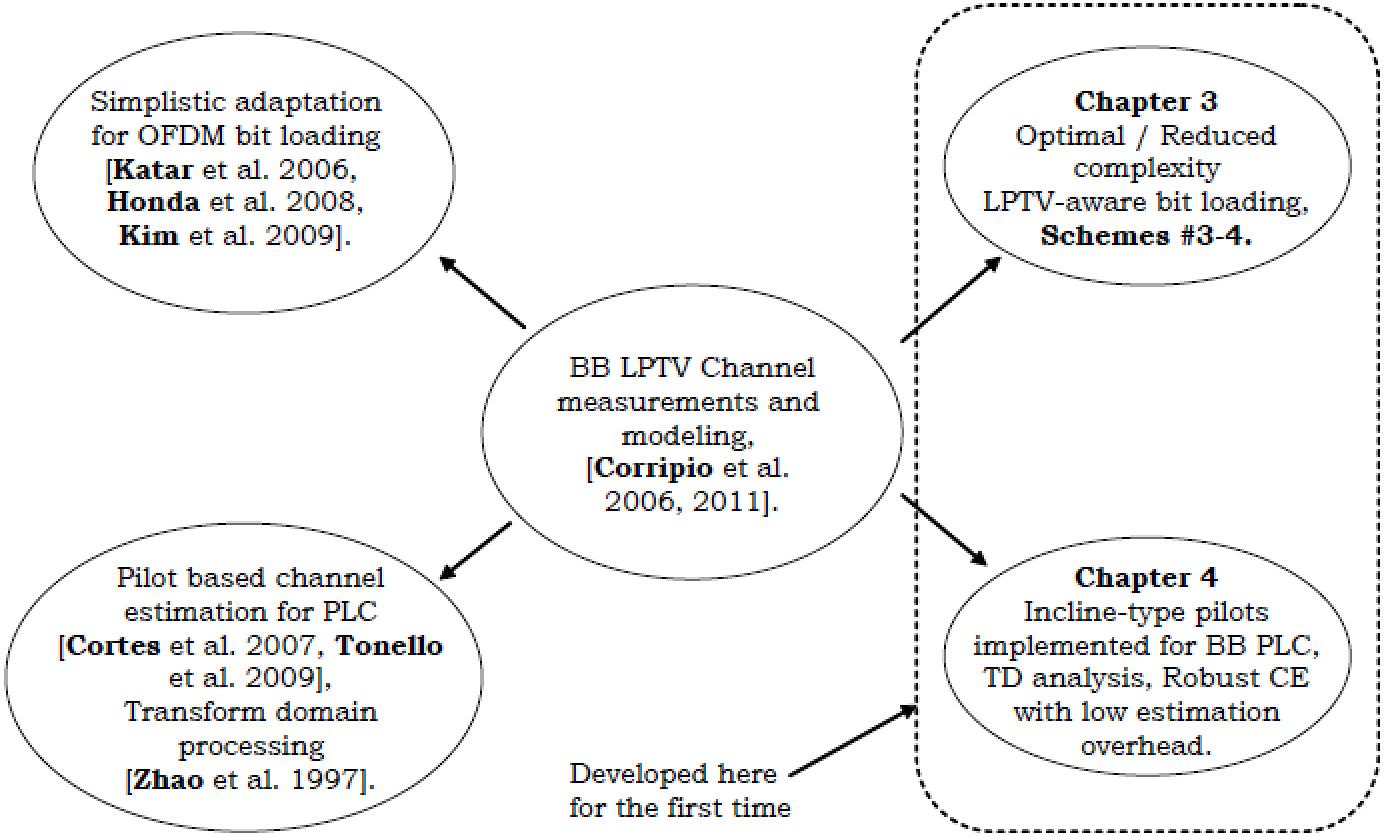
External Contributions

Chapter 1	Introduction and Motivation
Chapter 2	System Model
Chapter 3	Bit and Power Allocation
Chapter 4	**Channel Estimation**
Chapter 5	Conclusion

Tunc M. A., Perrins E., “Pilot Based Channel Estimation and Transform Domain Analysis in Broadband PLC for Smart Grid,” *IEEE SmartGridComm*, October 2013

Tunc M. A., Perrins E., “Robust Channel Estimation via Transform Domain Analysis in Broadband PLC,” in review at *IEEE Transactions on Communications*, February 2014.

External Contributions



Simplistic adaptation for OFDM bit loading [**Katar** et al. 2006, **Honda** et al. 2008, **Kim** et al. 2009].

BB LPTV Channel measurements and modeling, [**Corripio** et al. 2006, 2011].

Chapter 3
Optimal / Reduced complexity LPTV-aware bit loading, **Schemes #3-4.**

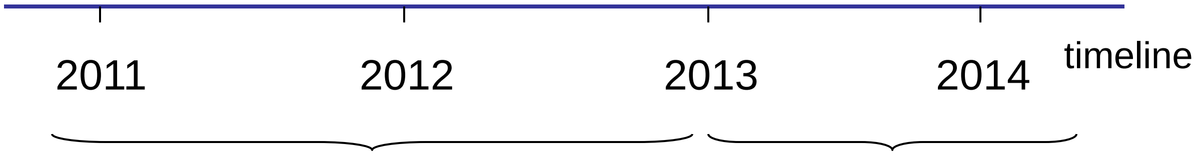
Pilot based channel estimation for PLC [**Cortes** et al. 2007, **Tonello** et al. 2009], Transform domain processing [**Zhao** et al. 1997].

Chapter 4
Incline-type pilots implemented for BB PLC, TD analysis, Robust CE with low estimation overhead.

Developed here for the first time

Fig.1 Development of optimal and reduced complexity LPTV-aware bit loading schemes.

Research Timeline



2011 2012 2013 2014 timeline

- First major part
- Initial research until comprehensive exam
- Bit and power allocation for LPTV channels
- Optimal and reduced complexity schemes

- Second major part
- Channel estimation (CE) for LPTV channels
- Pilot geometry
- Transform domain (TD) analysis approach
- Robust CE with low overhead

Outline of this Presentation

- Introduction to Power line communication (PLC)
  - Broadband (BB) PLC channel
    - Linear Periodically Time Varying (LPTV) channel and impulsive noise
- System Model
  - LPTV Channel modeling and OFDM
- Bit and power allocation
  - Optimal and reduced complexity schemes
- Channel estimation (CE)
  - Pilot-based CE: pilot geometry
  - Impulsive noise mitigation – transform domain (TD) analysis
  - Robust CE based on TD analysis with low overhead
- Conclusion

Outline of this Presentation

- Introduction to Power line communication (PLC)
  - Broadband (BB) PLC channel
    - Linear Periodically Time Varying (LPTV) channel and impulsive noise
- System Model
  - LPTV Channel modeling and OFDM
- Bit and power allocation ⟵ brief review
  - Optimal and reduced complexity schemes
- Channel estimation (CE) ⟵ new!
  - Pilot-based CE: pilot geometry
  - Impulsive noise mitigation – transform domain (TD) analysis
  - Robust CE based on TD analysis with low overhead
- Conclusion

Brief History of PLC

- Back to early 20th century
  - Switching in substations, metering and basic control
- Gained momentum after 1980s
  - Especially after 1990s
- Power lines
  - High voltage, > 100 kV
  - Medium voltage, 1 – 100 kV
  - Low voltage, < 1 kV
    - Most research
    - Easy access to network in most buildings
    - Interest from utility companies: load management, automatic metering
    - Disaster recovery

Power Line Communication (PLC)

- A topic of continued interest
  - Allows dual use of existing power line infrastructure
  - Economic, since no additional cost for cable installation is required

Power Line Communication (PLC)

- A topic of continued interest
  - Allows dual use of existing power line infrastructure
  - Economic, since no additional cost for cable installation is required
- PLC applications
  - Broadband (BB) distribution over power lines (BPL)
    - Internet access through power lines
  - Automatic metering infrastructure (AMI)
  - Smart Grid (SG) infrastructure

Power Line Communication (PLC)

- A topic of continued interest
  - Allows dual use of existing power line infrastructure
  - Economic, since no additional cost for cable installation is required
- PLC applications
  - Broadband (BB) distribution over power lines (BPL)
    - Internet access through power lines
  - Automatic metering infrastructure (AMI)
  - Smart Grid (SG) infrastructure
- PLC technology
  - Ultra narrow band (UNB): 0.3 – 3 kHz. frequency band
  - Narrowband (NB): 3 – 500 kHz. frequency band
  - Broadband (BB): 1.8 – 250 MHz. frequency band

BB PLC

- Applications in the in-home (IH) domain of SG
  - Collection and distribution of data on energy consumption
  - Demand response and management programs
  - Dynamic pricing and flexible power control of appliances
  - Communication
    - Plug-in Electric Vehicles (PEV) and their charging stations

Fig.2 SG home [4]

BB PLC

- Design criteria for devices targeting IH domain:
  - Low power consumption
  - Reduced complexity, large quantities to be deployed
- BB PLC standards
  - IEEE 1901
  - ITU-T G.hn
  - HomePlug Green PHY (HPGP)

Fig.2 SG home [4]

BB PLC Channel Characteristics

- Linear periodically time varying (LPTV) channel
  - Due to time-varying impedances of the electrical devices

Broadband PLC Channel Characteristics

- Linear periodically time varying (LPTV) channel
  - Due to time-varying impedances of the electrical devices
  - Commuted channel
    - Due to devices with two separate impedances
      - Ex: low power lamps and light dimmers
    - Alternates sharply between high and low values

Broadband PLC Channel Characteristics

- Linear periodically time varying (LPTV) channel
  - Due to time-varying impedances of the electrical devices
  - Commuted channel
    - Due to devices with two separate impedances
      - Ex: low power lamps and light dimmers
    - Alternates sharply between high and low values
  - Harmonic channel
    - Due to devices with smooth variation in impedances
      - Ex: monitors and microwave ovens
    - Results in a combination of several transfer functions
      - With progressive variation

Broadband PLC Channel Characteristics

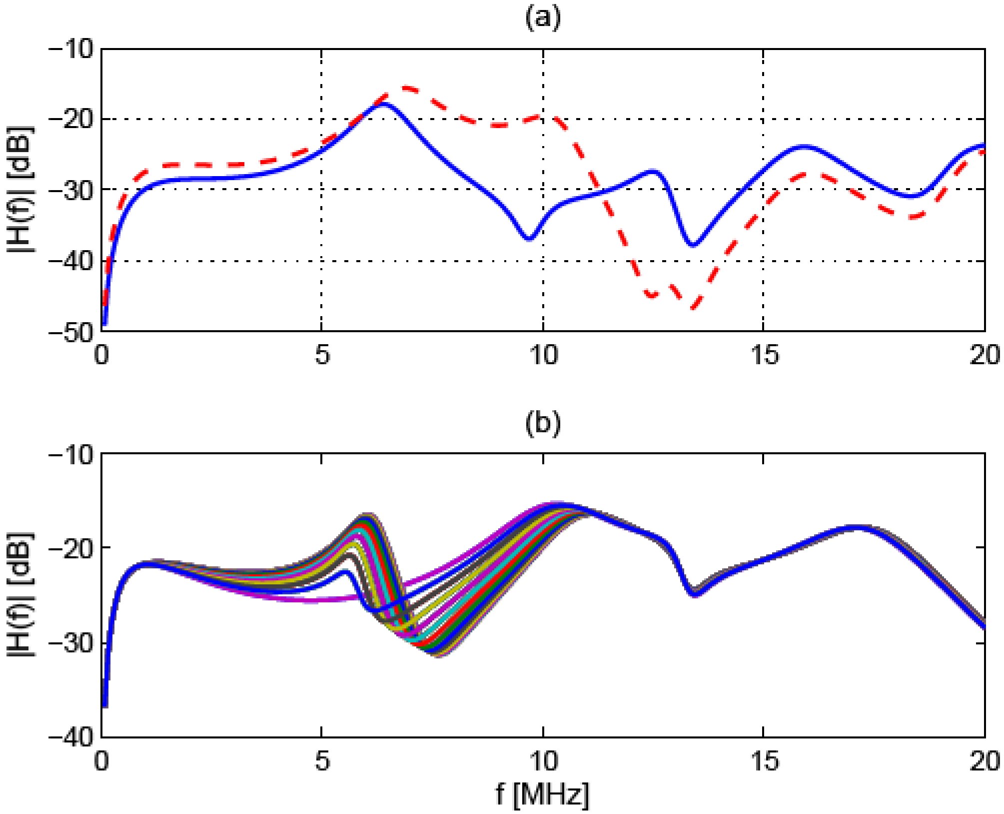


Fig. 3. (a) Commuted and (b) harmonic channels

- Each transfer function is a realization of the channel for a small portion of the AC mains cycle

- The transfer function pattern repeats itself for the following AC mains cycles for a certain period of time

BB PLC Channel Characteristics

- Linear periodically time varying (LPTV) channel
  - Due to time-varying impedances of the electrical devices
  - Commuted channel
    - Due to devices with two separate impedances
      - Ex: low power lamps and light dimmers
    - Alternates sharply between high and low values
  - Harmonic channel
    - Due to devices with smooth variation in impedances
      - Ex: monitors and microwave ovens
    - Results in a combination of several transfer functions
      - With progressive variation
- Impulsive noise
  - Due to switching events in the power line network
  - Much stronger than background noise, with short duration

Problem Statement

- Conventional bit loading algorithms
  - Simplistic adaptation
  - Relative variation over time
  - Not optimal
  - LPTV-aware bit loading

Problem Statement

- Conventional bit loading algorithms
  - Simplistic adaptation
  - Relative variation over time
  - Not optimal
  - LPTV-aware bit loading
- Conventional CE schemes
  - Lots of channels to estimate!
  - Pilot-based
    - Estimation overhead
    - Interpolation error
  - Decision-directed
    - Abrupt changes in channel and noise
    - Channel tracking
  - LPTV-aware, robust, and low overhead CE

LPTV Channel Model

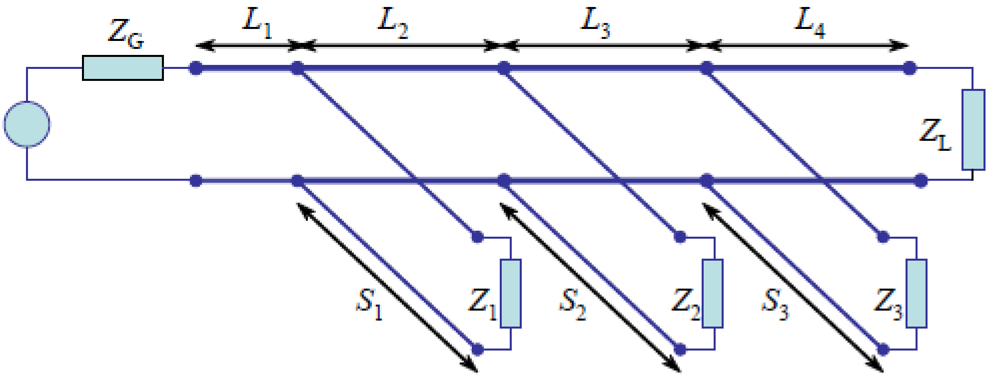


Fig. 4 Network topology used for the channel model [1, Fig. 1]

- Channel model in [1] is used
  - Generates realistic channel realizations
  - Based on a simplified topology
  - Z_G and Z_L: transmitter and receiver impedances
  - $Z_1 \ldots Z_3$: loads connected to the power line
  - $L_1 \ldots L_4$, and $S_1 \ldots S_3$: length parameters for different topologies

LPTV Channel Model

- AC mains cycle is divided into *M microslots* in time
  - Microslots are used for adaptation to the channel
  - Each microslot has a distinct transfer function $H_j(f)$
  - $j \in \{0,1,\ldots,M-1\}$, where M = 50
- Orthogonal Frequency Division Multiplexing (OFDM)
  - In each microslot, spectrum is divided into *N* subchannels
  - We choose *N* = 256 subchannels
  - $H_{j,i}(f)$ for jth microslot, ith subchannel, where $i \in \{0,1,\ldots,N-1\}$

Channel Parameters

- Excursion parameter:
  - Strength of the LPTV behavior
  - For *i*-th subchannel of *j*-th microslot

$$\gamma_{j,i} = \frac{|H_{j,i}|}{|H_{\text{low},i}|} \qquad H_{\text{low},i} = H_{j_{\text{low}},i} : j_{\text{low}} = \underset{0 \le j \le M-1}{\arg\min} |H_{j,i}|$$

  - $H_{\text{low},i}$ is the lowest of all transfer functions for subchannel *i*
  - $[\gamma]_{\text{avg}}$: average of $\gamma_{j,i}$ values – in dB – over all subchannels and microslots
- Average attenuation

$$[H_{\text{avg}}] = 10\log_{10}\left(\frac{1}{MN}\sum_{j=0}^{M-1}\sum_{i=0}^{N-1}|H_{j,i}|^2\right)$$

OFDM System

- Available spectrum is divided into many subchannels
  - Channel response is assumed to be flat in each subchannel
  - One tap simple equalizer at each subchannel
  - Deals with highly frequency selective channels

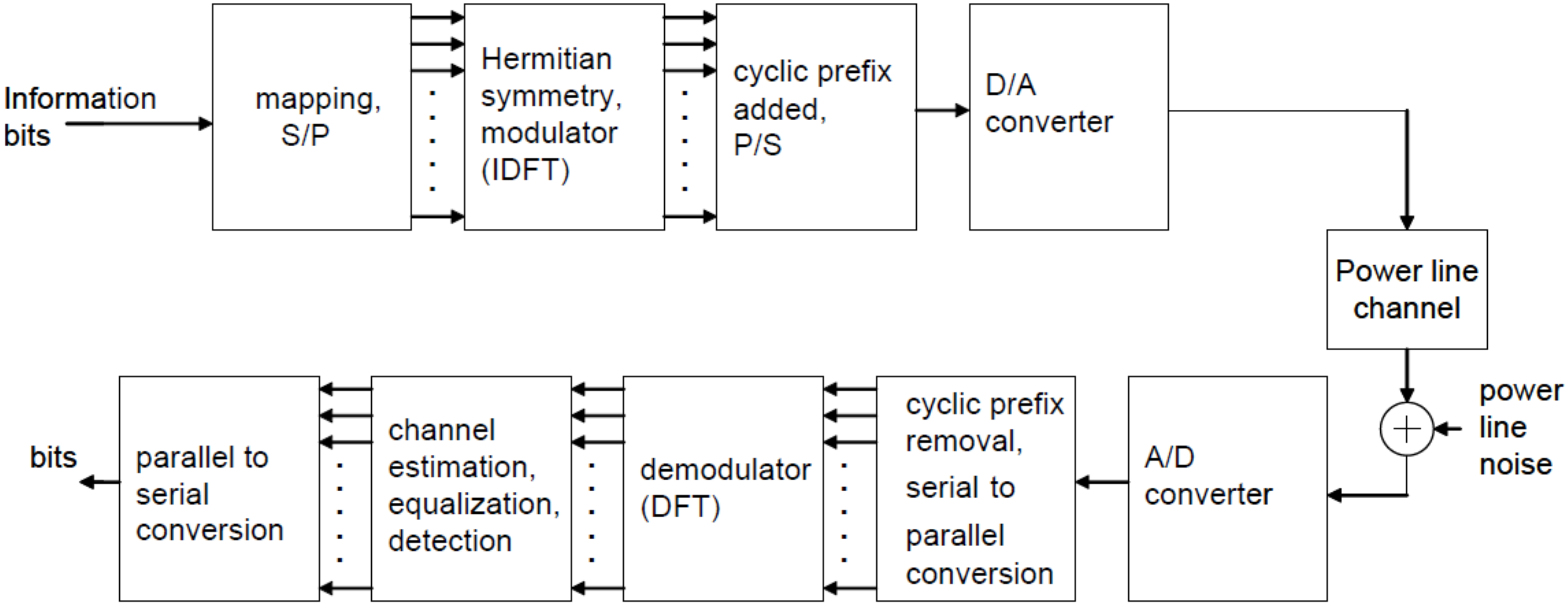


Fig. 5. Illustration of an OFDM system for PLC

OFDM System

- *i*-th subchannel QAM signal

$$\begin{aligned} u_i(t) &= \sqrt{\frac{2}{T}}A_{ic}\cos(2\pi f_i t) - \sqrt{\frac{2}{T}}A_{is}\sin(2\pi f_i t) \\ &= \mathrm{Re}\left[\sqrt{\frac{2}{T}}A_i e^{j\theta_i} e^{j2\pi f_i t}\right] \\ &= \mathrm{Re}\left[\sqrt{\frac{2}{T}}X_i e^{j2\pi f_i t}\right], \end{aligned}$$

where

$$X_i = A_i e^{j\theta_i} \qquad A_i = \sqrt{A_{ic}^2 + A_{is}^2} \qquad H_i(f_i) = H_i = |H_i|e^{j\phi_i}$$

$$\theta_i = \tan^{-1}\left(\frac{A_{is}}{A_{ic}}\right)$$

- Received signal

$$\begin{aligned} r_i(t) &= \sqrt{\frac{2}{T}}|H_i|A_{ic}\cos(2\pi f_i t + \phi_i) + \sqrt{\frac{2}{T}}|H_i|A_{is}\sin(2\pi f_i t + \phi_i) + n_i(t) \\ &= \mathrm{Re}\left[\sqrt{\frac{2}{T}}H_i X_i e^{j2\pi f_i t} + n_i(t)\right] \end{aligned}$$

OFDM System

- Receiver basis functions:

$$\psi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_i t + \phi_i), \quad 0 \le t \le T$$
$$\psi_2(t) = -\sqrt{\frac{2}{T}}\sin(2\pi f_i t + \phi_i), \quad 0 \le t \le T \quad ,$$

- Received signal vector:

$$y_i = (|H_i|A_{ic} + \eta_{ir},\ |H_i|A_{is} + \eta_{ii})$$

$$\eta_i = \eta_{ir} + j\eta_{ii}$$

$$Y_i = |H_i|X_i + \eta_i$$

- Reverse operation at receiver:

$$Y_i' = \frac{Y_i}{|H_i|} = X_i + \eta_i' \qquad \eta_i' = \frac{\eta_i}{|H_i|}$$

OFDM System

- Receiver basis functions:

$$\psi_1(t) = \sqrt{\frac{2}{T}} \cos(2\pi f_i t + \phi_i), \quad 0 \le t \le T$$

$$\psi_2(t) = -\sqrt{\frac{2}{T}} \sin(2\pi f_i t + \phi_i), \quad 0 \le t \le T \ ,$$

2*N* matched filters needed to implement!

- Received signal vector:

$$y_i = (|H_i| A_{ic} + \eta_{ir},\ |H_i| A_{is} + \eta_{ii})$$

$$\eta_i = \eta_{ir} + j\eta_{ii}$$

$$Y_i = |H_i| X_i + \eta_i$$

- Reverse operation at receiver:

$$Y_i' = \frac{Y_i}{|H_i|} = X_i + \eta_i' \qquad \eta_i' = \frac{\eta_i}{|H_i|}$$

OFDM System

- Receiver basis functions:

$$\psi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_i t + \phi_i), \quad 0 \le t \le T$$

$$\psi_2(t) = -\sqrt{\frac{2}{T}}\sin(2\pi f_i t + \phi_i), \quad 0 \le t \le T \quad ,$$

2*N* matched filters needed to implement!

DFT to implement modulation and demodulation

- Received signal vector:

$$y_i = (|H_i|A_{ic} + \eta_{ir},\ |H_i|A_{is} + \eta_{ii})$$

$$\eta_i = \eta_{ir} + j\eta_{ii}$$

$$Y_i = |H_i|X_i + \eta_i$$

- Reverse operation at receiver:

$$Y_i' = \frac{Y_i}{|H_i|} = X_i + \eta_i' \qquad\qquad \eta_i' = \frac{\eta_i}{|H_i|}$$

Bit Loading Research (Review)

- Goal: develop optimal and reduced complexity mechanisms
  - For bit and power allocation
    1) Increase throughput ➔ reduce power consumption
       - Optimal bit and power allocation
    2) Reduce complexity
       - Mechanisms to reduce complexity of the proposed optimal bit loading
- Considered bit loading schemes
    1) Non-adaptation
    2) Adaptation

Bit Loading Research (Review)

- Goal: develop optimal and reduced complexity mechanisms
  - For bit and power allocation

    1) Increase throughput ➔ reduce power consumption
       - Optimal bit and power allocation

    2) Reduce complexity
       - Mechanisms to reduce complexity of the proposed optima bit loading
- Considered bit loading schemes

    1) Non-adaptation

    2) Adaptation

    3) Optimal LPTV-aware

    4) Reduced complexity LPTV-aware (sub-optimal, practical)

Bit Loading

- Water filling approach
  - Optimal to maximize the capacity for band-limited channels
  - Allows non-integer values for bits, not practical

- Greedy approach
  - Optimal for integer bit loading

Bit Loading

- Greedy approach
  - Optimal for integer bit loading
  - Maximize:

$$\max_{\{b_i, i=0,\ldots,N-1\}} B_{\text{tot}} = \sum_{i=0}^{N-1} b_i$$

  - Subject to:

$$\sum_{i=0}^{N-1} \epsilon_i \le \epsilon_{\text{tot}},$$

$$\{b_i, i = 0, \ldots, N-1\} \text{ are nonnegative integers}$$

$$0 \le \epsilon_i \le \epsilon_i^{\max}, i = 0, \ldots, N-1$$

Bit Loading

- Optimality of the greedy algorithm
  - Due to the matroid structure of the optimization problem
  - Searching for the maximal minimum-weight member of a matroid
- Let *S* be the set of all possible (*k,i*) pairs
  - (*k,i*) stands for *k*-th bit in the *i*-th subchannel
  - *k* does not exceed a certain maximum b_i^{max}
  - Let *J* be collection of all subsets of *S* for which:
    - Number of elements in each subset is less than *c*, the *cardinality*
    - Each *J* represents a particular bit allocation pattern
    - Total transmission less than *c*
  - Weight of each element (*k,i*): excess energy to transmit *k*-th bit
    - Results in bit allocation pattern with minimum energy for a given *c*

Bit Loading

- In the context of LPTV channels, for *j*-th microslot with $H_j(f)$

$$\max_{\{b_{j,i}, i=0,\ldots,N-1\}} B_{j,\text{tot}} = \sum_{i=0}^{N-1} b_{j,i}$$

- Subject to:

$$\sum_{i=0}^{N-1} P_{j,i} \leq P,$$

$$\{b_{j,i}, i = 0, \ldots, N-1\} \text{ are nonnegative integers}$$

- Weight function: excess power required for *k*-th bit

$$w_j(k,i) = P_{j,i}(k) - P_{j,i}(k-1),\ 1 \leq k \leq b_{j,i}^{\max},\ P_{j,i}(0) = 0$$

Weight Function

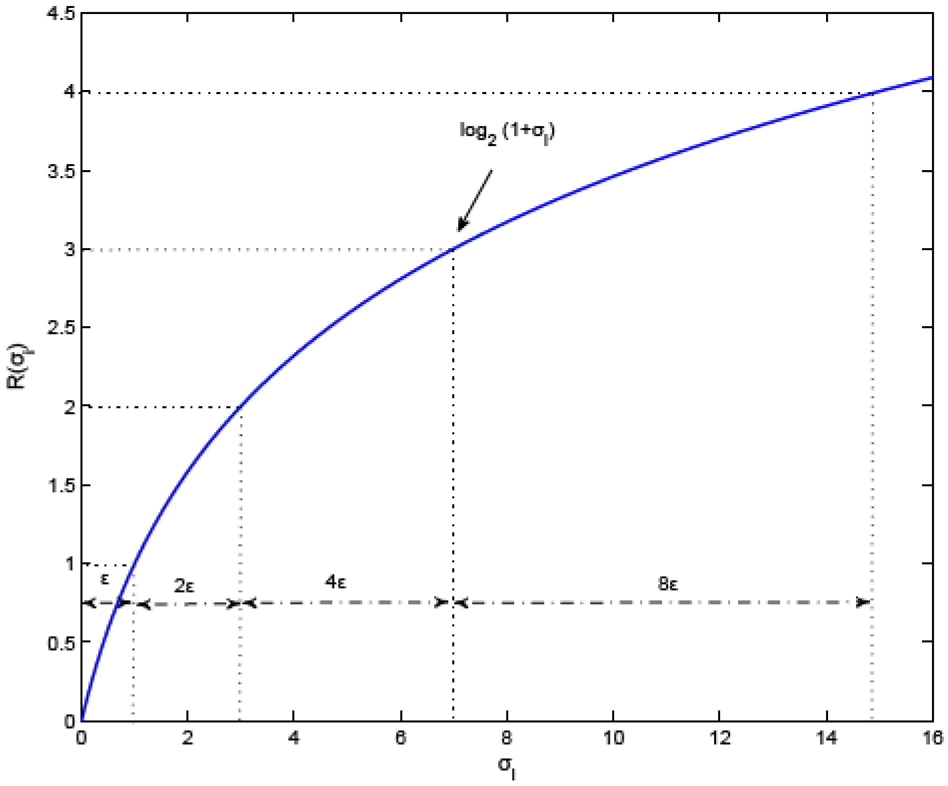
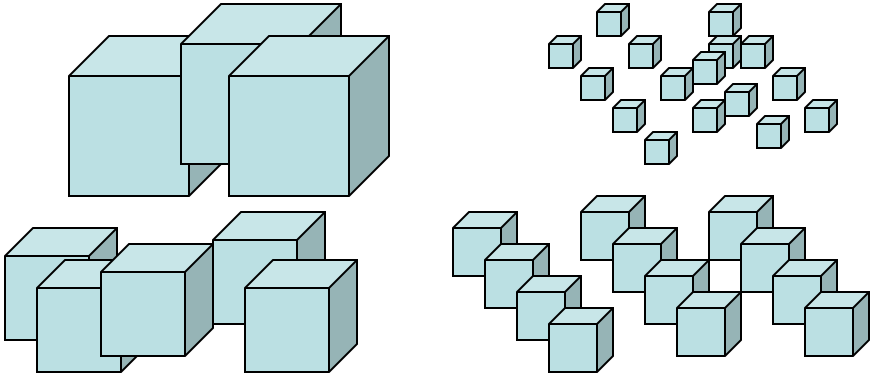


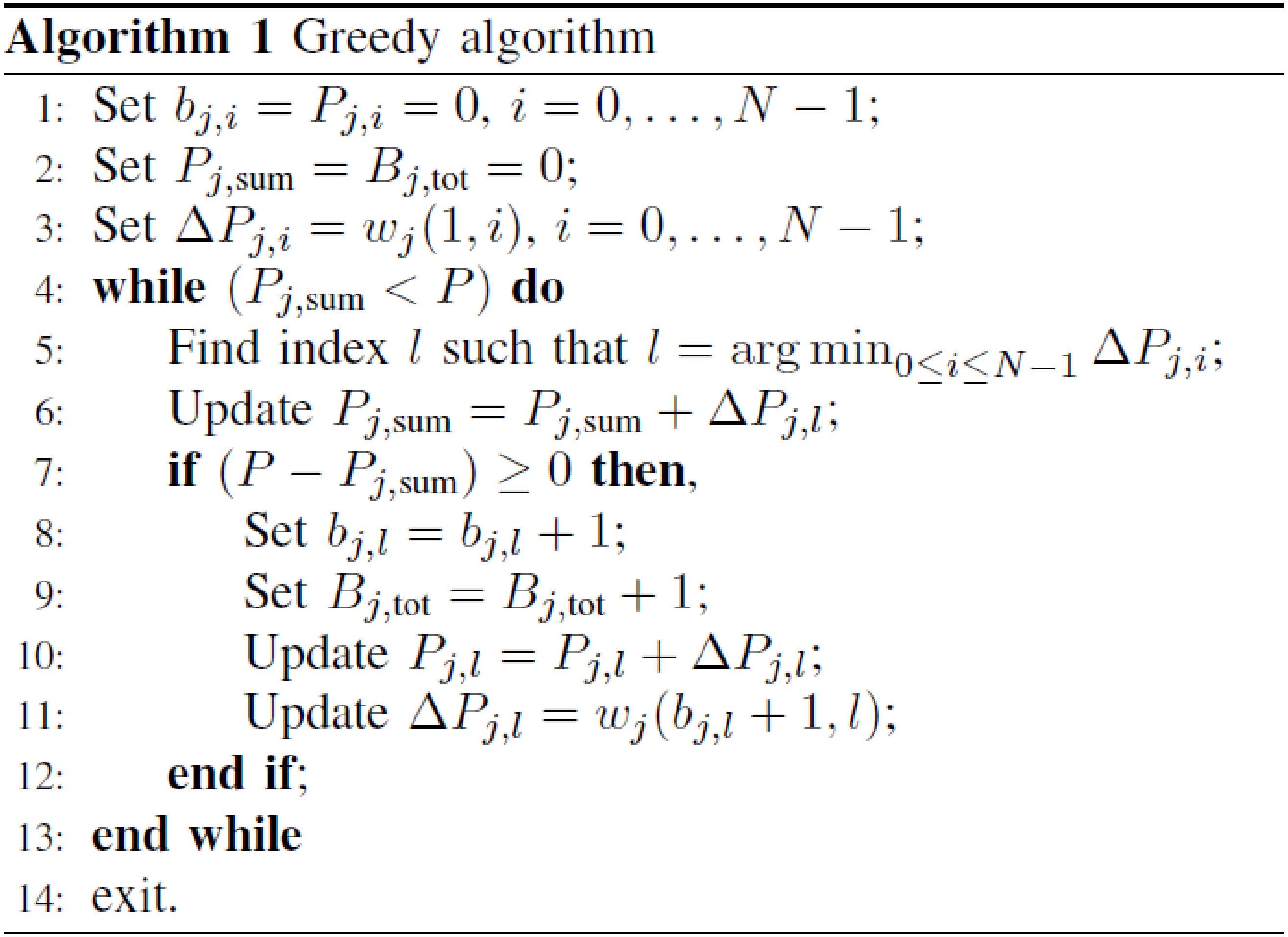
Fig. 6. Strictly increasing concave rate function illustrated as a function of overall SNR with ideal case of no SNR-gap.

Bit Loading

- Greedy algorithm
  - Iterative fashion
  - least amount of power to transmit an additional bit
- Analogy: maximize the value of the knapsack:
  - Each box $1 value, different weights
  - Knapsack can only carry certain weight
  - Maximize number of items



Bit Loading



Algorithm 1 Greedy algorithm

```
Set $b_{j,i} = P_{j,i} = 0,\ i = 0, \ldots, N-1$;
Set $P_{j,\text{sum}} = B_{j,\text{tot}} = 0$;
Set $\Delta P_{j,i} = w_j(1, i),\ i = 0, \ldots, N-1$;
while $(P_{j,\text{sum}} < P)$ do
    Find index $l$ such that $l = \arg\min_{0 \le i \le N-1} \Delta P_{j,i}$;
    Update $P_{j,\text{sum}} = P_{j,\text{sum}} + \Delta P_{j,l}$;
    if $(P - P_{j,\text{sum}}) \ge 0$ then,
        Set $b_{j,l} = b_{j,l} + 1$;
        Set $B_{j,\text{tot}} = B_{j,\text{tot}} + 1$;
        Update $P_{j,l} = P_{j,l} + \Delta P_{j,l}$;
        Update $\Delta P_{j,l} = w_j(b_{j,l} + 1, l)$;
    end if;
end while
exit.
```

LPTV-aware Bit Loading

- Question: How can we exploit LPTV channel information further?
  - The success of water filling and greedy approaches
    - Favor subchannels with less attenuation
  - Simplistic adaptation
    - Greedy approach only within microslot transfer function
    - Does not consider relative variation of the microslot transfer functions
    - Regards each microslot equal in power distribution
  - LPTV-aware
    - Allow different power levels for microslots
    - Maintain the average power to be equal to simplistic adaptation
    - Aggregate two-dimensional $H_{j,i}$ into a *combined transfer function*

LPTV-aware Bit Loading

- Maximize:

$$\max_{\{b_{j,i}, i=0,\ldots,N-1, j=0,\ldots,M-1\}} B_{\text{tot}} = \sum_{j=0}^{M-1} \sum_{i=0}^{N-1} b_{j,i}$$

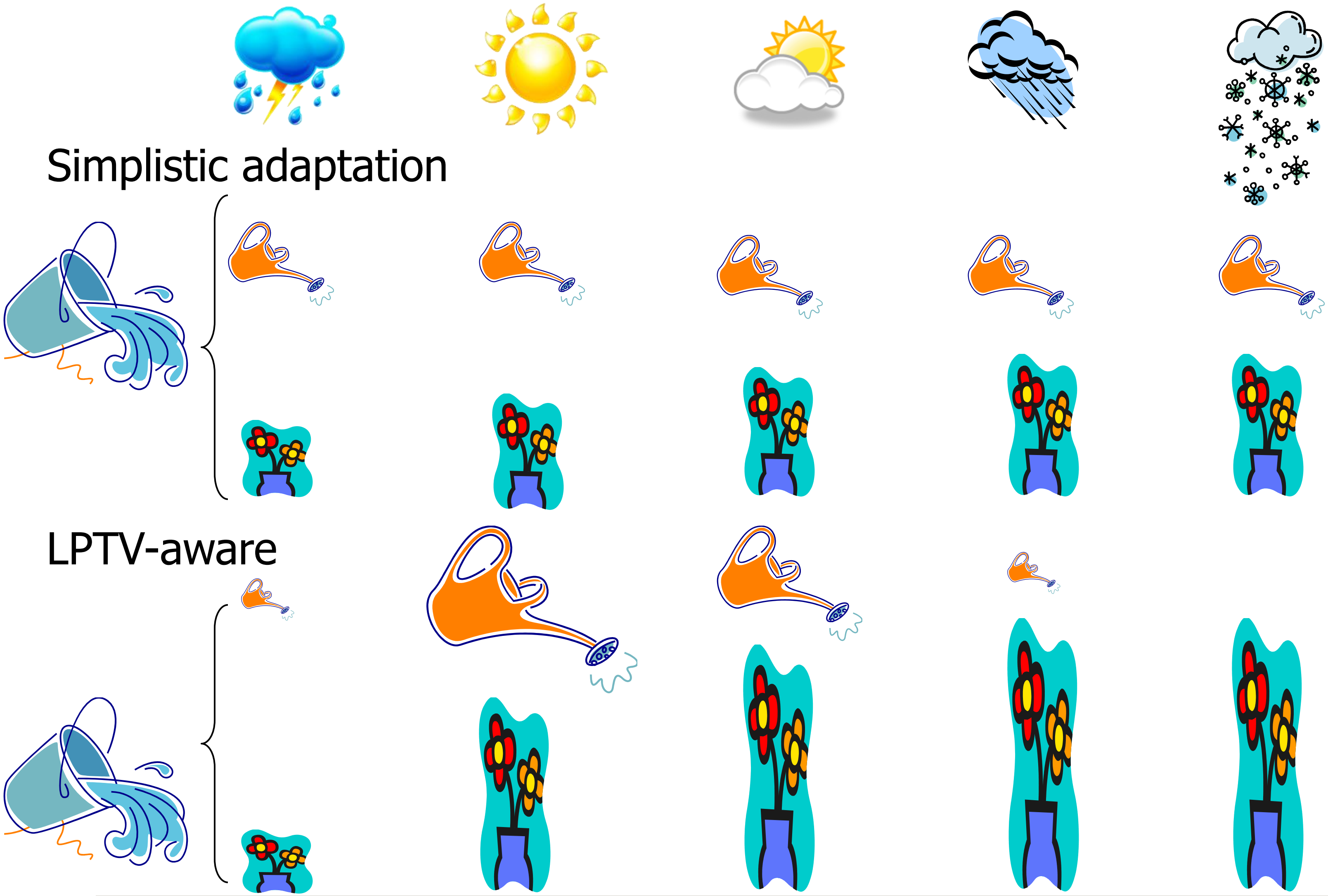
- Subject to:

$$\sum_{j=0}^{M-1} \sum_{i=0}^{N-1} P_{j,i} \leq MP$$

$$\{b_{j,i}, i = 0, \ldots, N-1, j = 0, \ldots, M-1\} \text{ are nonnegative integers}$$

  - Total power constraint
  - Combined transfer function: bit loading *across* microslots
  - Similar matroid structure as the single transfer function case
  - Greedy approach for optimal solution

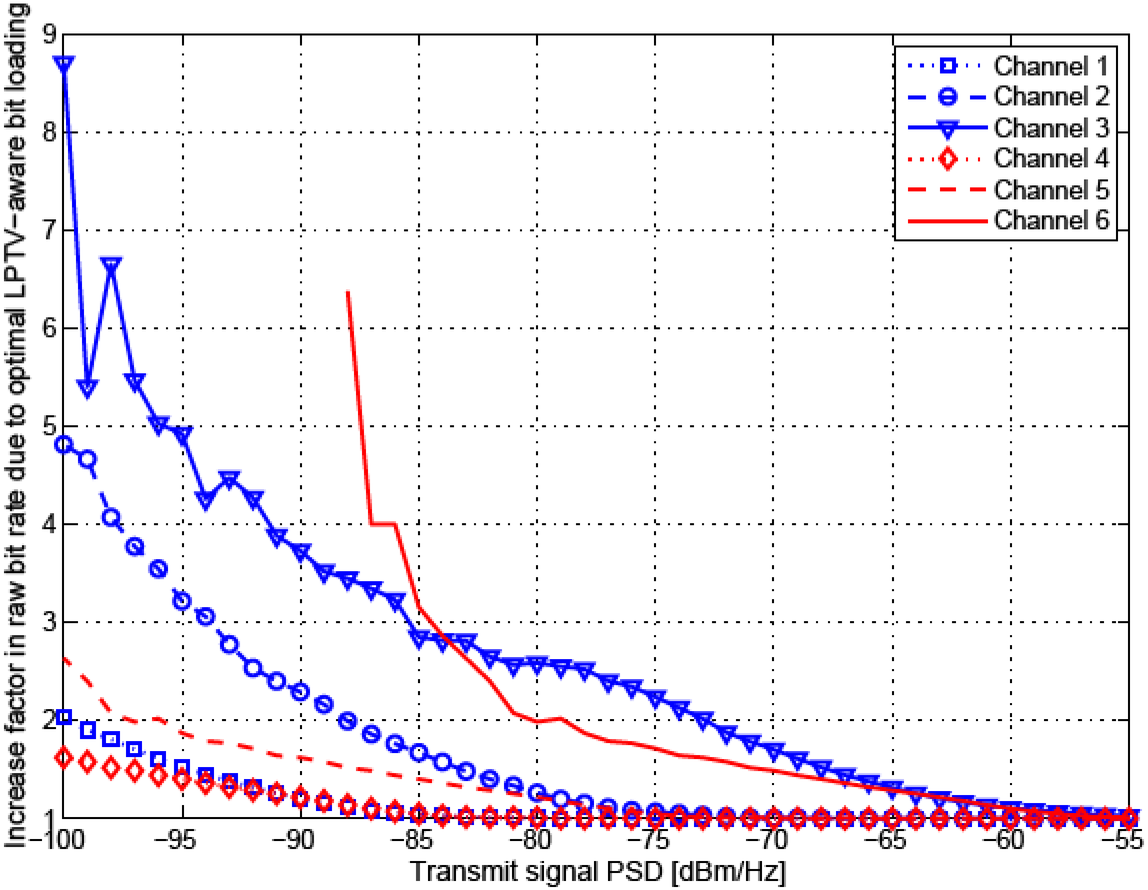
LPTV-aware Bit Loading



Simplistic adaptation

LPTV-aware

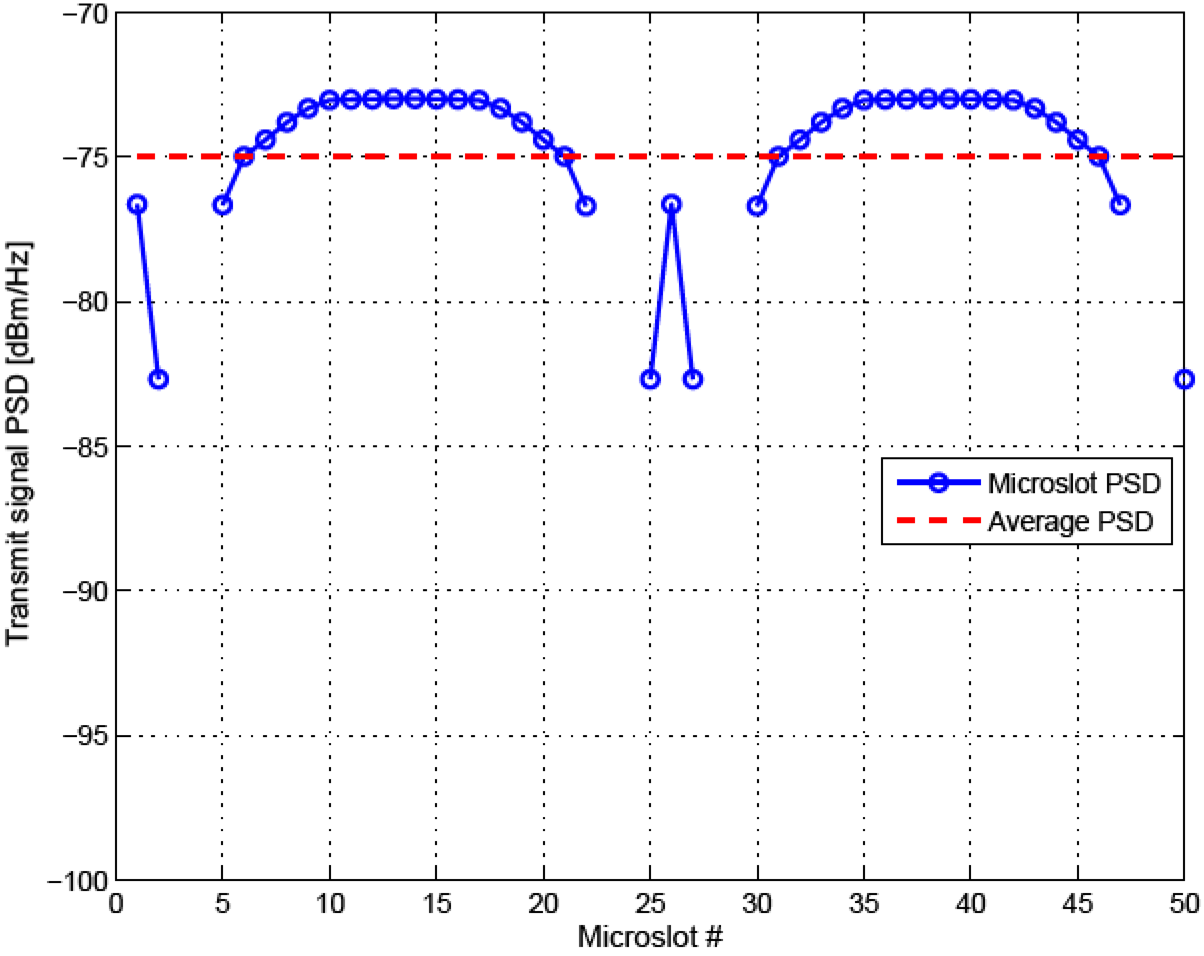
Performance Analysis



- Increase factor >1
- Optimal
- Ch 6, below -88 dBm/Hz
  - No transmission for simplistic adaptation

Fig. 7. Increase in raw data rate due to the optimal LPTV-aware bit loading compared to the simplistic adaptation scheme for commuted and harmonic channels

Performance Analysis



- Up to 2 dB excess power
- 5 % improvement
- Less variation and gain for higher transmit signal levels

Fig. 8. Resultant microslot transmit signal PSD levels for Channel 5, with -75 dBm/Hz average transmit signal PSD over one AC mains cycle, for the optimal LPTV-aware bit loading.

Energy Efficiency

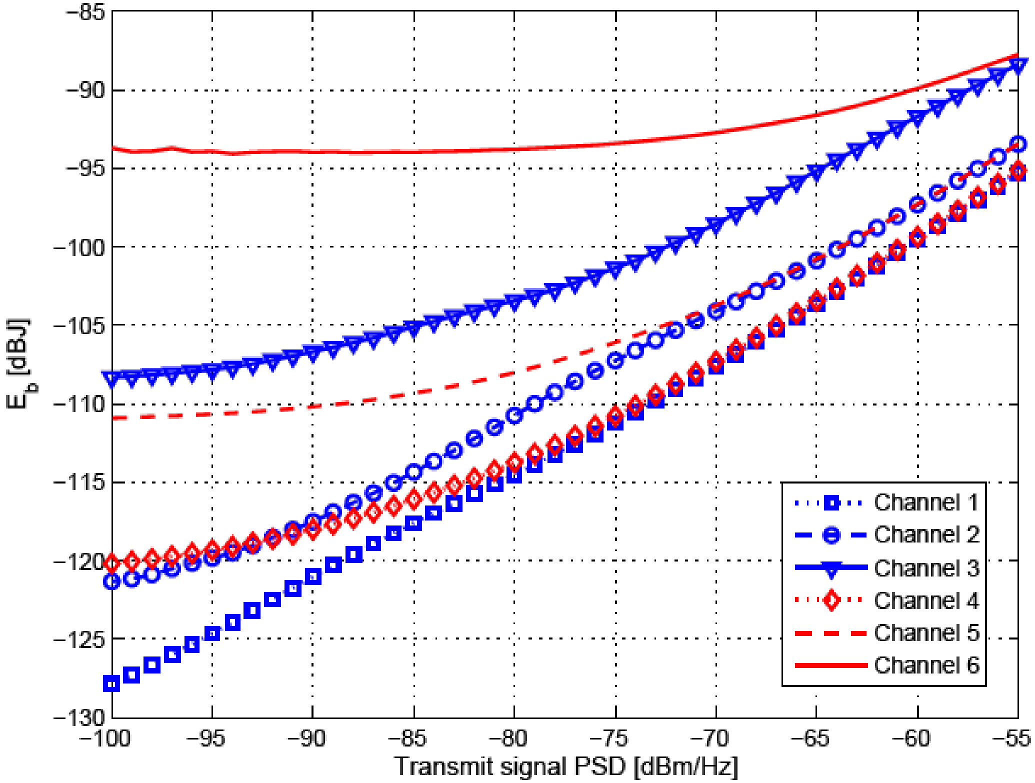


Fig. 9. Energy per one bit transmission for the optimal LPTV-aware bit loading scheme in commuted and harmonic channels

- Energy saving
- SG applications
- Reduced power levels
    - More efficient
    - More improvement due to LPTV-aware bit loading
    - Reduced interference
    - Reduced encoding complexity and tone maps
    - Reduced data rate
- Power saving in standards
- PAPR analysis

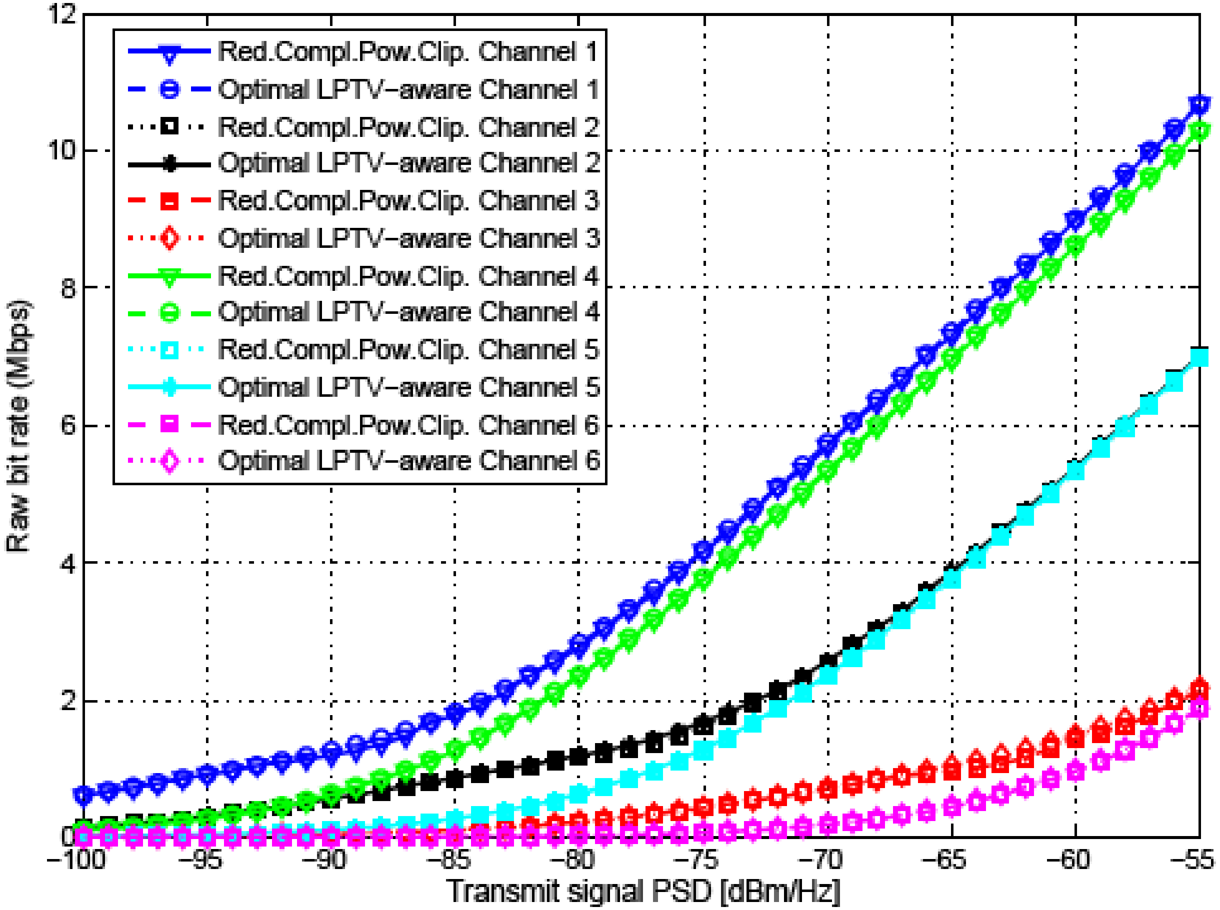
Reduced Complexity LPTV-aware Bit Loading

- LPTV-aware bit loading
  - Increased system complexity
  - Works on a combined transfer function of size MN
    - Ex: $M = 50$, $N = 256$, $MN = 12800$
- Reduced complexity
  - First, find out microslot power levels P_j
  - Initially, works on a data set of size M
  - Once P_j is stored, same complexity as the simplistic adaptation

Reduced Complexity LPTV-aware Bit Loading

- In order to find out P_j
  - Represent transfer function for the j-th microslot $H_{j,i}$
  - By a single value
    - Maximum magnitude value, magnitude mean, or a weighted sum
    - Average capacity for a given transmit signal PSD
  - Scale power to allocate to M microslots accordingly
  - Run greedy bit loading algorithm
    - With $\tilde{H}_j$ and scaled power as inputs
    - Normalize to eliminate rounding errors
- Power Clipping
  - To eliminate peak power levels
  - Not needed in the reduced power levels
  - Clip excess power and distribute to other microslots
    - Favoring the ones with better channel conditions

Reduced Complexity with Power Clipping



- Sub-optimal scheme
- Very close to the optimal scheme
- Maximum magnitude values used
  - Good for reduced power levels
- Power clipping
  - not needed for reduced power levels

Fig. 9. Raw data rate for the sub-optimal reduced complexity LPTV-aware bit loading with power clipping, and the optimal LPTV-aware bit loading schemes in commuted and harmonic channels

Key Points

- Greedy type bit allocation
  - Optimal when combined transfer function
  - Average power constraint over one AC mains cycle used
- LPTV-aware bit loading
  - Maximizes throughput over one AC mains cycle
  - Outperforms simplistic adaptation
- Reduced power levels
  - More energy efficient
  - More improvement due to LPTV-aware bit loading
- Complexity reduction
  - Using representative values
  - Maintain high improvements in bit loading
  - Relevant to Broadband PLC standards power saving mechanisms
- Ideas applicable to other algorithms

Channel Estimation (CE)

- Must be done prior to bit loading
- LPTV channel CE challenges
  - LPTV channel
  - Impulsive noise
- Pilot-based (data-aided, supervised, trained) CE
  - High estimation overhead
  - Interpolation error
- Decision-directed CE
  - Rely on decisions, low overhead
  - Abrupt changes in channel and noise
- Goal:
  1) Pilot-based CE ➔ Reduce interpolation error
  2) Develop a robust CE scheme with low estimation overhead

OFDM Channel Estimation

- LS and LMMSE estimators:

$$\mathbf{h}_{\mathrm{LS}} = \mathbf{X}^{-1}\mathbf{y}$$

$$\mathbf{h}_{\mathrm{LMMSE}} = \mathbf{R}_{\mathbf{hy}}\mathbf{R}_{\mathbf{yy}}{}^{-1}\mathbf{y}$$

$$\begin{aligned}\mathbf{R}_{\mathbf{hy}} &= E[\mathbf{h}\mathbf{y}^{H}] = E[\mathbf{h}(\mathbf{X}\mathbf{h}+\mathbf{n})^{H}]\\ &= E[\mathbf{h}\mathbf{h}^{H}\mathbf{X}^{H} + \mathbf{h}\mathbf{n}^{H}]\\ &= \mathbf{R}_{\mathbf{hh}}\mathbf{X}^{H}\end{aligned}$$

$$\begin{aligned}\mathbf{R}_{\mathbf{yy}} &= E[\mathbf{y}\mathbf{y}^{H}] = E[(\mathbf{X}\mathbf{h}+\mathbf{n})(\mathbf{X}\mathbf{h}+\mathbf{n})^{H}]\\ &= E[\mathbf{X}\mathbf{h}\mathbf{h}^{H}\mathbf{X}^{H} + \mathbf{X}\mathbf{h}\mathbf{n}^{H} + \mathbf{n}\mathbf{h}^{H}\mathbf{X}^{H} + \mathbf{n}\mathbf{n}^{H}]\\ &= \mathbf{X}\mathbf{R}_{\mathbf{hh}}\mathbf{X}^{H} + E[\mathbf{n}\mathbf{n}^{H}] = \mathbf{X}\mathbf{R}_{\mathbf{hh}}\mathbf{X}^{H} + \sigma_n^2 I\end{aligned}$$

$$\mathbf{h}_{\mathrm{LMMSE}} = \mathbf{R}_{\mathbf{hh}}\mathbf{X}^{H}(\mathbf{X}\mathbf{R}_{\mathbf{hh}}\mathbf{X}^{H} + \sigma_n^2 I)^{-1}\mathbf{y}$$

- Practical considerations
  - Complexity
  - Noise and channel statistics ➔ Effect on performance

OFDM Channel Estimation

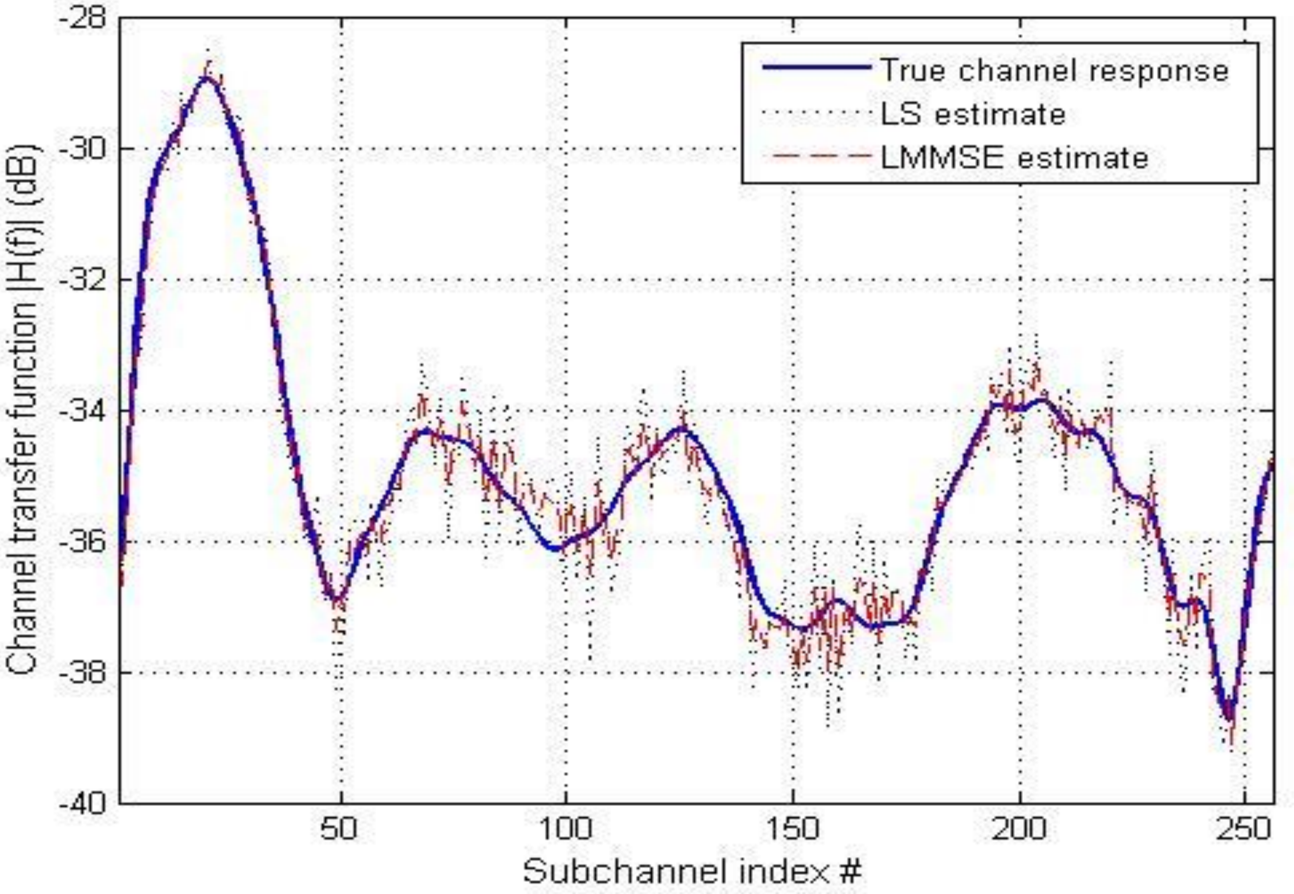


Fig. 10. LS and LMMSE estimates for a single channel

Pilot Based CE

- Block type
  - All pilots for one AC mains cycle
  - High overhead
- Comb type
  - Reduced overhead
  - Better channel tracking capability with same overhead
  - Interpolation error for non-pilot locations
- Incline type
  - Pilot positions shifted each time
  - Reduction in interpolation error
  - More accurate channel estimation for the most part

Pilot Geometry

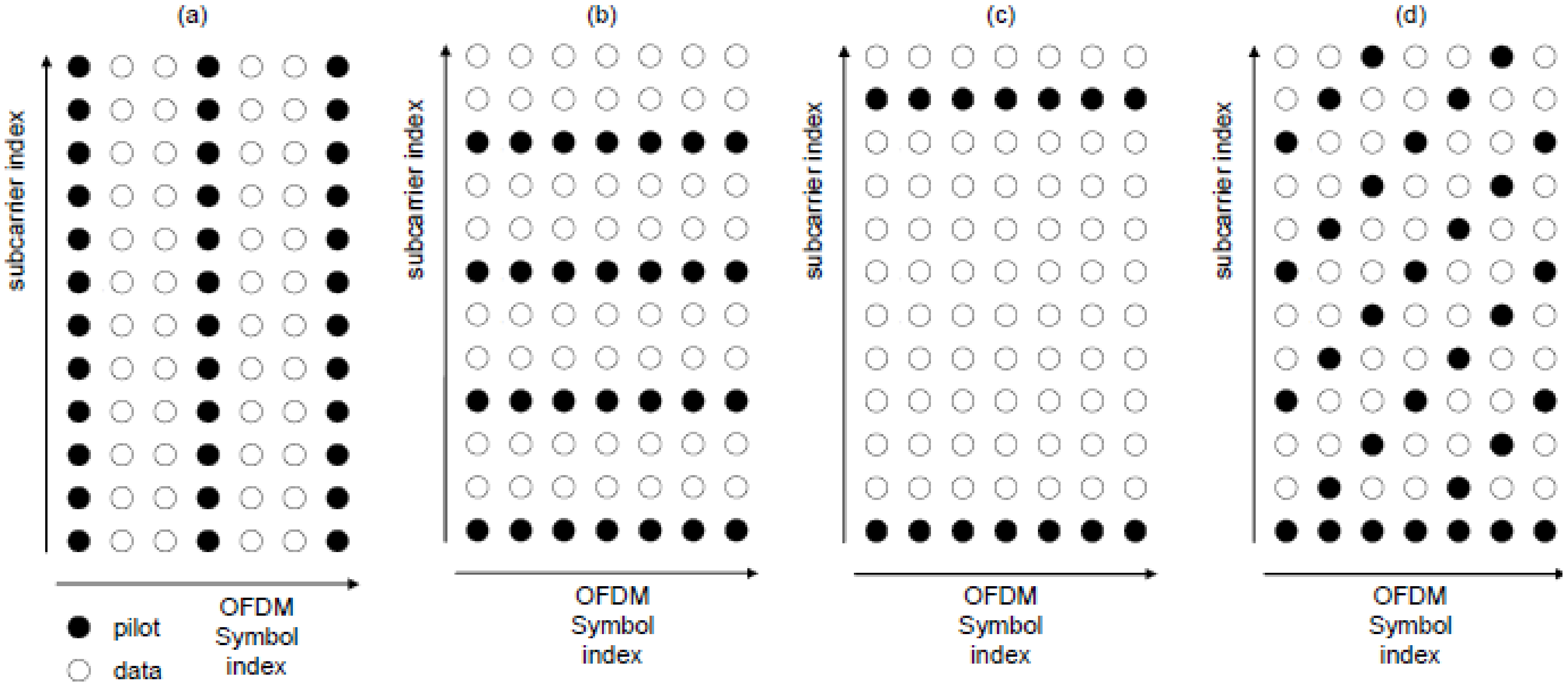


Fig. 11. Different types of pilot arrangement: (a) block-type pilots; (b) comb-type pilots; (c) comb-type pilots where pilots are placed widely apart; (d) incline-type pilots

Interpolation Error

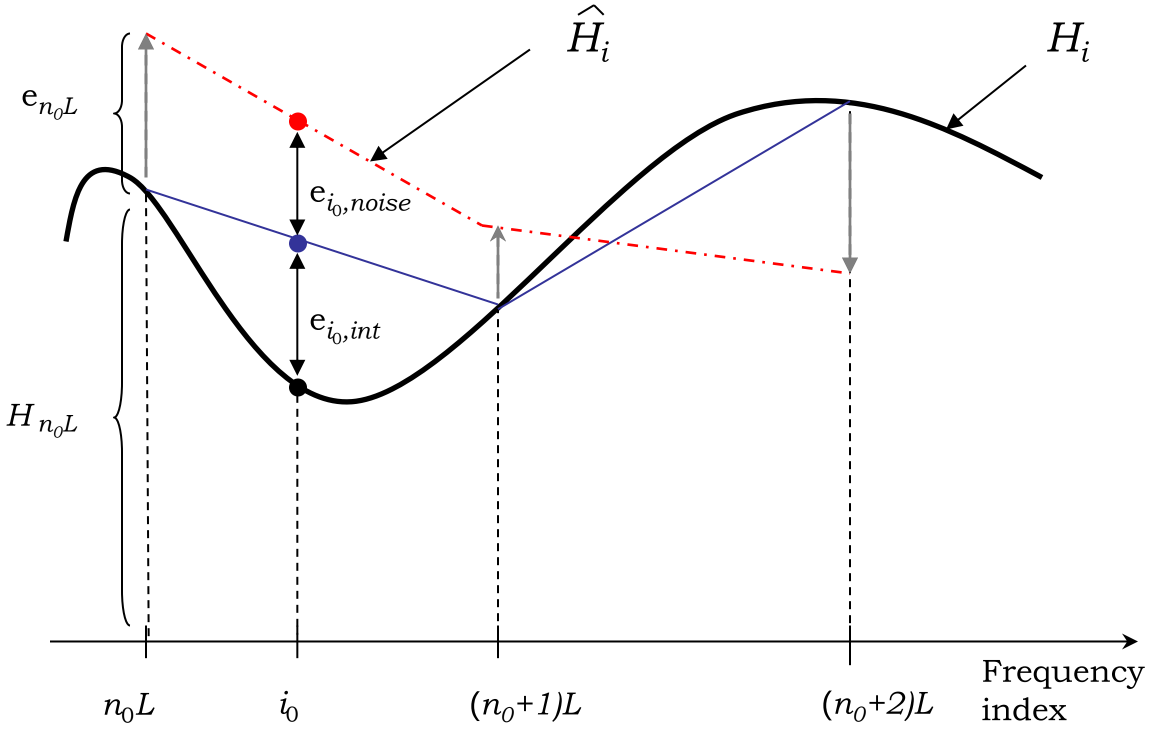


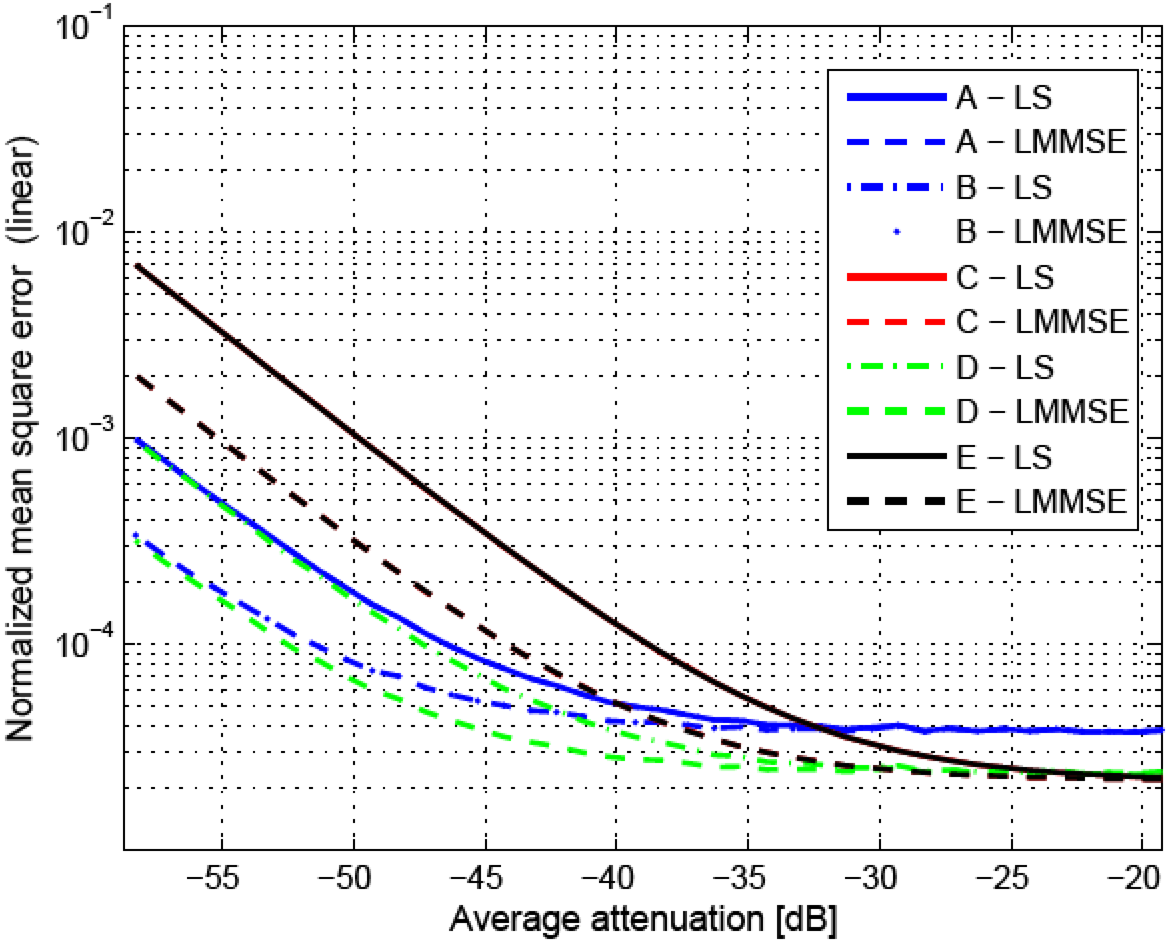
Fig. 12. Decomposition of interpolation error [22, Fig. 3]

Pilot-based CE Schemes

- For a communication channel that remains the same for *L* symbols:
  - Linear and cubic interpolation for each scheme

Scheme A	Comb-type	Pilot estimates averaged first	One time interpolation
Scheme B	Comb-type	Interpolation done at each OFDM symbol	Interpolated values averaged
Scheme C	Incline-type	-	Pilot estimates combined
Scheme D	Incline-type	Interpolation done at each OFDM symbol	Interpolated values averaged
Scheme E	Block-type	-	-

Channel Estimation Schemes



- LMMSE > LS
- Cubic interpolation > linear interpolation
- Scheme C ~ Scheme E
  - Better channel tracking
- Scheme D > Scheme A-B for the most part
- Scheme D > Scheme E for the most part

Fig. 13. Normalized mean square error using linear interpolation, L = 5.

Transform Domain Analysis

- Impulsive noise mitigation
  - Present in the power line due to switching events
  - Very poor estimates in its presence
- Question: Can the changes in the channel estimate identified?
  - Due to a change in the transfer function
  - Due to the presence of impulsive noise
- Approach:
  - Frequency content of the change in the transfer function
  - Transform domain: Fourier transform of Fourier transformed data
  - Expectation: Changes due to a change in transfer function
    - Smoother ➔ Low frequency content
    - Check the energy in low and high frequencies

Transform Domain Analysis

Case A	$h_2 = h_1$	AWGN noise
Case B	$h_2 = h_1$	AWGN and impulsive noise
Case C	$h_2 \neq h_1$	AWGN noise
Case D	$h_2 \neq h_1$	AWGN and impulsive noise

- **Case A →** use $\hat{\mathbf{h}}_2$ to improve $\hat{\mathbf{h}}_1$
- **Case B →** discard $\hat{\mathbf{h}}_2$
- **Case C →** replace $\hat{\mathbf{h}}_1$ with new estimate $\hat{\mathbf{h}}_2$
- **Case D →** upgrade the noise variance for LMMSE, wait for better estimates

Transform Domain Analysis

- Compute:

$$\Delta h_{\text{TD}} = \mathcal{DFT}(|\hat{\mathbf{h}}_2| - |\hat{\mathbf{h}}_1|)$$

- Low and high frequency metrics, $f_c = 20$:

$$\gamma_{\text{LF}} = \sum_{i=1}^{f_c} |\Delta h_{\text{TD}}(i)|^2, \quad \gamma_{\text{HF}} = \sum_{i=N/2}^{N/2+f_c-1} |\Delta h_{\text{TD}}(i)|^2$$

Transform Domain Analysis

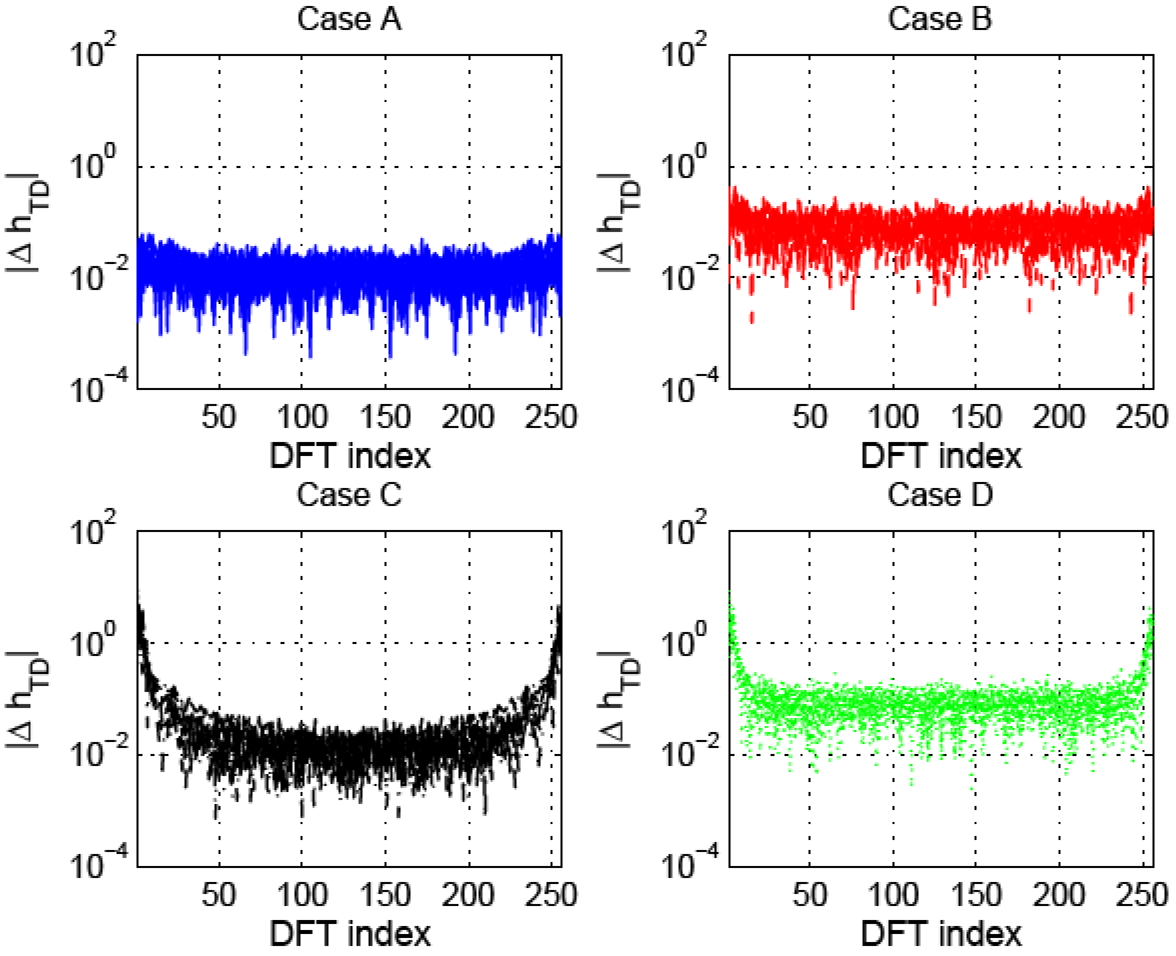


Fig. 14 TD analysis for three random channels using LMMSE estimator.

Transform Domain Analysis

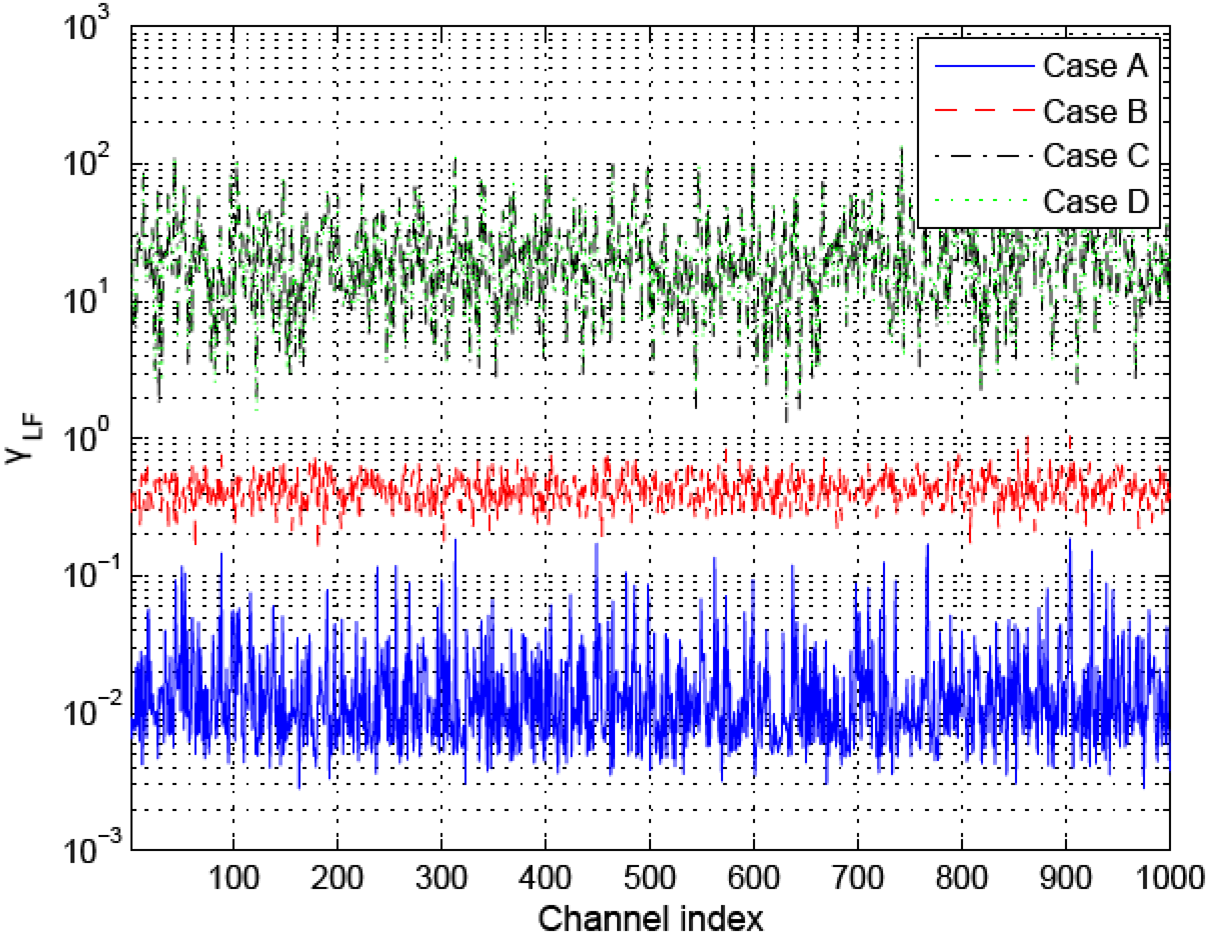


Fig. 15 Low frequency metric for Cases A–D.

Transform Domain Analysis

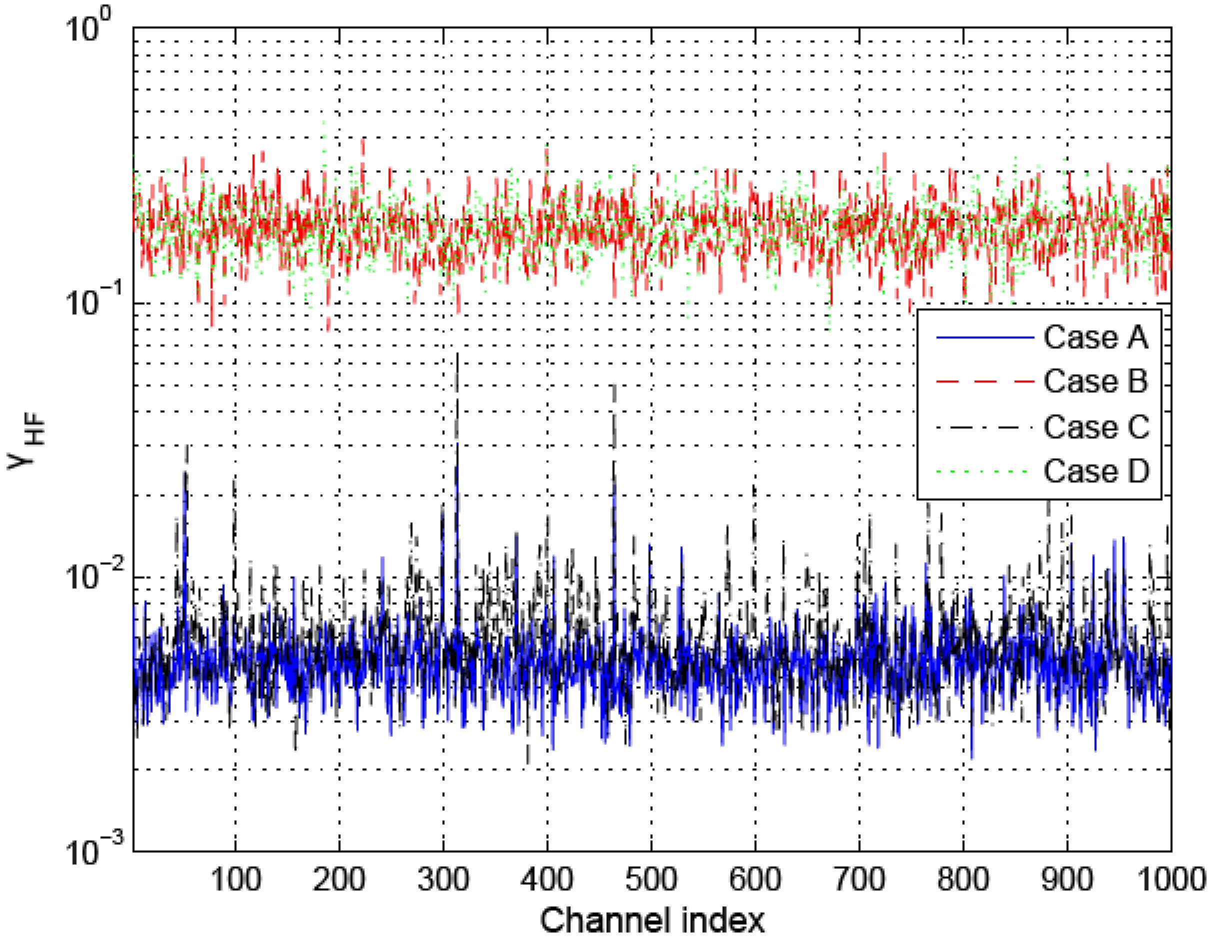


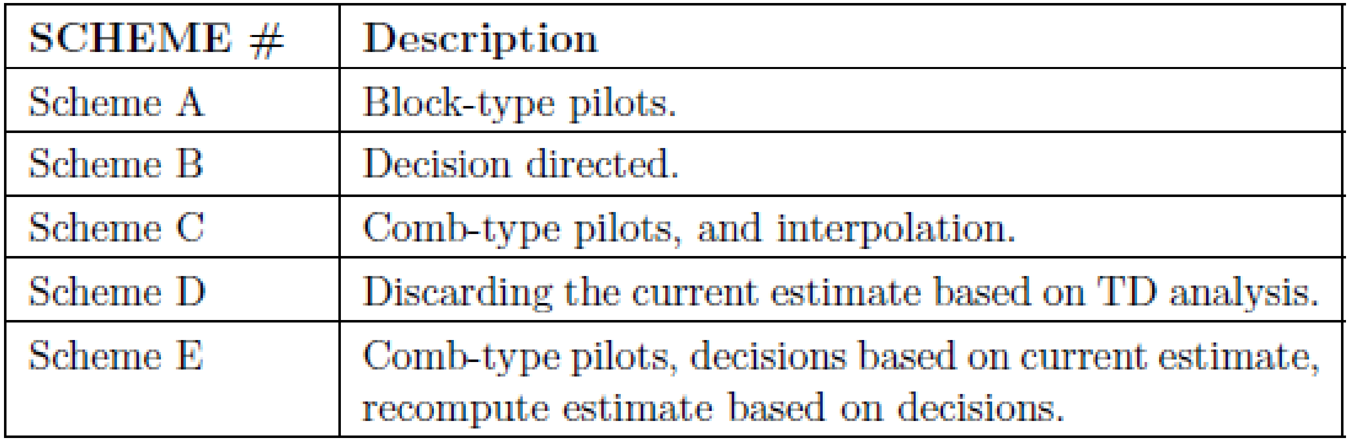
Fig. 16 High frequency metric for Cases A–D.

Proposed CE Scheme

- Exploit TD analysis
- Low overhead, pilots wide apart

- Goal:
  - Keep estimation overhead low
  - Robust to LPTV channel and impulsive noise
  - Switch between various schemes
    - Unlike conventional schemes

CE Schemes for Comparison



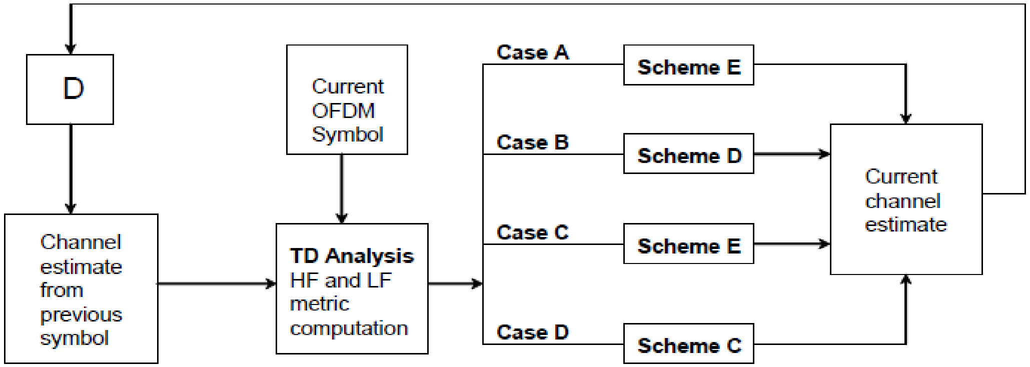
SCHEME #	Description
Scheme A	Block-type pilots.
Scheme B	Decision directed.
Scheme C	Comb-type pilots, and interpolation.
Scheme D	Discarding the current estimate based on TD analysis.
Scheme E	Comb-type pilots, decisions based on current estimate, recompute estimate based on decisions.

Table 1. CE schemes considered.

Performance Analysis

CASE #	Scheme A	Scheme B	Scheme C	Scheme D	Scheme E
Case A - [NMMSE$_{avg}$]	-47.32	-47.12	-42.04	N/A	-42.70
Case A - $E_{d,avg}/N_d$	N/A	0.61 / 256	1.51 / 229	N/A	1.51 / 229
Case B - [NMMSE$_{avg}$]	-30.96	-31.78	-26.68	-42.04	-29.93
Case B - $E_{d,avg}/N_d$	N/A	27.97 / 256	43.15 / 229	25.77 / 229	43.15 / 229
Case C - [NMMSE$_{avg}$]	-47.35	-21.03	-42.02	N/A	-42.74
Case C - $E_{d,avg}/N_d$	N/A	192.92 / 256	1.54 / 229	N/A	1.54 / 229
Case D - [NMMSE$_{avg}$]	-30.99	-20.63	-30.10	N/A	-29.89
Case D - $E_{d,avg}/N_d$	N/A	192.53 / 256	43.28 / 229	N/A	43.28 / 229

Table 2. Performance analysis.



D

Channel estimate from previous symbol

Current OFDM Symbol

TD Analysis
HF and LF metric computation

Case A
Scheme E

Case B
Scheme D

Case C
Scheme E

Case D
Scheme C

Current channel estimate

Fig. 17. Proposed scheme.

Key Points

- Incline-type pilot geometry
  - Reduce interpolation error
- TD analysis
  - Change in transfer function in low frequencies
  - Impulsive noise in all frequencies
- Pilots placed widely apart
  - Low estimation overhead
- Robust CE
  - Switch between various CE schemes
  - Based on TD analysis

Future Research Ideas

- Interdependency of bit loading and CE
  - Performance evaluation

- Advanced TD analysis metrics for various noise models

- TD analysis applied to decision-directed schemes

Conclusion

- A complete solution for two major problems for BB PLC
  - Bit and power allocation for LPTV channels
    - Optimal and sub-optimal schemes developed
    - Suitable for devices in IH domain of SG
    - Significant improvements in throughput
  - Channel estimation for LPTV channels
    - Incline type pilot arrangement for interpolation error reduction
    - Transform domain analysis for impulsive noise mitigation
    - Robust CE with low overhead

Bibliography

[1] H. C. Ferreira, L. Lampe, J. Newbury, and T. G. S. (Editors), Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines. John Wiley & Sons, June 2010.

[2] S. Galli, A. Scaglione, and Z. Wang, "For the grid and through the grid: The role of power line communications in the smart grid," in *Proceedings of the IEEE*, vol. 99, pp. 998 - 1027, June 2011.

[3] V. Oksman and J. Egan, "Applications of ITU-T G.9960, ITU-T G.9961 transceivers for smart grid applications: Advanced metering infrastructure, energy management in the home and electric vehicles," in *ITU-T Technical Paper*, Jun 2010.

[4] HomePlug Powerline Alliance, "Homeplug Green PHY specification," June 2010. Release Version 1.00.

[5] "IEEE standard for broadband over power line networks: Medium access control and physical layer specifications," IEEE Std 1901, pp. 1 - 1586, 2010.

[6] F. Canete Corripio, J. Cortes Arrabal, L. Dez Del Ro, and J. Entrambasaguas Munoz, "Analysis of the cyclic short-term variation of indoor power line channels," *IEEE Journal on Selected Areas in Communications*, vol. 24, pp. 1327-1338, July 2006.

[7] S. Katar, B. Mashbum, K. Afkhamie, H. Latchman, and R. Newman, "Channel adaptation based on cyclo-stationary noise characteristics in PLC systems," in *IEEE Intl. Symp. on*

- *Power Line Commun. and Its Appl.(ISPLC),* pp. 16{21, 2006.

Bibliography

[8] S. Honda, D. Umehara, T. Hayasaki, S. Denno, and M. Morikura, “A fast bit loading algorithm synchronized with commercial power supply for in-home PLC systems,” in *IEEE Intl. Symp. on Power Line Commun. and Its Appl. (ISPLC)*, pp. 336-341, April 2008.

[9] K.-H. Kim, H.-B. Lee, Y.-H. Kim, and S.-C. Kim, “Channel adaptation for time-varying powerline channel and noise synchronized with AC cycle,” in *IEEE Intl. Symp. on Power Line Commun. and Its Appl. (ISPLC)*, pp. 250-254, April 2009.

[10] T.-E. Sung, A. Scaglione, and S. Galli, “Time-varying power line block transmission models over doubly selective channels,” in *IEEE Intl. Symp. on Power Line Commun. and Its Appl.(ISPLC)*, pp. 193 - 198, Apr 2008.

[11] F. Canete Corripio, J. Cortes Arrabal, L. Dez Del Ro, and J. Entrambasaguas Munoz, “A channel model proposal for indoor power line communications,” *IEEE Communications Magazine*, vol. 49, pp. 166-174, Dec 2011.

[12] J. G. Proakis and M. Salehi, “Digital Communications.” New York: McGraw-Hill, 2008.

[13] A. Picorone, L. Amado, and M. Ribeiro, “Linear and periodically time-varying PLC channels estimation in the presence of impulsive noise,” in *IEEE Intl. Symp. on Power Line Commun. and Its Appl.(ISPLC)*, pp. 255 - 260, Mar. 2010.

Bibliography

[14] K. Watanabe, D. Umehara, S. Denno, and M. Morikura, "An initial acquisition method for channel synchronization on in-home power line communications," in *IEEE Intl. Symp. on Power Line Commun. and Its Appl. (ISPLC)*, pp. 137-142, April 2009.

[15] D. Umehara, T. Hayasaki, S. Denno, and M. Morikura, "The influence of time-varying channels synchronized with commercial power supply on PLC equipments," in *IEEE Intl. Symp. on Power Line Commun. and Its Appl. (ISPLC)*, pp. 30-35, April 2008.

[16] A. Tonello, J. Cortes, and S. D'Alessandro, "Optimal time slot design in an OFDM-TDMA system over power-line time-variant channels," in *IEEE Intl. Symp. on Power Line Commun. and Its Appl.(ISPLC)*, pp. 41 -46, Apr 2009.

[17] M. A. Tunc, E. Perrins, and L. Lampe, "The effect of LPTV channel adaptation on the performance of broadband PLC for smart grid," in *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, Oct 2011.

[18] J. Campello, "Optimal discrete bit loading for multicarrier modulation systems," in *IEEE International Symposium on Information Theory*, Aug 1998.

[19] E. Baccarelli and M. Biagi, "Optimal integer bit-loading for multicarrier ADSL systems subject to spectral-compatibility limits," Elsevier Signal Processing, pp. 729-741, 2004.

Bibliography

[20] A. Cully and O. Logvinov, "Optimizing power consumption in networked devices," in *IEEE Intl. Symp. on Power Line Commun. and Its Appl.(ISPLC)*, Mar 2012.

[21] M. A. Tunc, E. Perrins, and L. Lampe, "Reduced complexity LPTV-aware bit loading for channel adaptation in broadband PLC," in *IEEE Intl. Symp. on Power Line Commun. and Its Appl. (ISPLC),* Mar 2012.

[22] D. Bueche, P. Corlay, M. Gazalet, and F.-X. Coudoux,"A method for analyzing the performance of comb-type pilot-aided channel estimation in power line communications," *IEEE Transactions on Consumer Electronics*, vol. 54, pp. 1074-1081, Aug. 2008.

[23] A. Nayagam, S. Katar, D. Rende, K. Afkhamie, and L. Yonge, "Tradeoff between channel estimation accuracy and application throughput for in-home MIMO power line communication," in *IEEE International Symposium on Power Line Communications and Its Applications (ISPLC),* pp. 411-417, Apr. 2011.

[24] J. Cortes, A. Tonello, and L. Diez, "Comparative analysis of pilot-based channel estimators for DMT systems over indoor power-line channels," in *IEEE International Symposium on Power Line Communications and Its Applications (ISPLC),* pp. 372-377, Mar. 2007.

[25] M. Noh, Y. Lee, and H. Park, "Low complexity LMMSE channel estimation for OFDM," *Communications, IEEE Proceedings* , vol. 153, no. 5, pp. 645-650, 2006.

Bibliography

[26] L. Liu, X. Yang, J. Li, M. Bi, H. He, and W. Hu, "Experimental evaluation of pilot arrangement for channel estimation in OFDM systems," in *Communications and Photonics Conference and Exhibition, ACP*. Asia, pp. 1-6, 2011.

[27] Y. Zhao and A. Huang, "A novel channel estimation method for OFDM mobile communication systems based on pilot signals and transform-domain processing," in *IEEE Vehicular Technology Conference*, vol. 3, pp. 2089-2093, 1997.

[28] M. A. Tunc and E. Perrins, "Pilot based channel estimation and transform domain analysis in broadband PLC for smart grid," in *IEEE International Conference on Smart Grid Communications (SmartGridComm),* Oct 2013.

[29] J. Edmonds, Matroids and greedy algorithms, Math Programming 1. 1971.

Thank you for listening!

Questions?