ISPLC2007 Pisa Italy
2007 March 27

Keynote: Power line channels: frequency and time selective

Part 2- Noise Statististics of indoor PLC Channels

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What is a PLC system?

A communication system that uses power lines (wires) as its communication media.

PLC: Wireless-like System

- Radio (Wireless) Signal transmitted with Wires
  - CATV: energy is transmitted in coax cables.
  - ADSL: energy is transmitted along balanced wires.
  - PLC: energy is transmitted around unbalanced wires with branches and loads.
    - a wireless system using power-lines as a wave guide.
      A battery driven PLC modem may communicate with its plug off the power lines.
    - wires not designed for communications
    - wide variety of wiring topologies

Statistical treatment of power-line channel is necessary.

PLC: not a simple wireless system

- Super "Ultra Wide Band (UWB)" Signal
  - 2MHz～30MHz (λ =10m～150m)
    → bandwidth／center frequency 175%!
  - 10kHz～450kHz (λ =700m ～ 30km)
    → bandwidth／center frequency 200%!
- Propagation
  - Topology dependent propagation loss
    (not a simple distance based model)
  - Resonance and Absorbance
    (multi-path is not a single cause of frequency selectivity)
  - Time variant multi-path environment: often cyclostationary
    (in mobile radio scenario,
    this means construction/demolishment of buildings in 100-120 times a second)

PLC Noise

- Noise Source
  - **Wireless Systems:** thermal noise at receiver amplifiers.
  - **PLC Systems:** machine-made noise by electric appliances.
    - Interference from electric appliances, rather than simple noise
    - Estimation, Adaptation, and Cancellation are possible.

- Features
  - Non-Gaussian (less entropy)
  - Non-White (Frequency Dependent)
  - Non-Stationary (Time Dependent)
  - Noise waveforms at different frequencies,
    at different time-slots, and
    at different locations
    may have correlations.

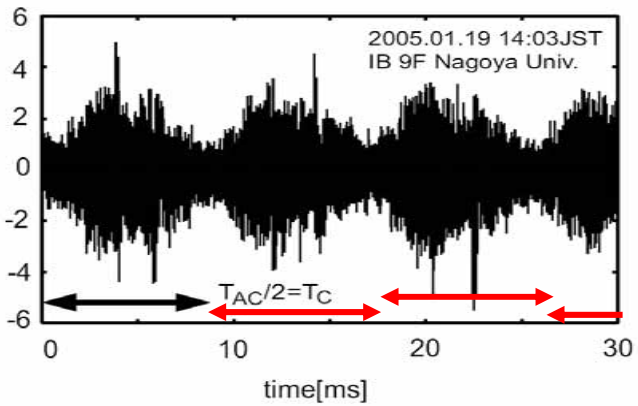
Some Studies on PLC Noise of our group

- Narrow-band (10kHz-450kHz)
  - Cyclo-stationary Gaussian noise model (ISPLC 1998,2000,2005,JSAC2006)
  - Signal and Receiver Structure for Cyclo-stationary Narrow-band Noise (ISPLC 2001)
- Wide-band (-30MHz)
  - Characteristics of Wide-band power-line noise based on the measurement (ISPLC 2003)
  - Signal and Receiver Structure for Cyclo-stationary Frequency Correlated Wide-band Noise (ISPLC 2004)
- Correlations of Noise at different Outlets
  - Correlations of noise waveforms at different outlets (ISPLC 2006)
  - Adaptive assignment of data at a transmitter and optimum reception at receivers. (ISPLC 2008?)

Narrow-band

Characteristics of PLC noise

- Peculiar characteristics of power-line noise
  - mainly caused by appliances
    - non-stationary
    - non-white



  - Statistic Feature of PLC noise
  - Simple, Tractable, and Accurate Mathematical Model

Narrow Band
(10kHz - 450kHz)

Narrow-Band PLC Renaissance

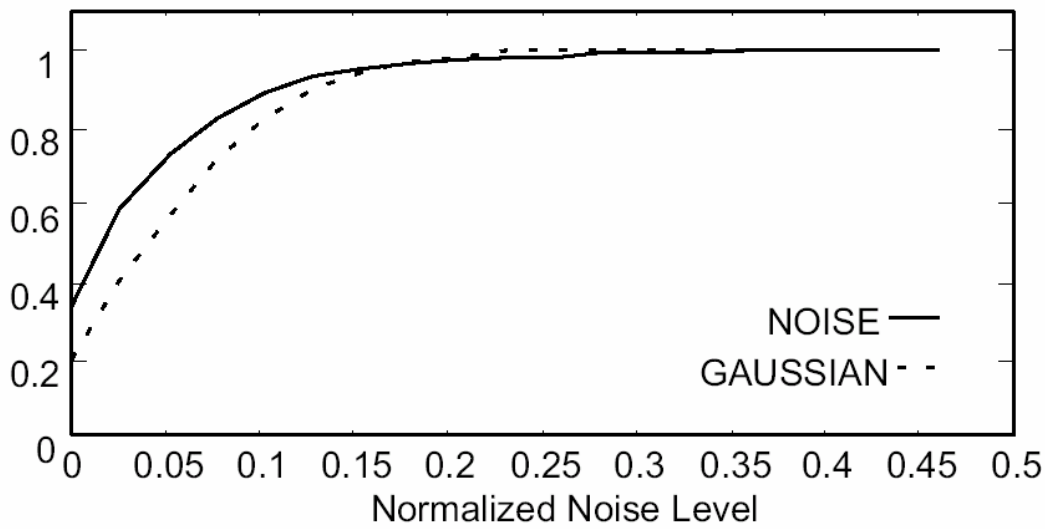
- Control / Remote Sensing in Wide Area
  - Low Speed
  - High Reliability

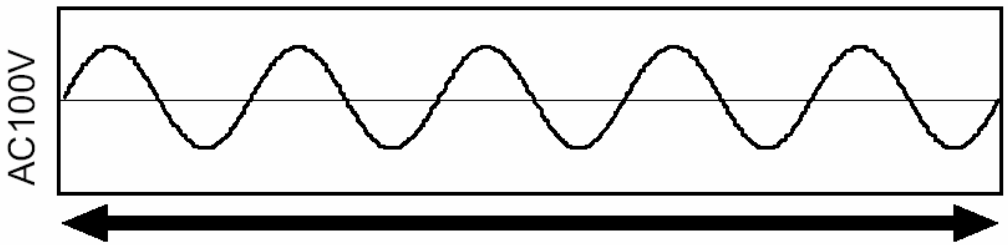
- Reserved Seat for PLC
  - 10Mbps < **802.11abg... , xDSL,** FTTH, PLC
  - 100Mbps < 802.11abg... , xDSL, **FTTH,** PLC
  - 10kbps > 802.11abg... , xDSL, FTTH, **PLC**

CDF of PLC Noise (1)

- If noise is measured at random timings, PLC Noise is Impulsive:
  - Higher Probability for Low-level noise and High-level noise
  - Lower Probability for Medium-level noise

  than Gaussian Noise





(C) Noise for phase of the observed duration

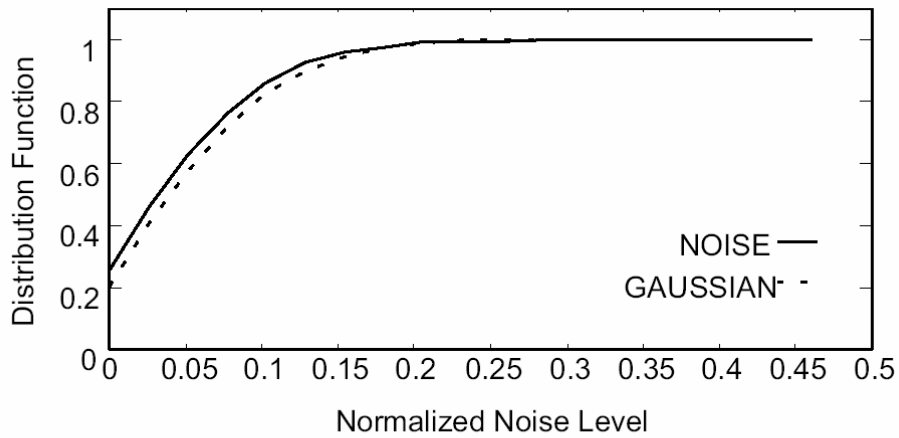
Non-Gaussian: if samples taken randomly

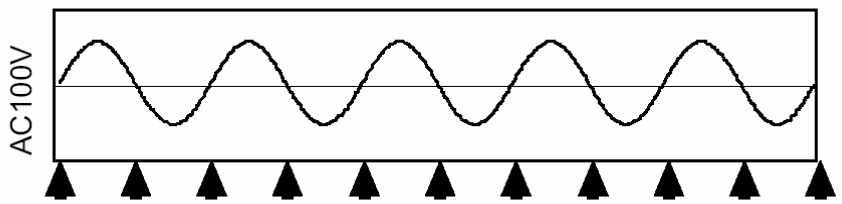
CDF of PLC Noise (2)

- PLC Noise is Gaussian
  - if sampled synchronously with mains AC
- If Gaussian
  - only (time-dependent) variance (instantaneous power)

$$\sigma^2(iT_S) = E[\eta^2(iT_S)]$$

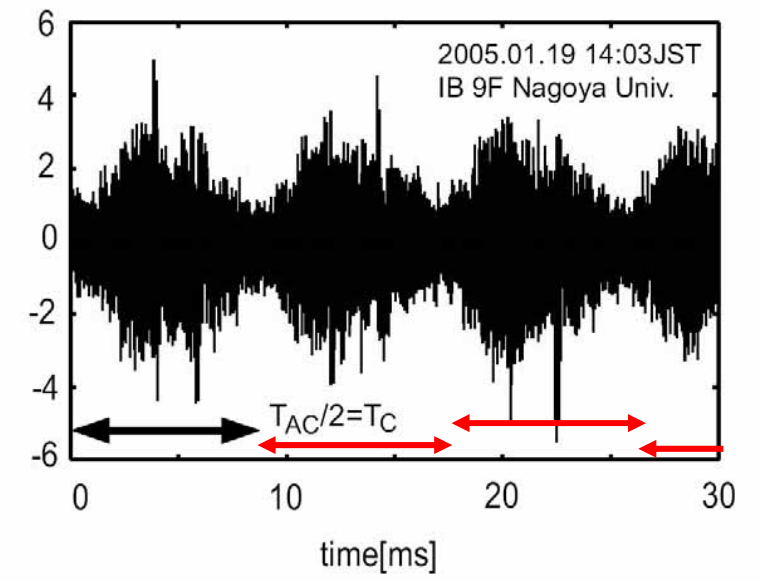
is necessary.





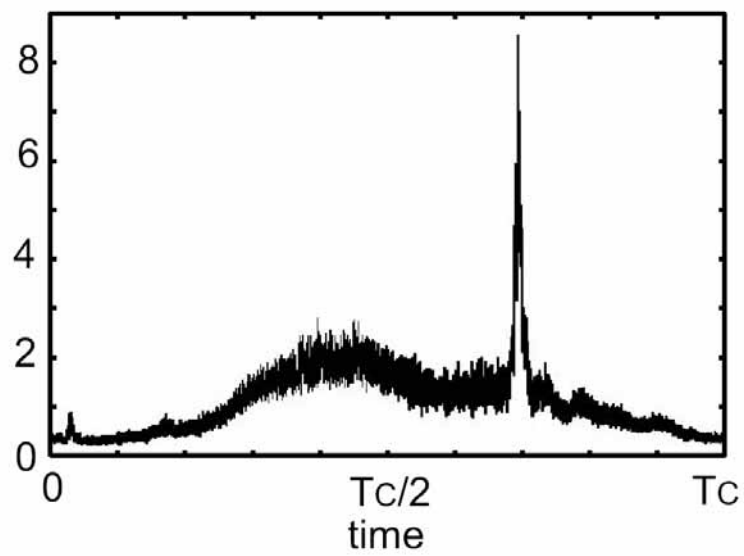
(A) Noise at same phase of AC voltage (0, 180, 360, • • •)

Variance (Instantaneous Power) as a cyclic function



Noise Waveform

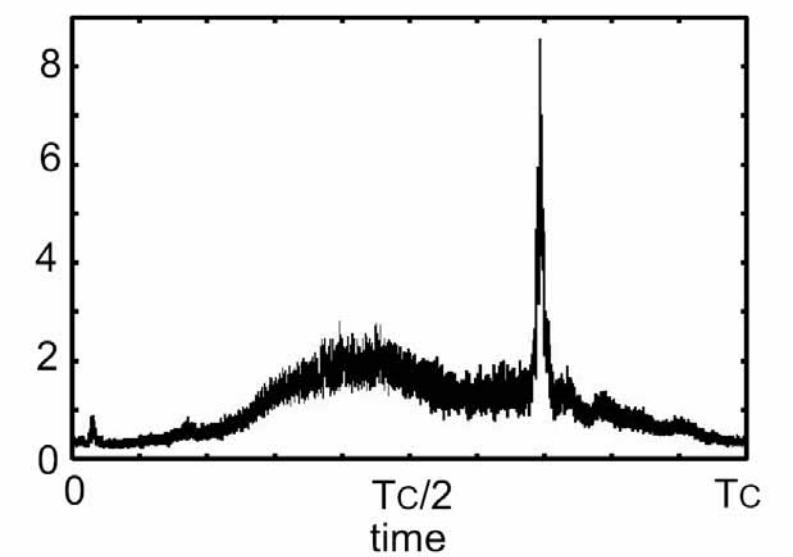
$$\eta(iT_S)$$



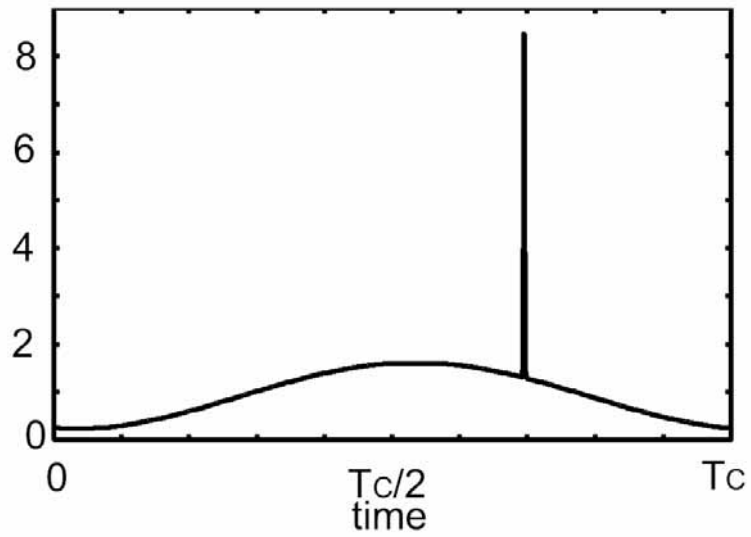
Cyclic Averaged Noise Power

$$\sigma_m^2(iT_S) = \frac{1}{2m}\sum_{j=0}^{2m-1}\eta^2(iT_S + jT_C)$$

Approximation of Instantaneous Power of PLC Noise



Cyclic Averaged Instantaneous Power of PLC Noise $\sigma_m^2(iT_S)$



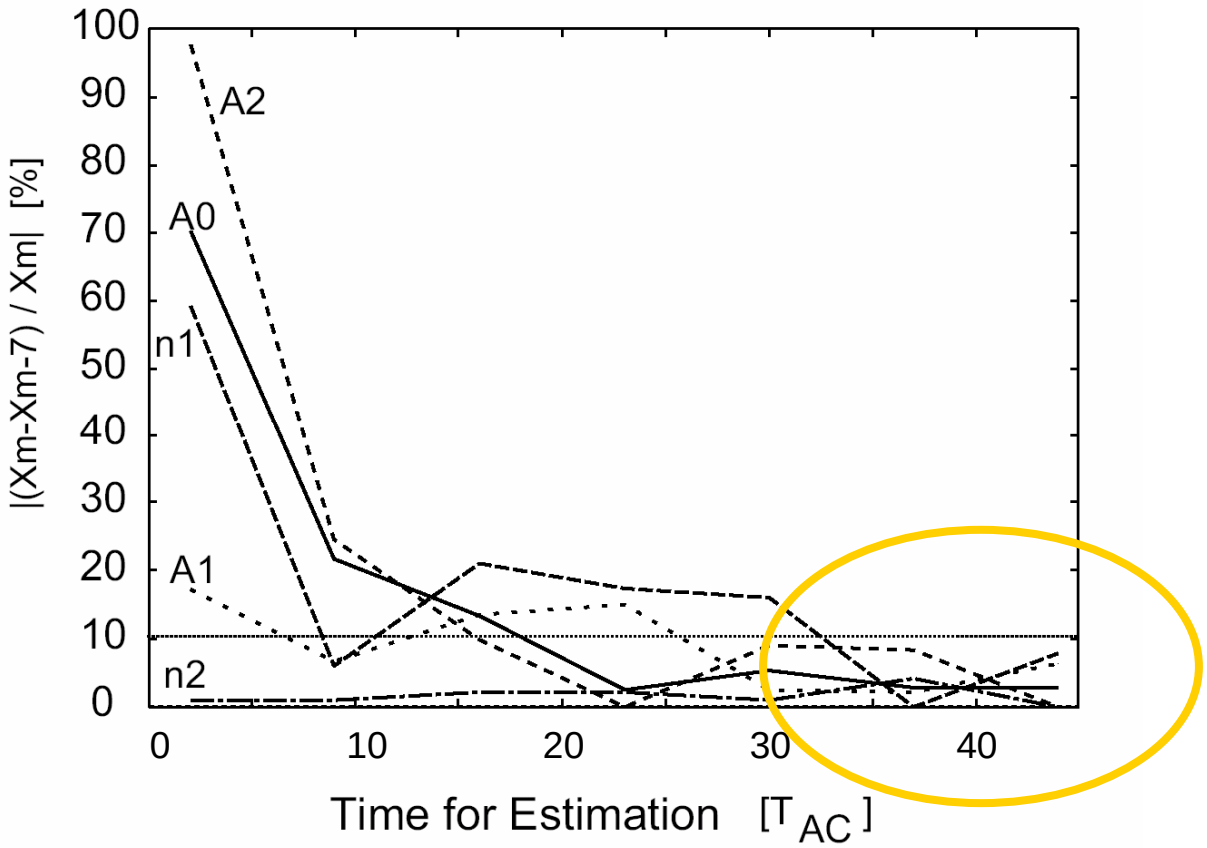
Approximated Instantaneous Power of PLC Noise $\hat{\sigma}^2(t)$

$$\hat{\sigma}^2(t) = \sum_{l=0}^{L-1} A_l \left| \sin(\pi t / T_C + \theta_l) \right|^{n_l}$$

$L = 3$

l	A_l	θ_l [deg]	n_l
0	0.23	–	0
1	1.38	-6	1.91
2	7.17	-35	1.57×10^5

Convergence of the Derived Parameters



about 40-50 cycles (1 second) to define parameters

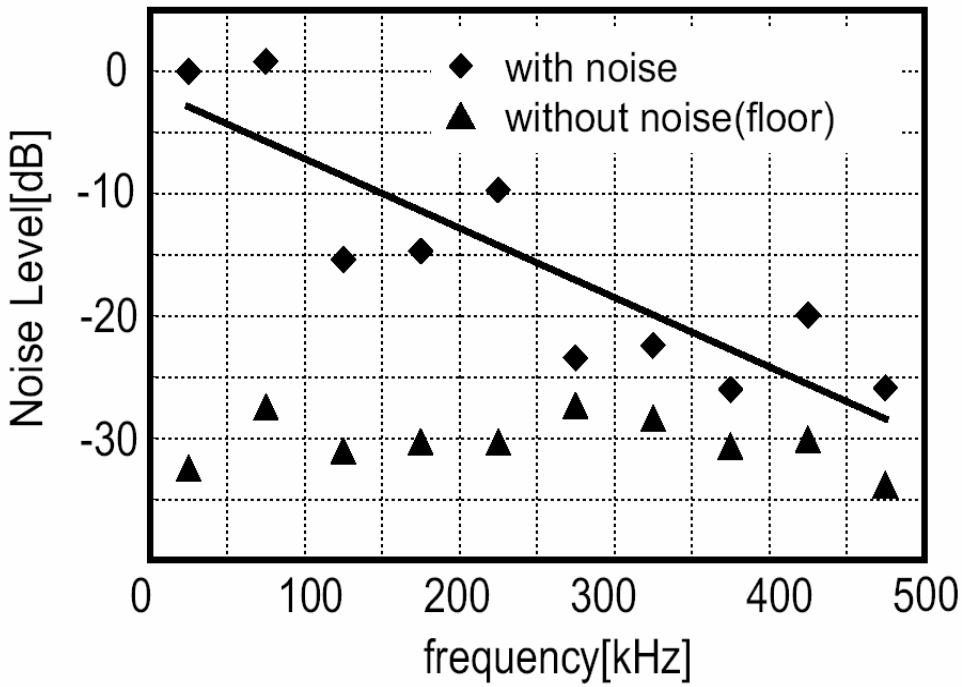
Approximation of Power Spectrum Density

- Noise Power for a given time-frequency

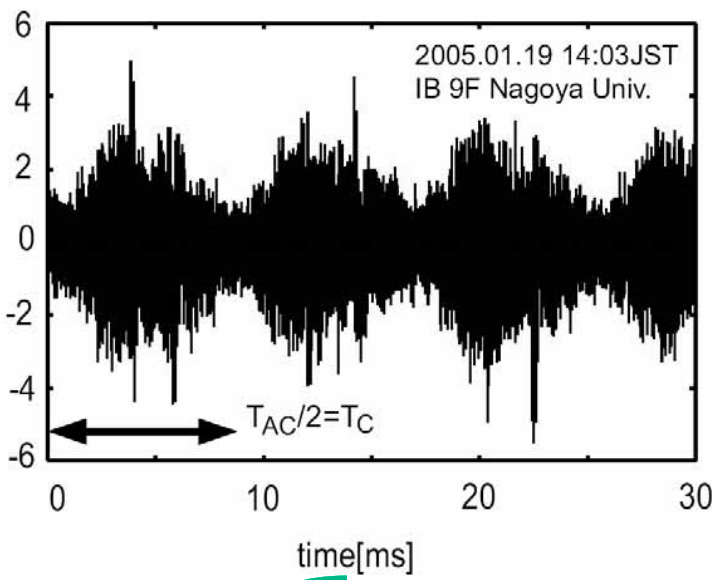
$$\sigma^2(t, \quad f) = \sigma^2(t)\alpha(f)$$

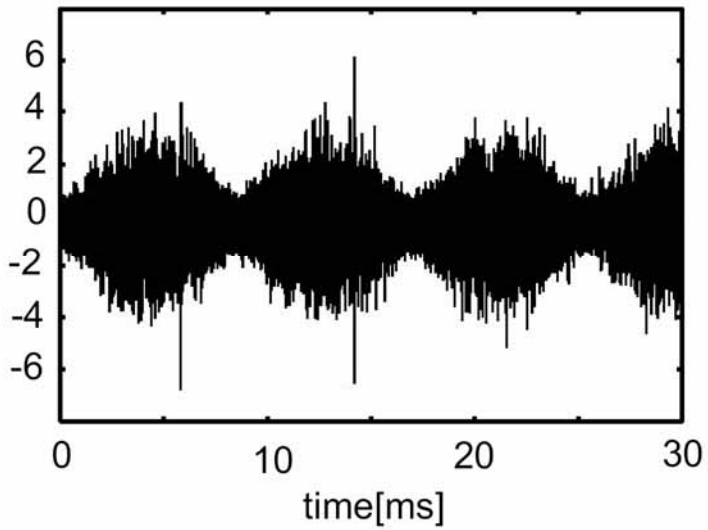
- Linear Approximation of PSD in dB

$$\ln \alpha(f) = -af + C \qquad \text{for} < f$$



Computer Simulated PLC Noise

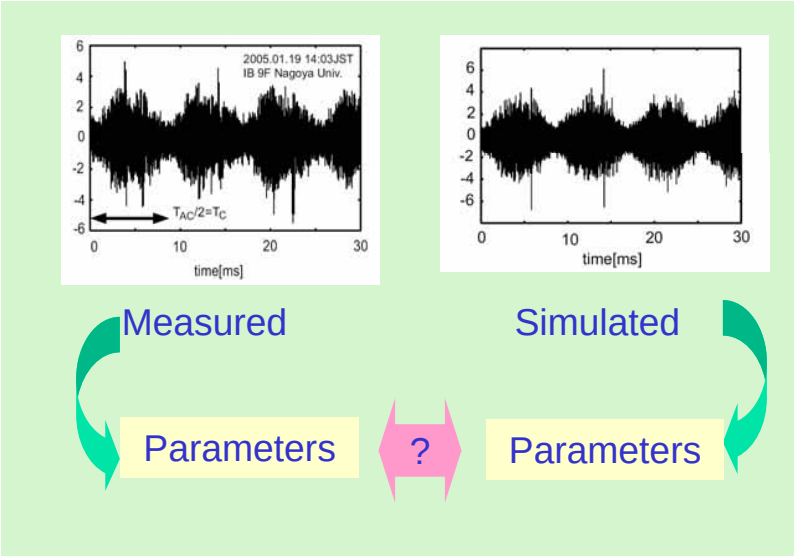


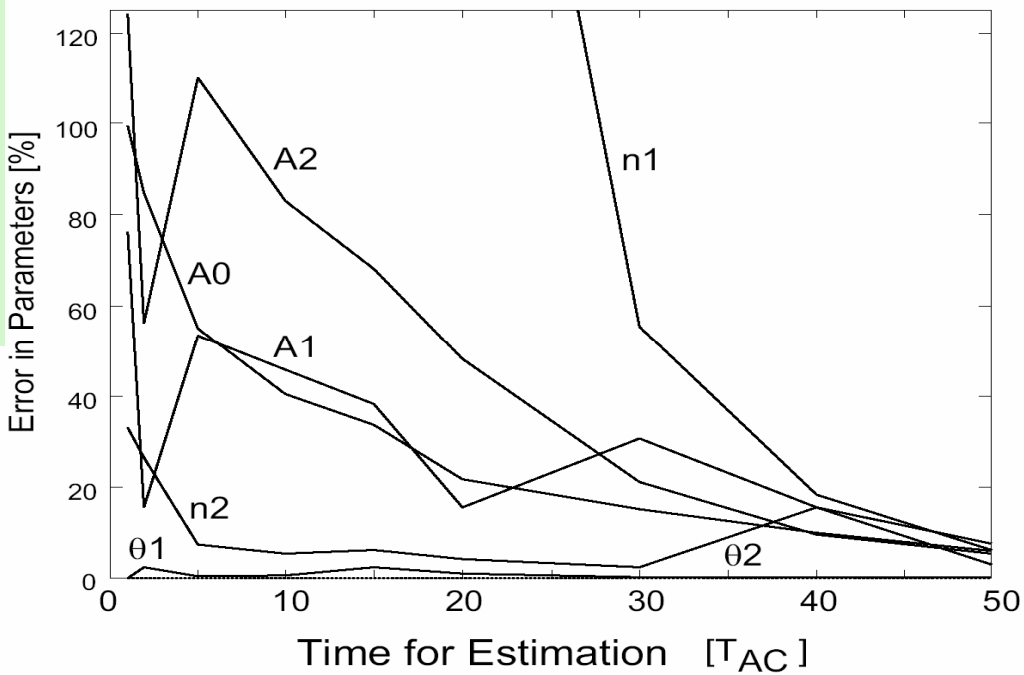


$L=3 \quad a=1.2\times10^{-5}$

l	A_l	θ_l [deg]	n_l
0	0.23	–	0
1	1.38	-6	1.91
2	7.17	-35	1.57×10^5

Robustness of Parameters





Summary

Narrow-band

- Approximations
  - Cyclostationary Gaussian
  - Linear Function for PSD in dB
- Simple Mathematical Representation of Narrow-Band PLC noise
  - 8-parameters
  - Necessary Observation: about 1second
- Benefits
  - Benchmark for Design/Evaluation of PLC Systems
  - Better Understandings of PLC Noise

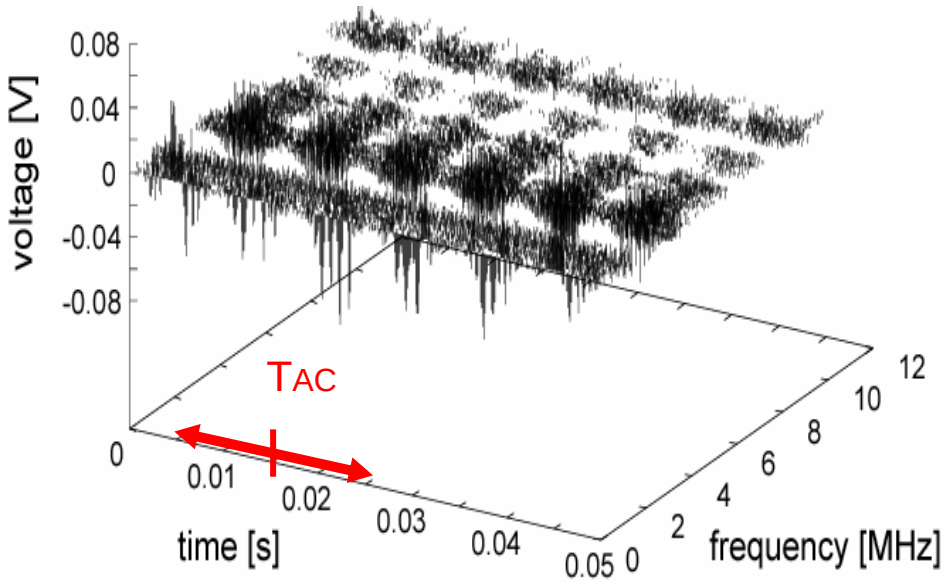
Future Works

Narrow-band

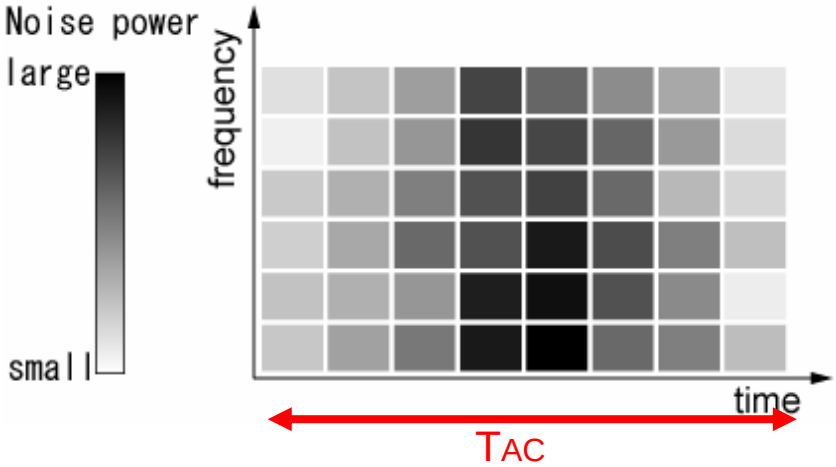
- Detailed Analysis in Frequency Domain
- Measurement Campaign in Various Environment
  - Data-base of Parameters
  - Standard Parameter Sets

Noise
in time-frequency plane

Wide-band

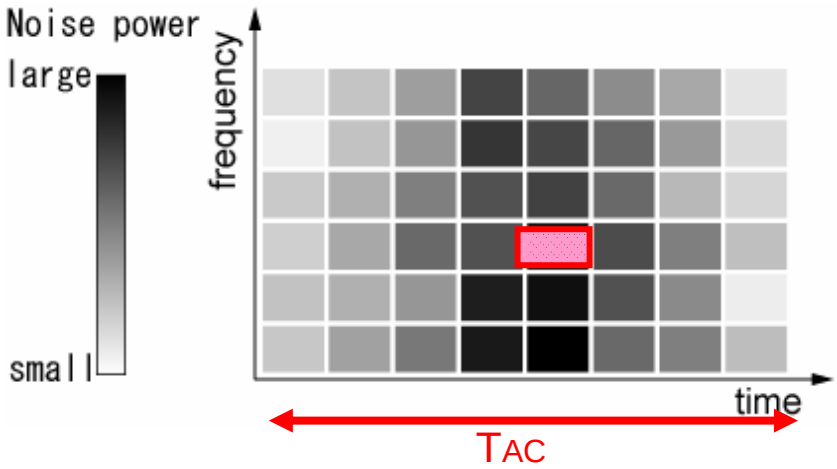


・Non-white: concentrated in lower frequency band.
・Cyclic change synchronous with a period TAC/2.



Performance Improvement under non-white/non-stationary Noise

- If noise statistics of each frequency-time cell (at a receiver) are known
  - by a receiver → optimum reception .
  - by a transmitter → adaptive modulation/coding
- Estimation of noise statistics is possible
  - by cyclic features
  - by the observation at vacant frequency/time slots.



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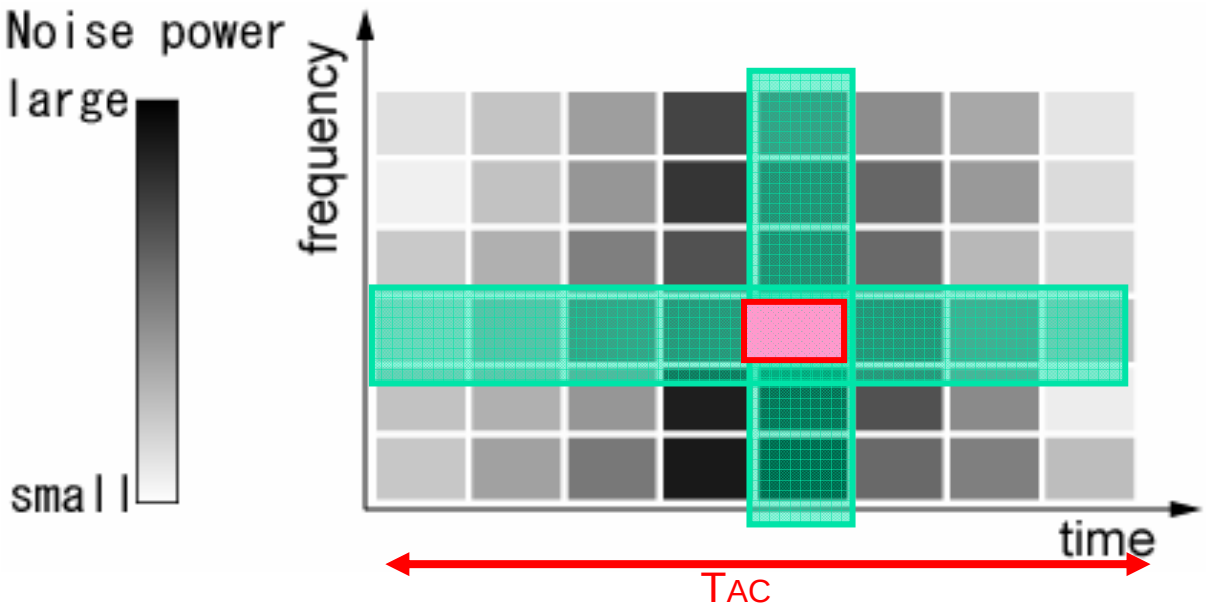
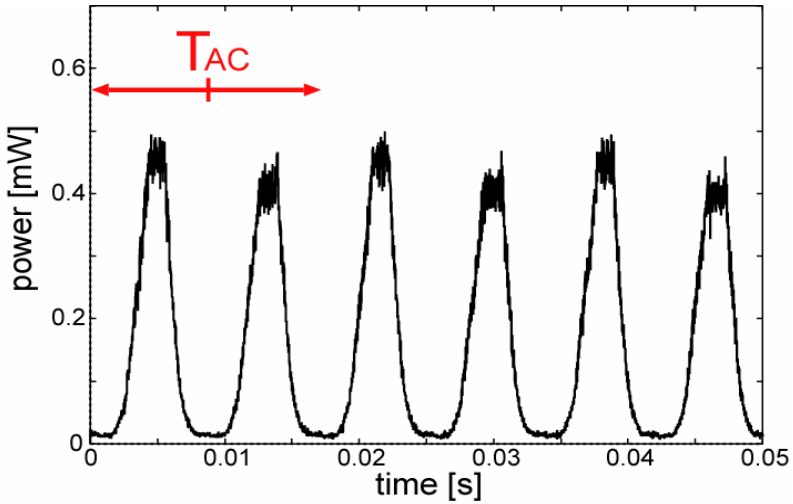
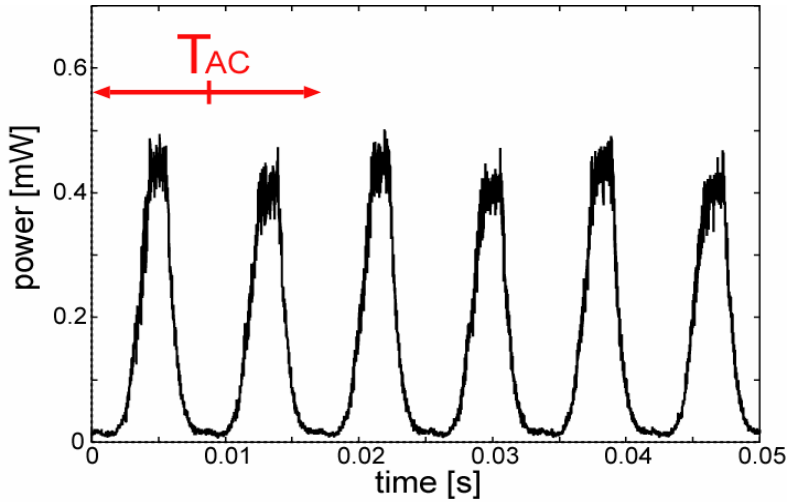


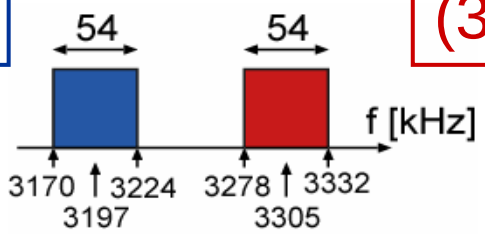
Instantaneous Power of Band-Limited Noise at different frequency sub-bands.

Measured at 22:00 on Nov. 25 2002.





(3.197MHz,54kHz)

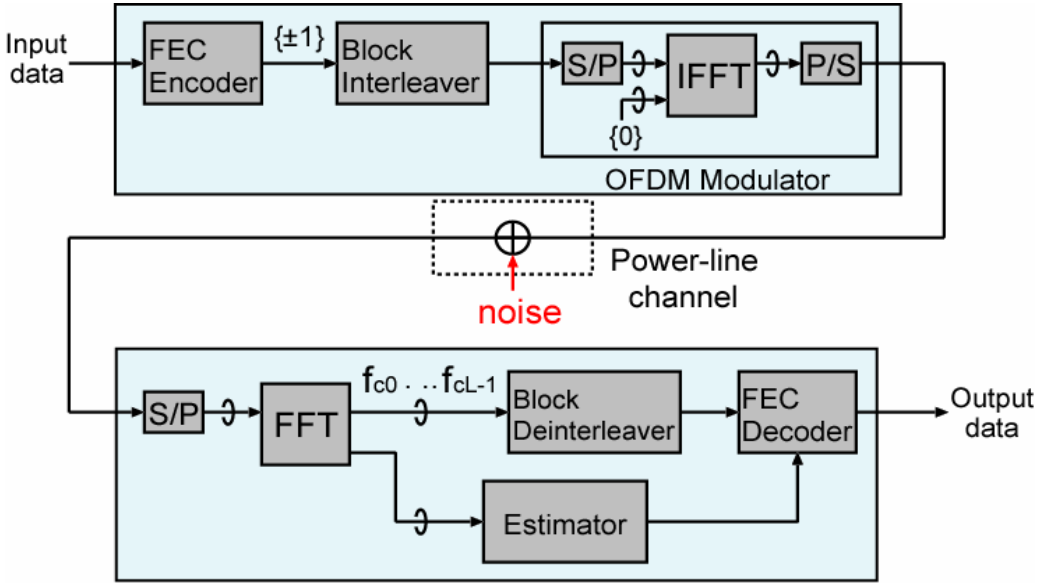


(3.305MHz,54kHz)

- Cyclo-Stationary with a period TAC/2.
- Instantaneous noise power in different frequency looks alike.

Simple Example

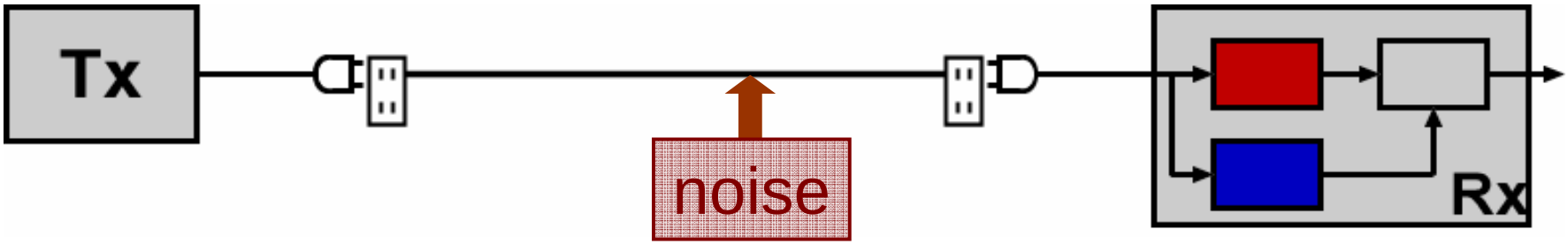
- OFDM: frame $=T_{AC}/2$
- Intentional vacant sub-channels
- FEC
  - Simple M repetition
- Interleaver
  - Mapping of a coded bit as far as possible in time-frequency plane



- FEC Decoder
  - Estimates of noise variance of each cells used for weighting.
- Estimation of noise variance
  - cyclic average of the noise variance
  - at the vacant sub-channel
  - for K frames.

System parameters for the simple examples

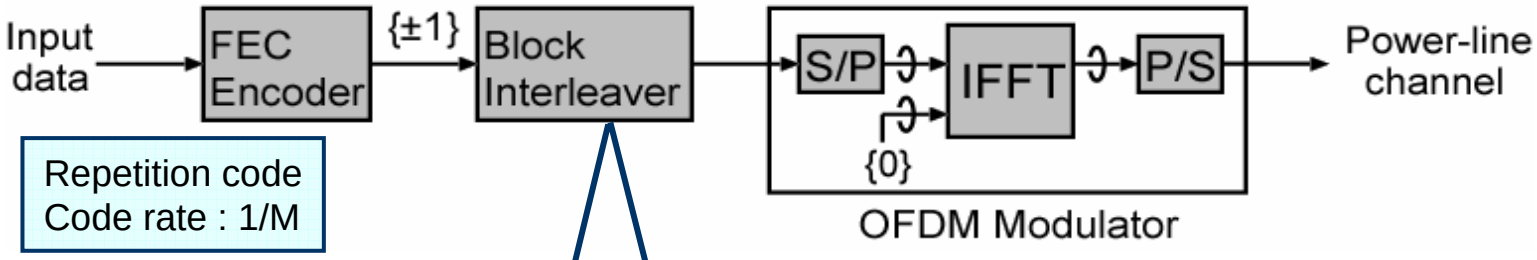
The number of subcarriers (communication band / outband)	2 (1/1)
The number of symbols in a frame	450
The number of frames to estimate the noise	1,5, 10,50
Code rate	1/3



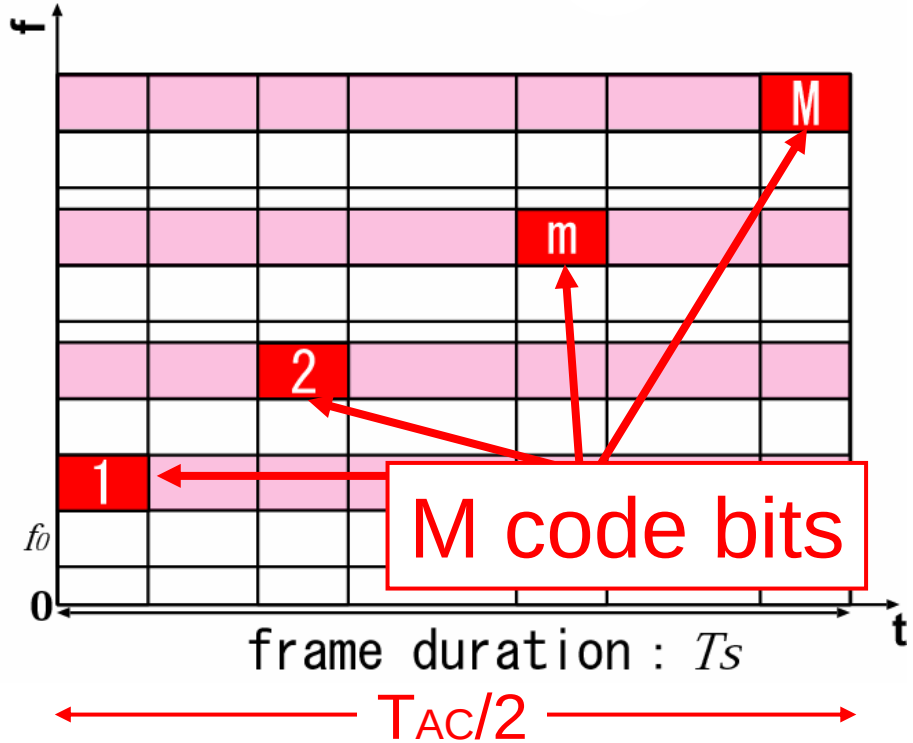
Real measured power-line noise

- Environment A
- Environment B

Transmitter



Repetition code
Code rate : 1/M

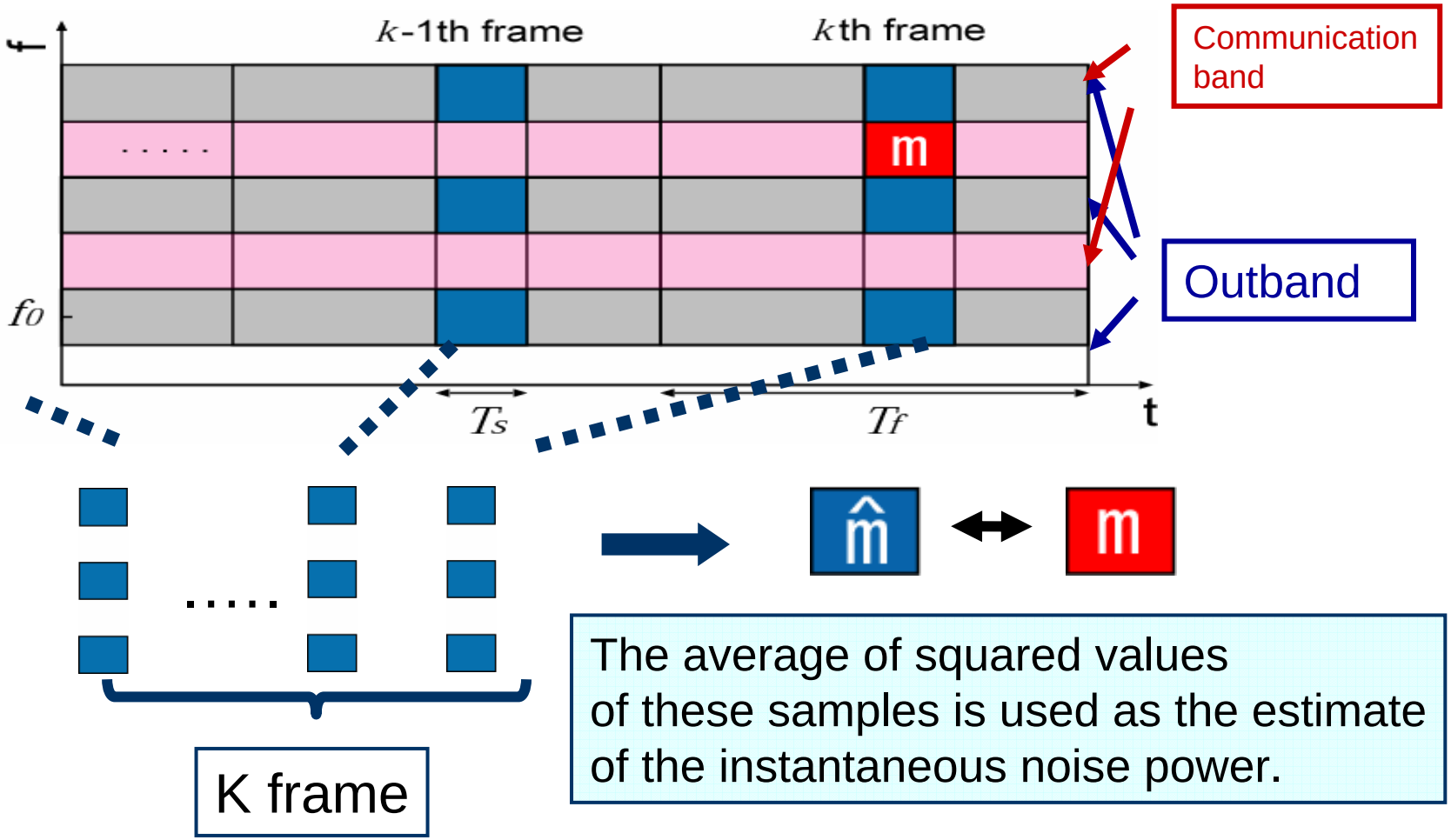


One frame = $T_{AC}/2$

Mapping rule：

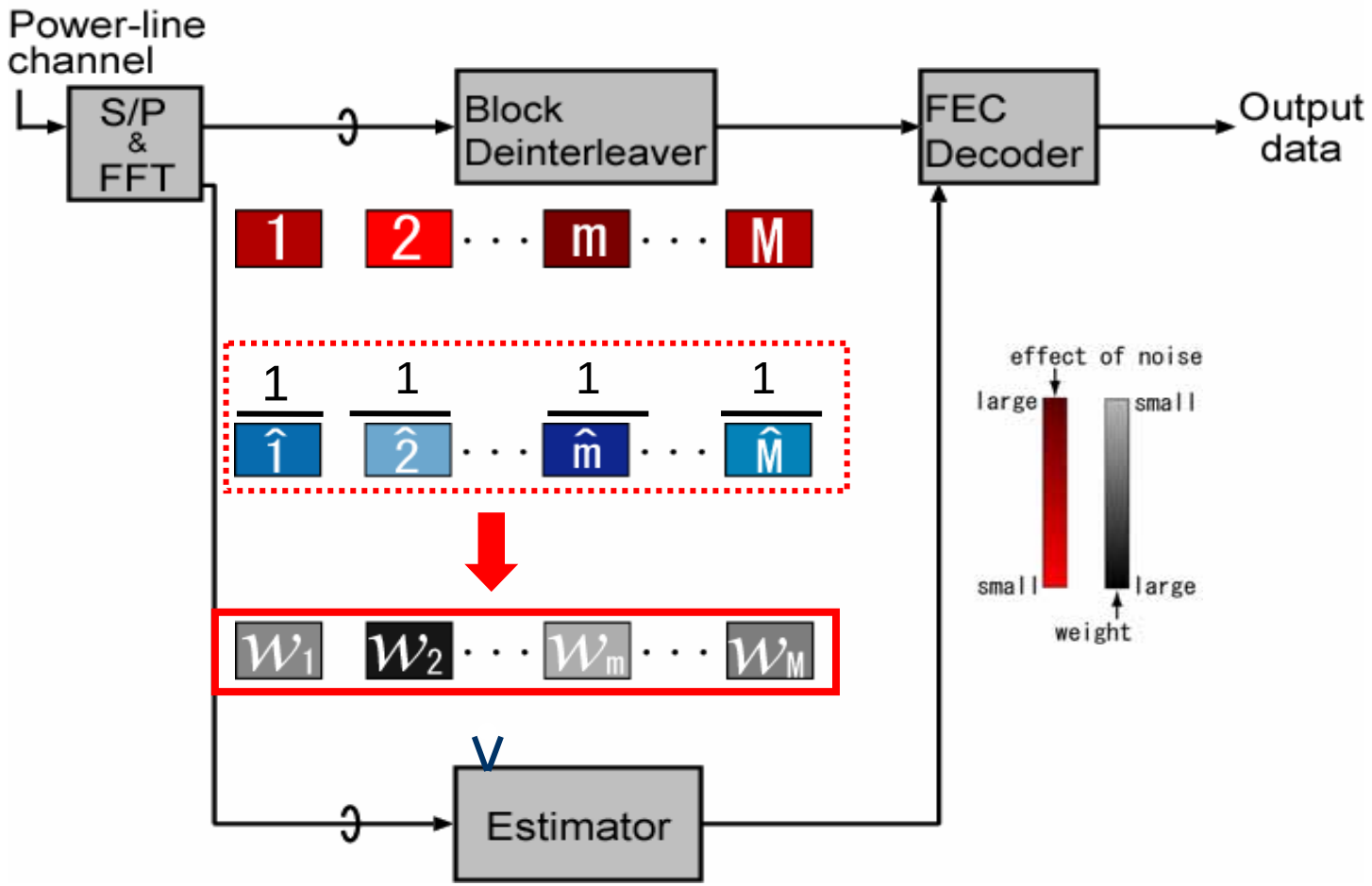
each bit in a code word is tried to be located as far as possible in time-frequency space

Estimation method

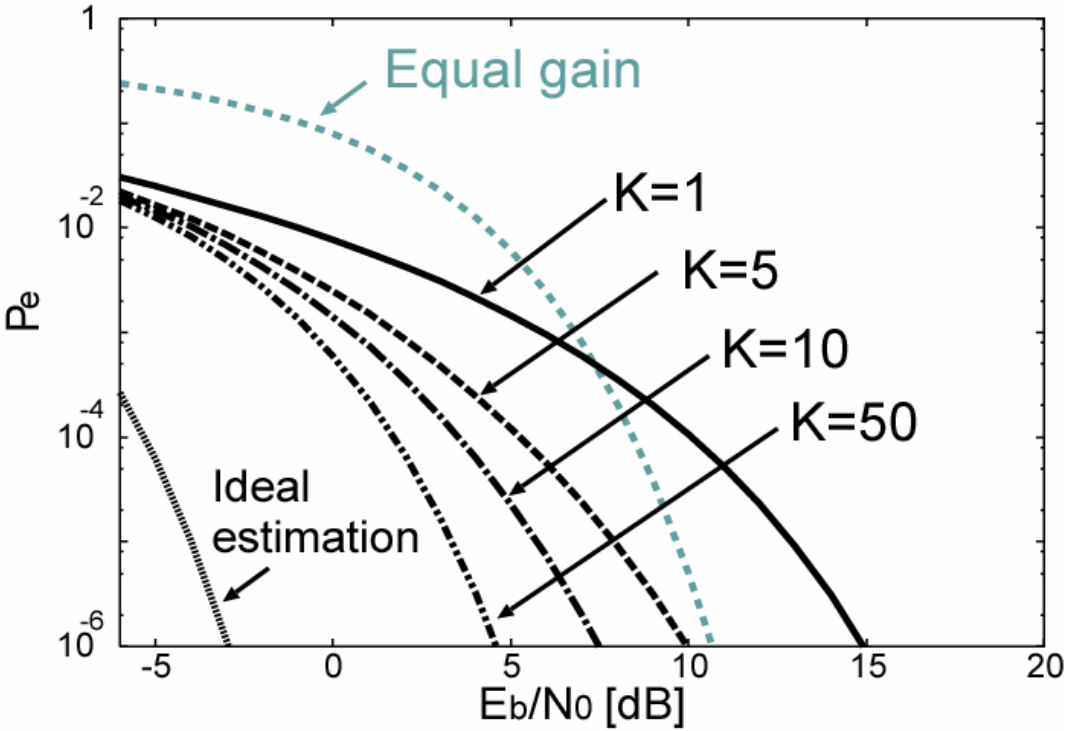


The average of squared values of these samples is used as the estimate of the instantaneous noise power.

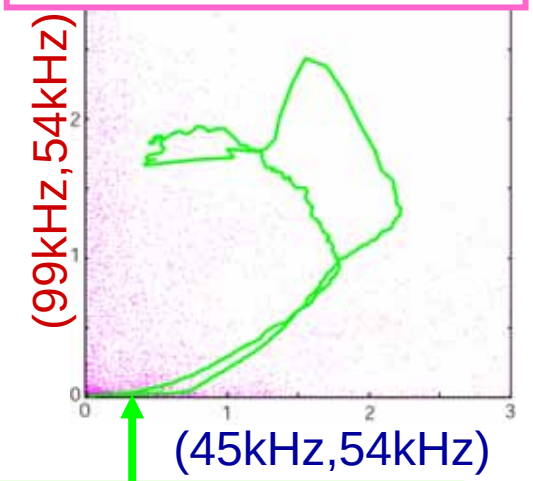
Receiver


Power-line channel
S/P & FFT
Block Deinterleaver
FEC Decoder
Output data
1
2
m
M
1
1
1
1
effect of noise
large
small
small
large
weight
Estimator

BER Performance (Environment A)

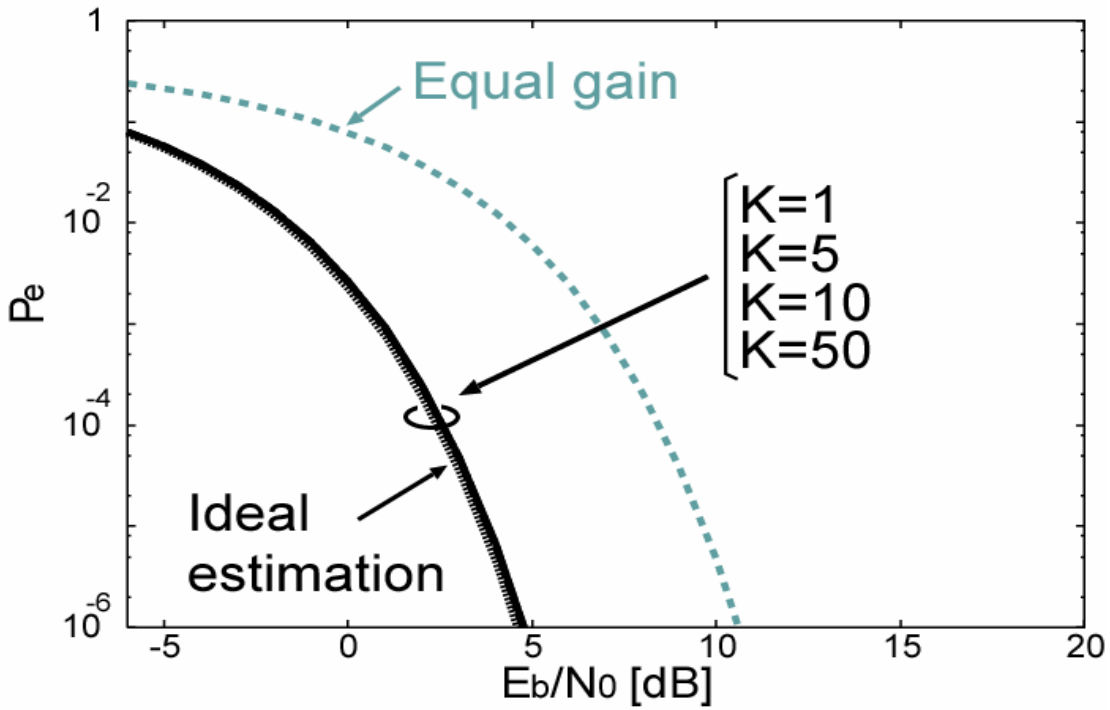


Instantaneous noise power
Correlation coefficient : 0.34

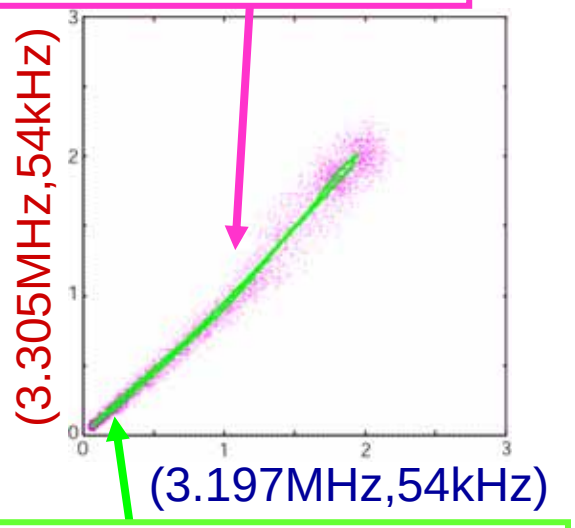


Cyclic-average noise power
Correlation coefficient : 0.75

BER Performance (Environment B)



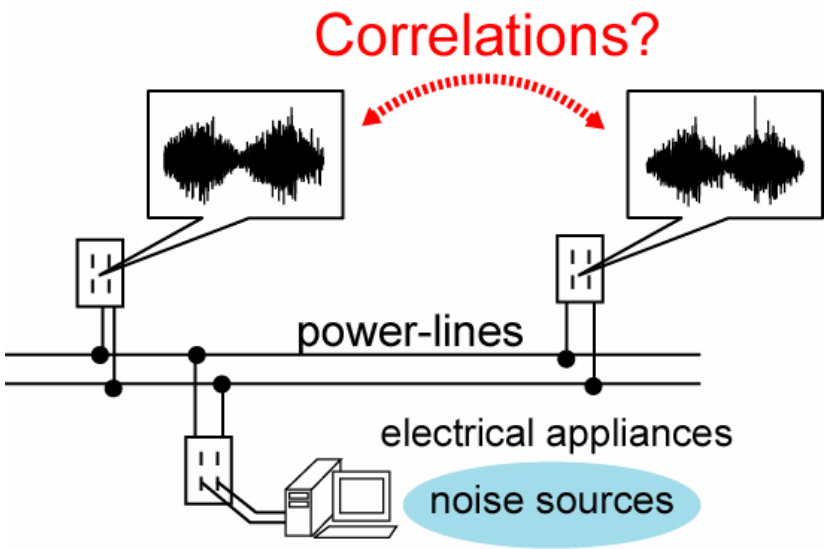
Instantaneous noise power
Correlation coefficient : 0.99



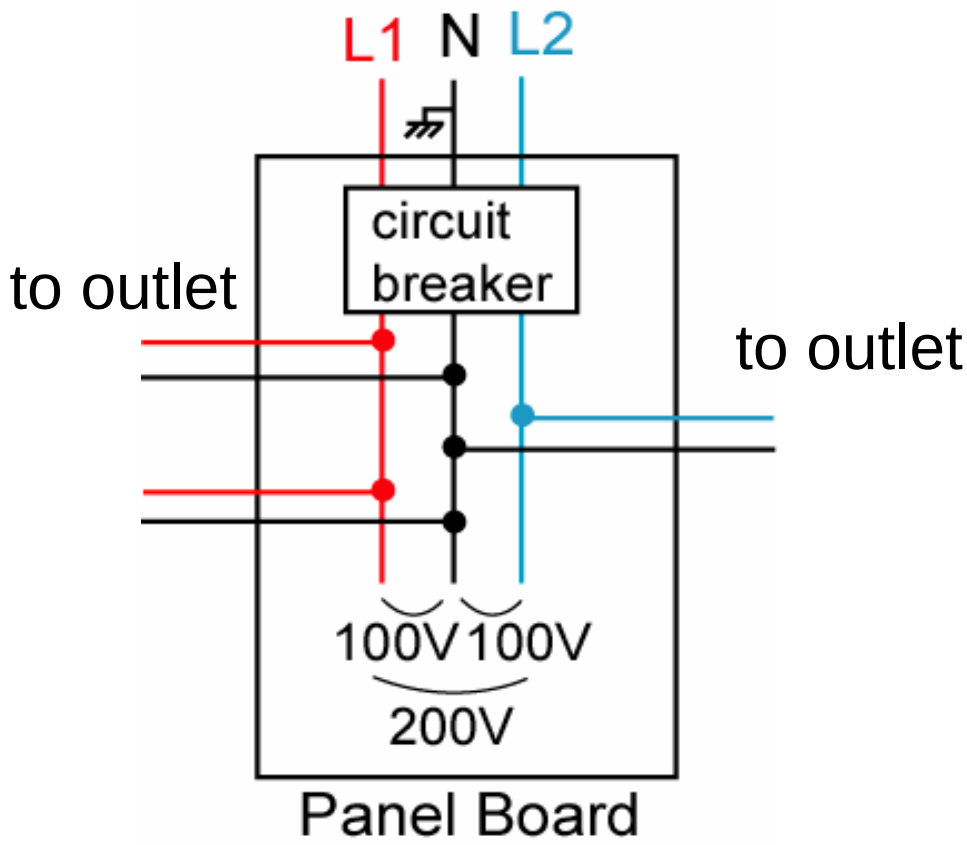
Cyclic-average noise power
Correlation coefficient :0.99

Relationship of noise waveforms

- Noise waveforms at different outlet
  - mainly caused by the same electrical appliances
  - Noise waveforms may have correlations

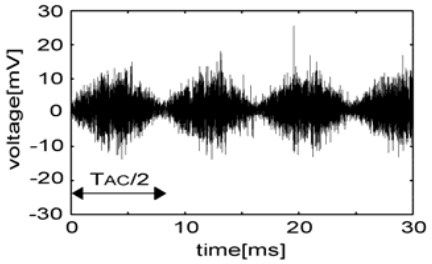


Typical cable structure in Japan

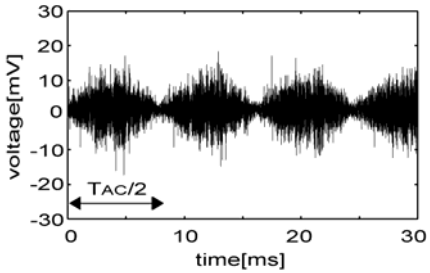


- Three-wire single-phase
  AC frequency: 60Hz

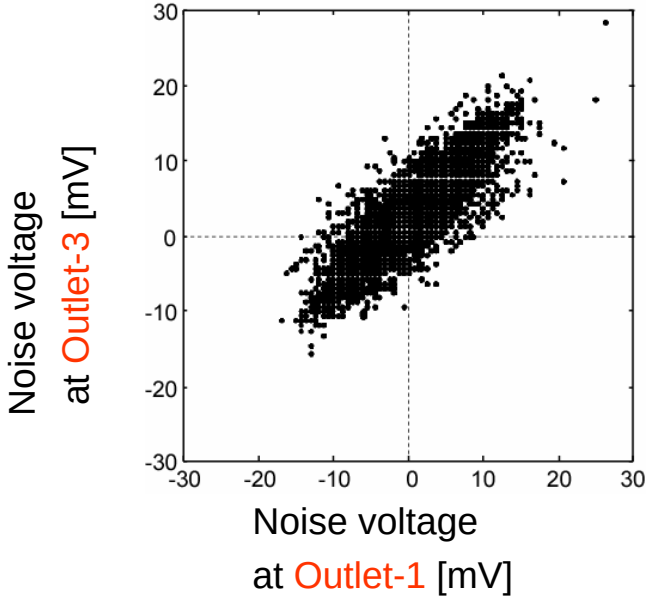
Case I (same mains phase/different branch)



Noise at Outlet-1



Noise at Outlet-3



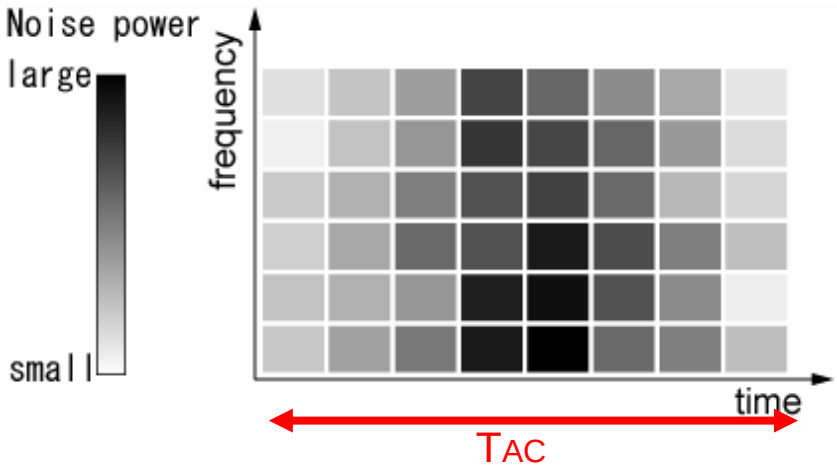
Correlation coefficients

- instantaneous noise voltages: $\rho = 86\%$
- instantaneous noise powers: $\rho_{\text{power}} = 77\%$
- cyclic-averaged noise powers : $\tilde{\rho} = 98\%$

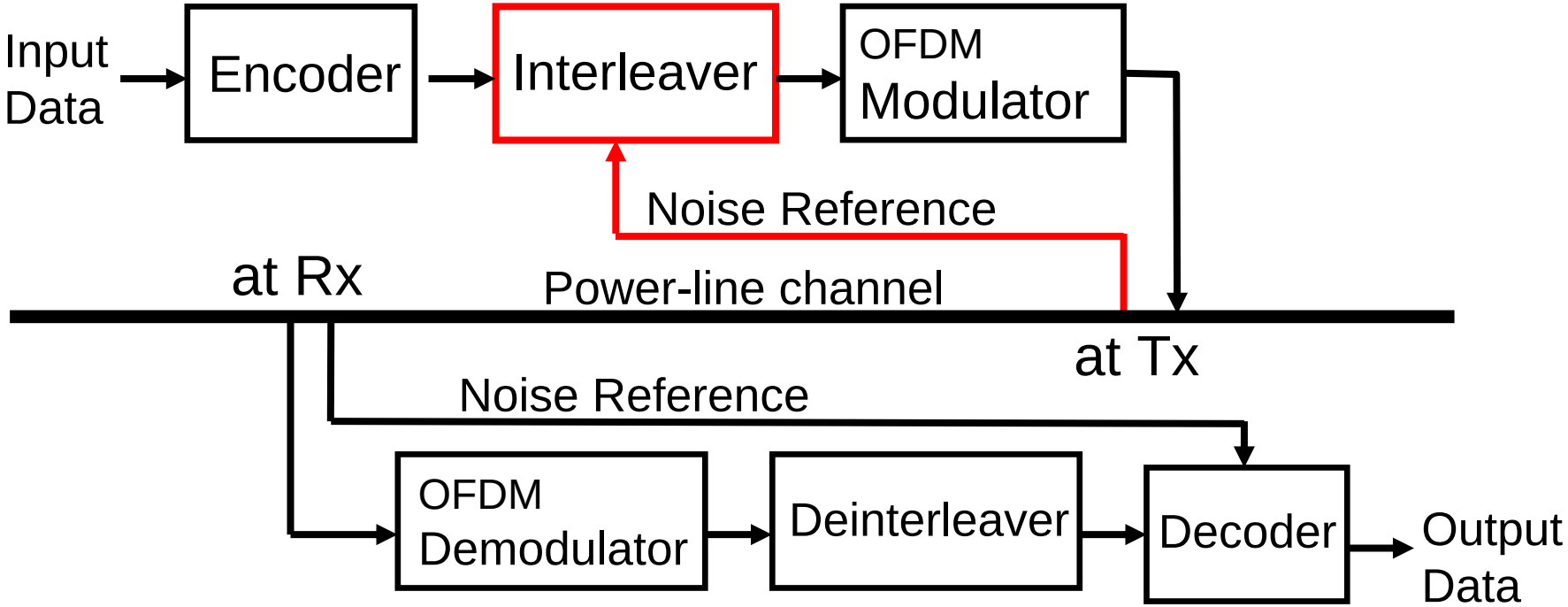
High correlations

Performance Improvement under non-white/non-stationary Noise

- If noise statistics of each frequency-time cell (at a receiver) are known
  - by a receiver → optimum reception .
  - by a transmitter → adaptive modulation/coding
- Estimation of noise statistics is possible <u>even at a transmitter</u>
  - because of the non-independence of noise at different location



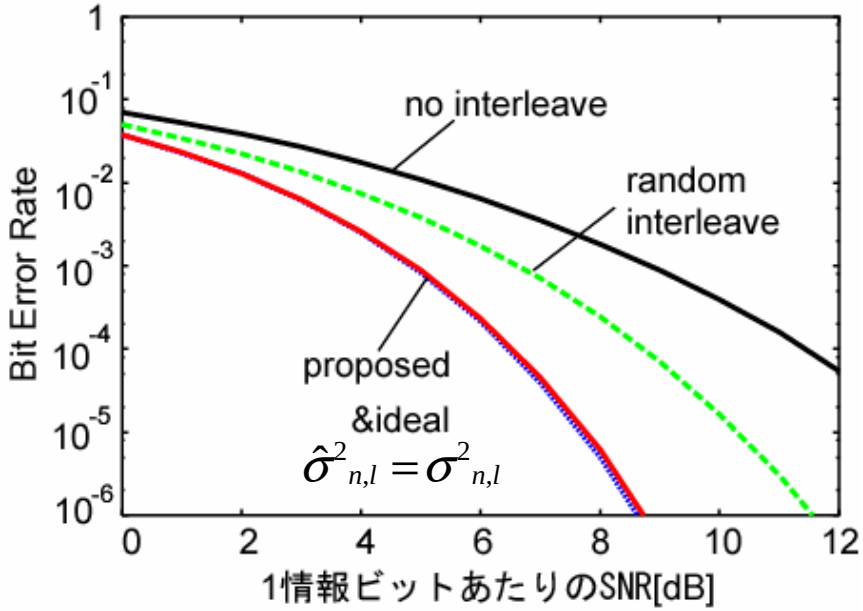
Adaptive data assignment



Parameters for numerical examples

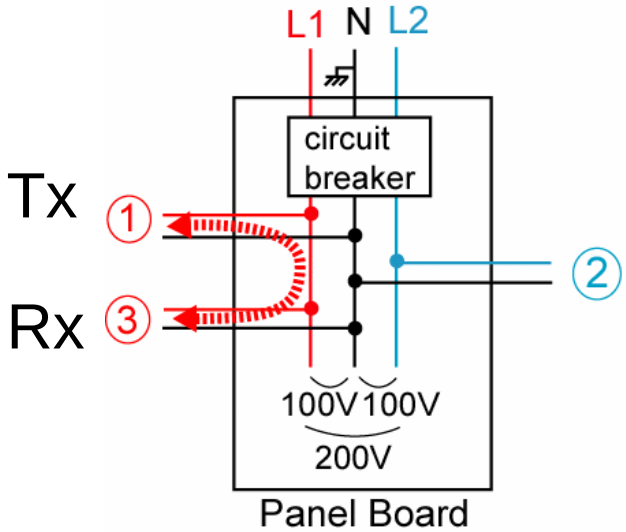
Parameters	
Number of Subcarriers	4
Symbols/Frame	450
Coding (Repetition) Rate	1/3
Freq. of the Lowest Subcarrier	250kHz
Bandwidth	54kHz

Bit Error Rate（High Correlation）

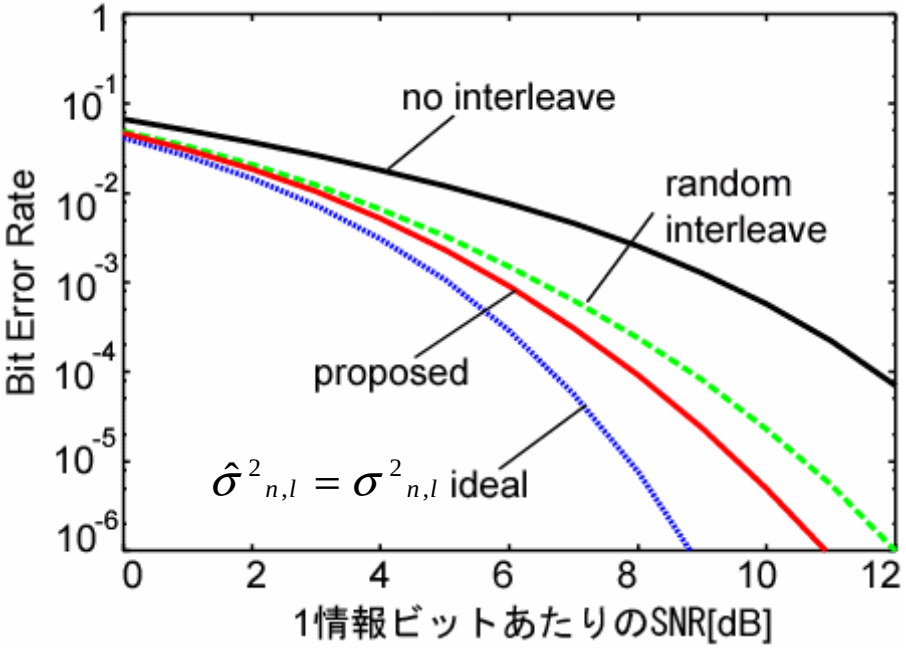


周期的平均電力

相関係数：97%

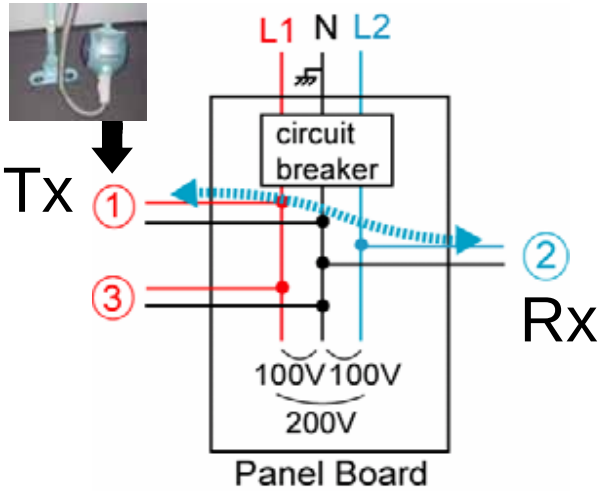


Bit Error Rate（Low Correlation）



周期的平均電力

相関係数：57%



PLC for researchers

Much more ***Interesting*** environment than conventional wireless

- Variety of PLC systems
  12V to Mega Volts / from a submarine to an aero plane.
- Interesting Noise Features
  Not Internal thermal Noise, but external machine made noise.
  - Non-stationary, Non-white, and Non-Gaussian.
  - Estimation, Adaptation, Cancellation.
- Interesting Propagation
  Radio System using power-lines as a guide-way
  - Cyclic Variation ←estimation, adaptation
  - Different Zoning Algorithm (not the same as cellular radio)
  - intra-branch, inter-branch, inter-phase, and inter-network propagation
- Super "Ultra Wide-Band"
- Coexistence
  Cognitive, DYSPAN (Hottest Topic for wireless systems)

We need co-operation with researchers of different fields who speak different technical languages.

Thank you for your interests.

Vi ringrazio molto.

御清聴ありがとうございました

Mi dankas vin pro via atenta aŭskulto.