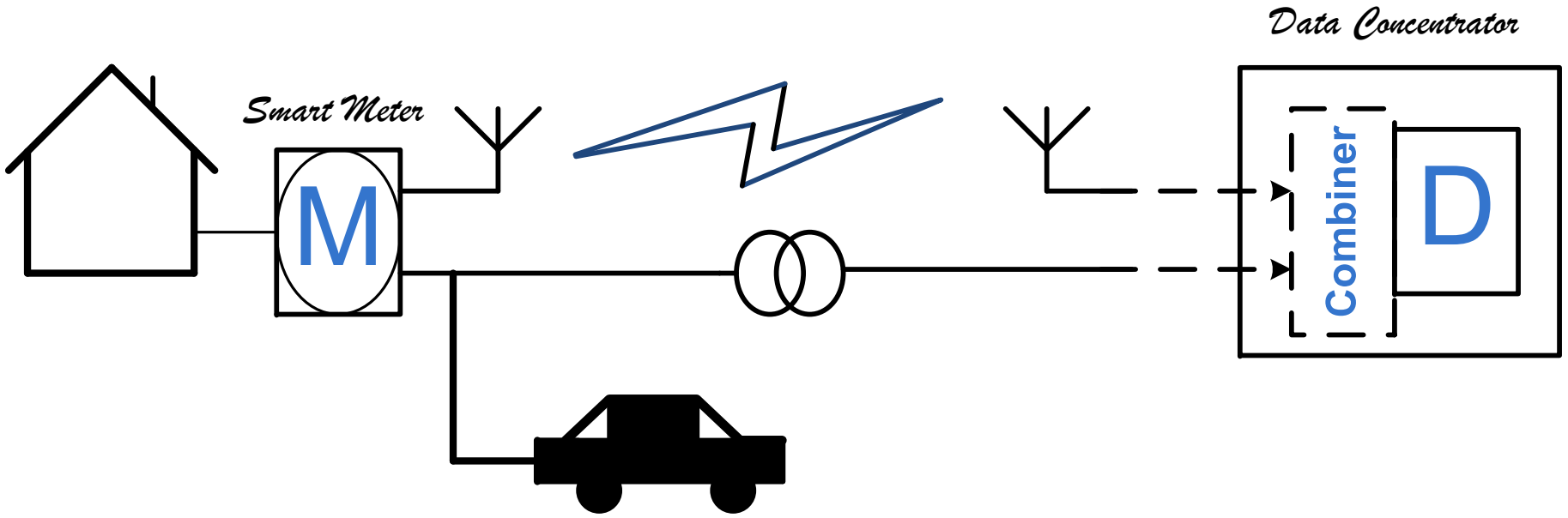
Efficient Diversity Technique for Hybrid Narrowband-Powerline/Wireless Smart Grid Communications

Mostafa Sayed, and Naofal Al-Dhahir
University of Texas at Dallas
Ghadi Sebaali, and Brian L. Evans,
University of Texas at Austin

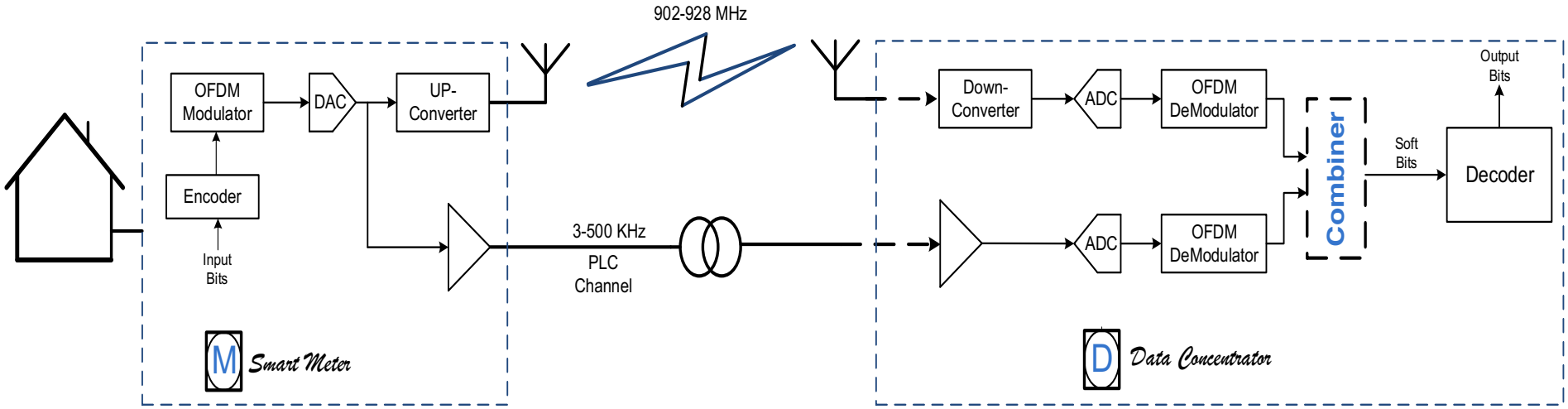
Smart Grid Communications



Focus: neighborhood-area smart utility network between a data concentrator and smart meters along two paths:

1) Low-voltage power lines in 3-500 kHz band
2) Unlicensed 902-928 MHz wireless band

PLC/Wireless Diversity

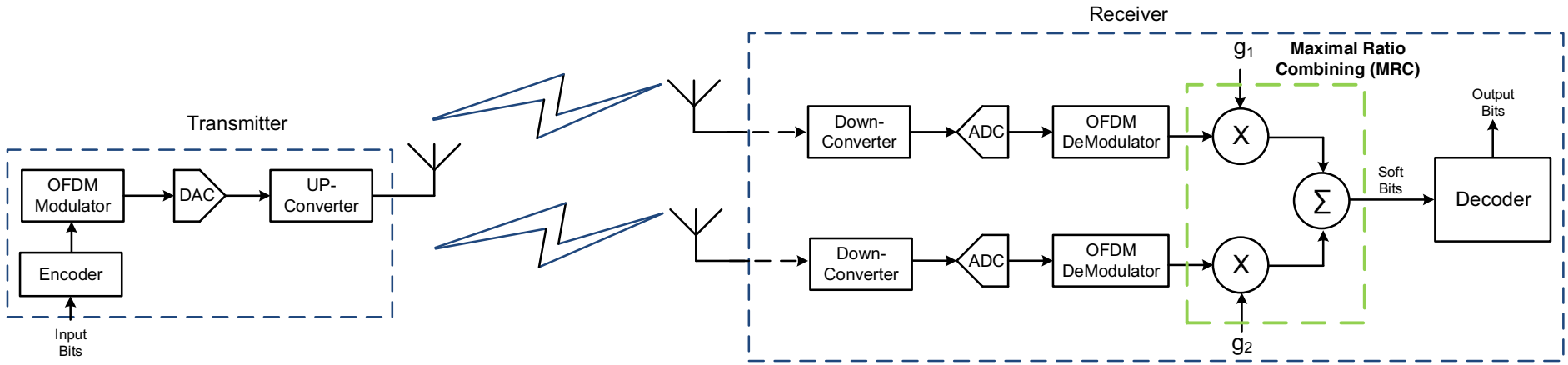


Simultaneous PLC/wireless transmissions using low-voltage power lines in 3-500 kHz band and unlicensed 902-928 MHz wireless band

- **Goal:** Improve reliability of smart grid communications using PLC/wireless receive diversity combining methods

Symmetric Diversity Combining

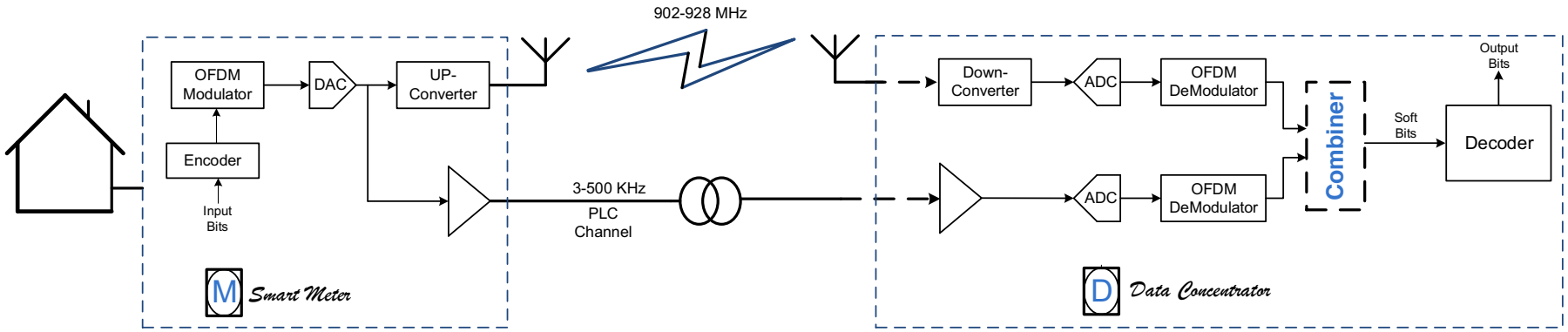
Old: Combining of two wireless links



- Same channel, noise, and interference statistics
- Same Average SNR

Asymmetric Diversity Combining

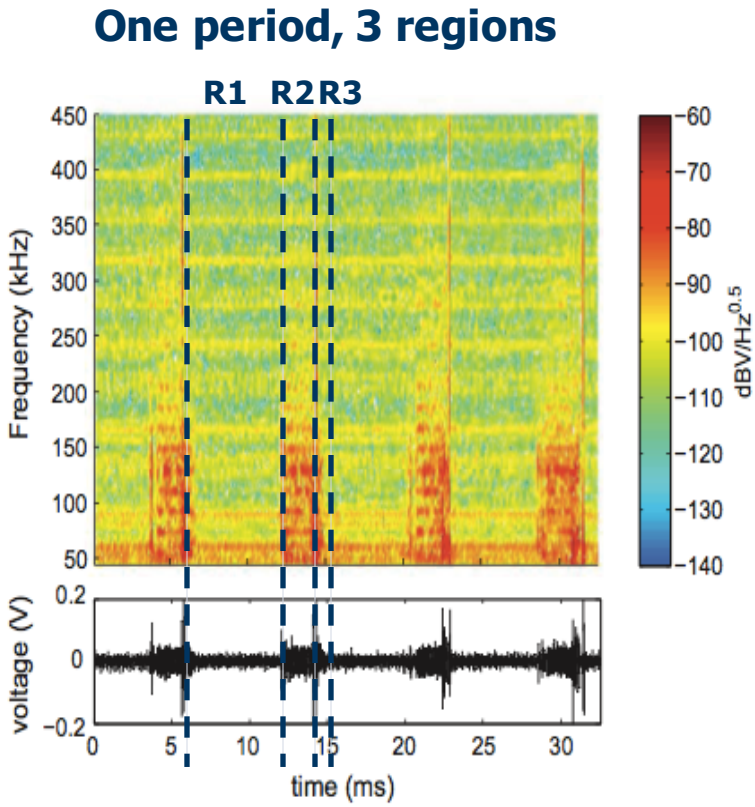
New : PLC/Wireless combining for Smart Grid Comm.

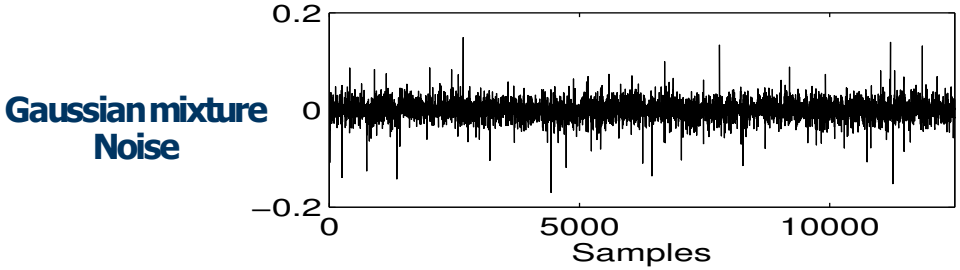


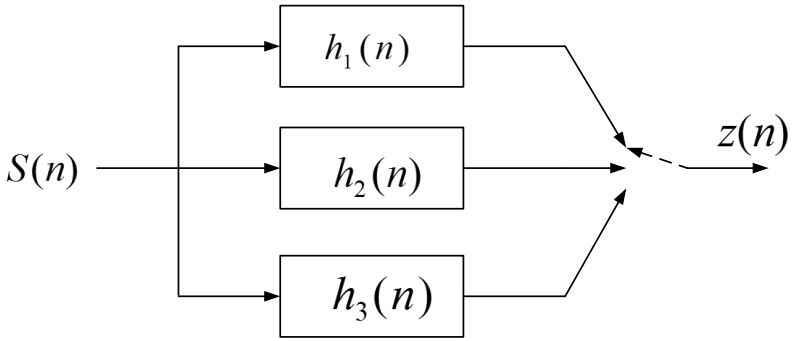
- Different channel, noise and interference statistics
- PLC and wireless might have different average SNR !

Noise Models

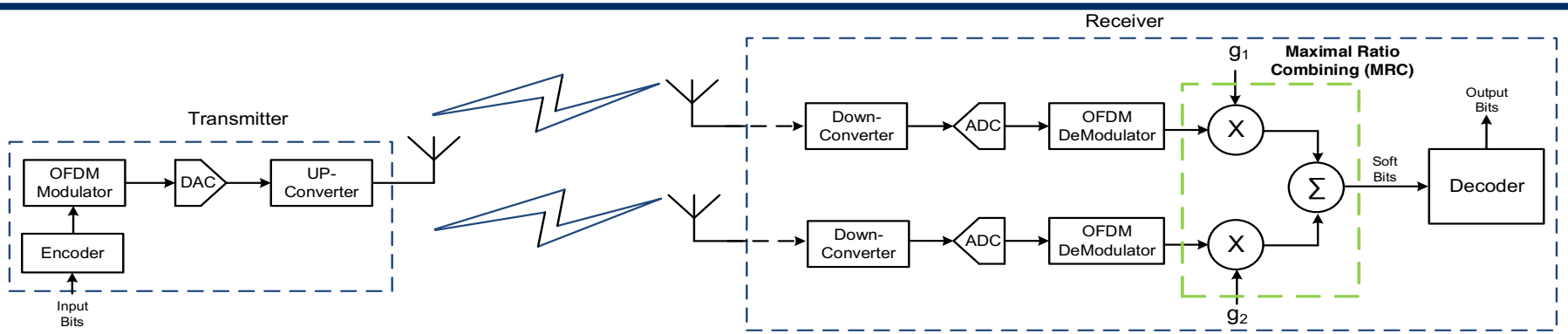
- Cyclo-stationary noise for PLC
  - Period is half AC cycle ~8.3 ms
  - Modeled as colored Gaussian
  - Spectrum varies with time
- Asynchronous noise in unlicensed wireless bands
  - Modeled as Gaussian mixture
  - PDF ~ $\alpha_0 G(0,\sigma_0^2)+\alpha_1 G(0,\sigma_1^2)$







Applying Conventional MRC



- Maximal Ratio Combining (MRC) is a maximum likelihood-optimal technique for white Gaussian noise
- The log-likelihood (LL) function of MRC is given by

$$LL\left(X_k^l\right) = \log\left[p\left(Y_{p,k}^l \middle| H_{p,k}^l X_k^l\right) p\left(Y_{w,k}^l \middle| H_{w,k}^l X_k^l\right)\right]$$
$$= -\frac{\left|Y_{p,k}^l - H_{p,k}^l X_k^l\right|^2}{\sigma_p^2} - \frac{\left|Y_{w,k}^l - H_{w,k}^l X_k^l\right|^2}{\sigma_w^2}$$

- l is the OFDM block index and k is the sub-channel index
- σ_p^2 and σ_w^2 denote average noise powers for PLC and wireless

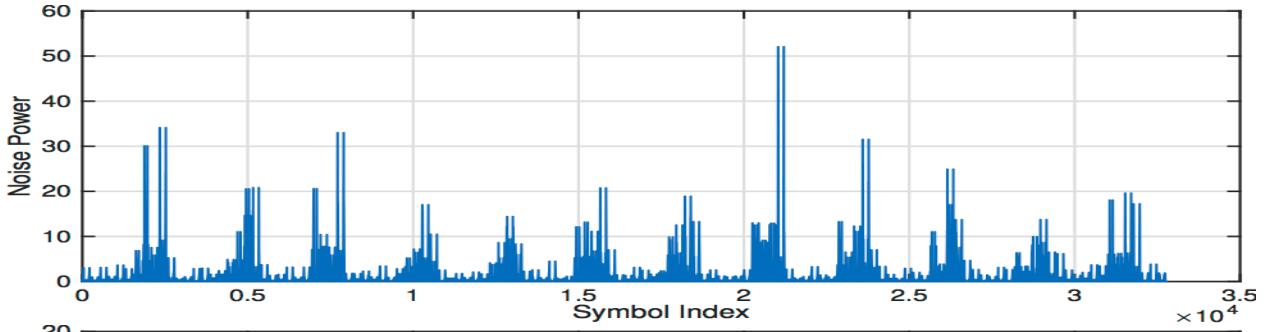
Motivation

- In symmetric combining, average noise powers σ_p^2 and σ_w^2 are equal,
- For asymmetric PLC/Wireless combining, the average noise powers σ_p^2 and σ_w^2 are not necessarily equal
- The instantaneous noise power level on both links shows rapid variations over both time and frequency
- The instantaneous noise powers have a high peak-to-average ratio, which is higher on PLC than on wireless link

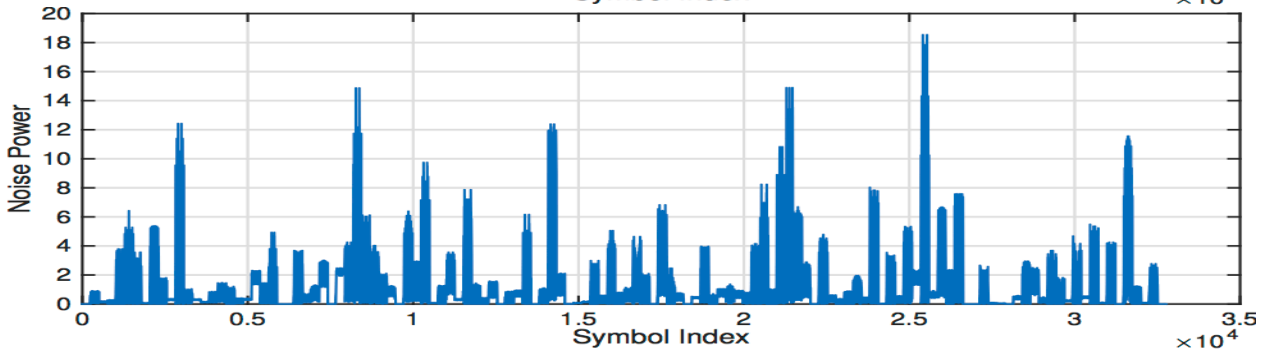
Impulsive Noise in PLC and Wireless

Noise power over frequency sub-channels across multiple OFDM blocks

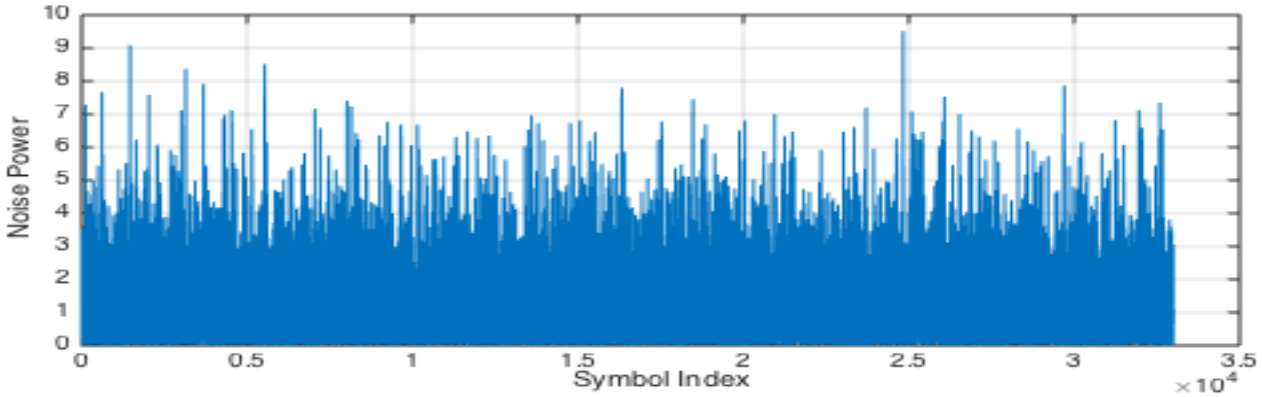
PLC
PAR = 21 dB



Wireless
PAR = 14 dB



AWGN
PAR = 10 dB



Proposed PLC/Wireless Combining

- For PLC/wireless combining, average noise powers σ_p^2 and σ_w^2 don't capture the impulsive noise variations in the PLC and unlicensed wireless links

- We compare three PLC/Wireless combining metrics
  - Average SNR (noise power averaged over both time and frequency)
  - Instantaneous SNR (no averaging)
  - Noise PSD (noise power time-average per OFDM sub-channel)

Proposed PLC/Wireless Combining

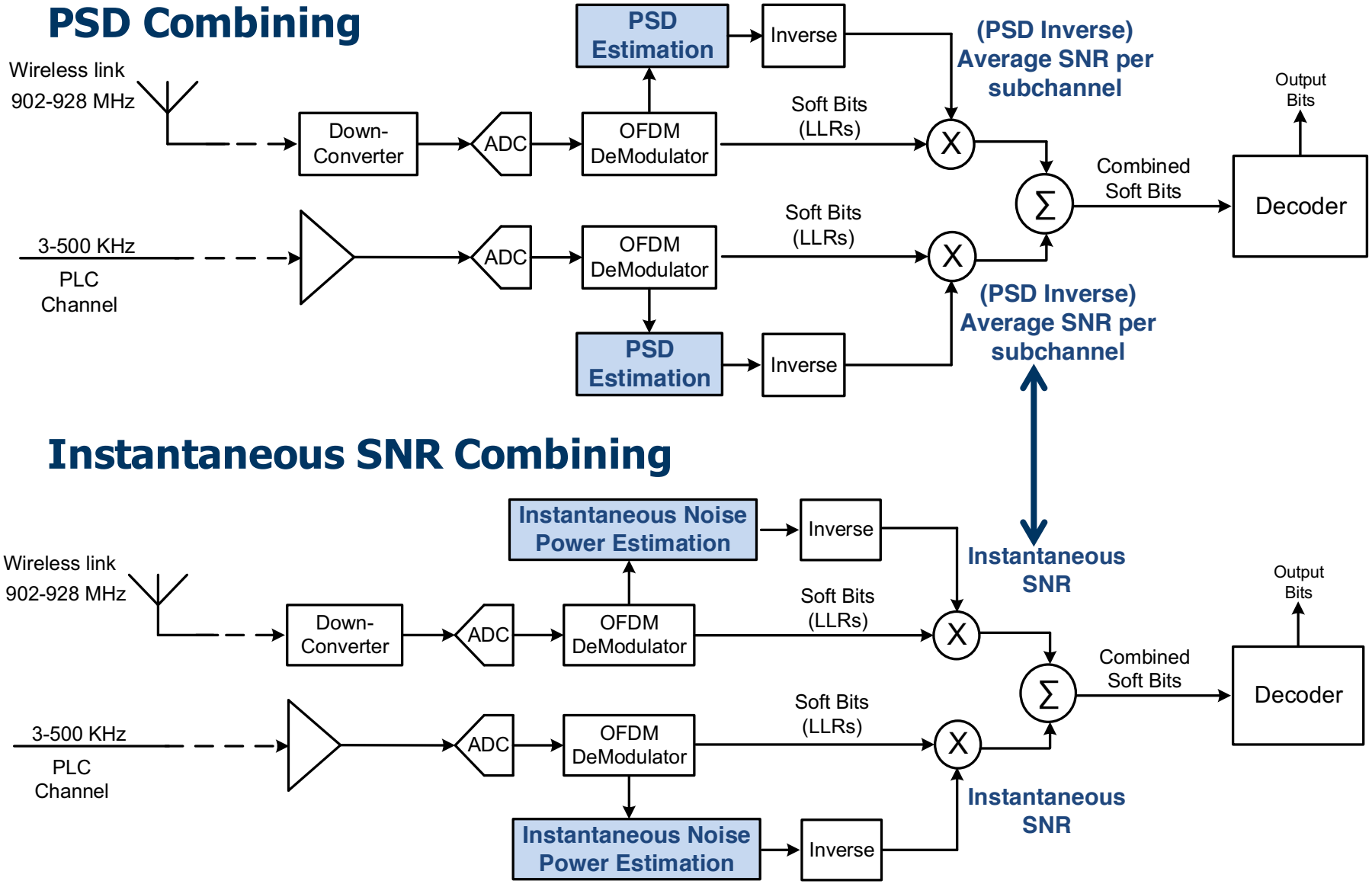
- The log-likelihood (LL) function for the instantaneous SNR and the PSD combining can be expressed as

$$LL_{Inst}\left(X_k^l\right) = -\frac{\left|Y_{p,k}^l - H_{p,k}^l X_k^l\right|^2}{\breve{\sigma}_{p,lk}^2} - \frac{\left|Y_{w,k}^l - H_{w,k}^l X_k^l\right|^2}{\breve{\sigma}_{w,lk}^2}$$

$$LL_{PSD}\left(X_k^l\right) = -\frac{\left|Y_{p,k}^l - H_{p,k}^l X_k^l\right|^2}{\tilde{\sigma}_{p,lk}^2} - \frac{\left|Y_{w,k}^l - H_{w,k}^l X_k^l\right|^2}{\tilde{\sigma}_{w,lk}^2}$$

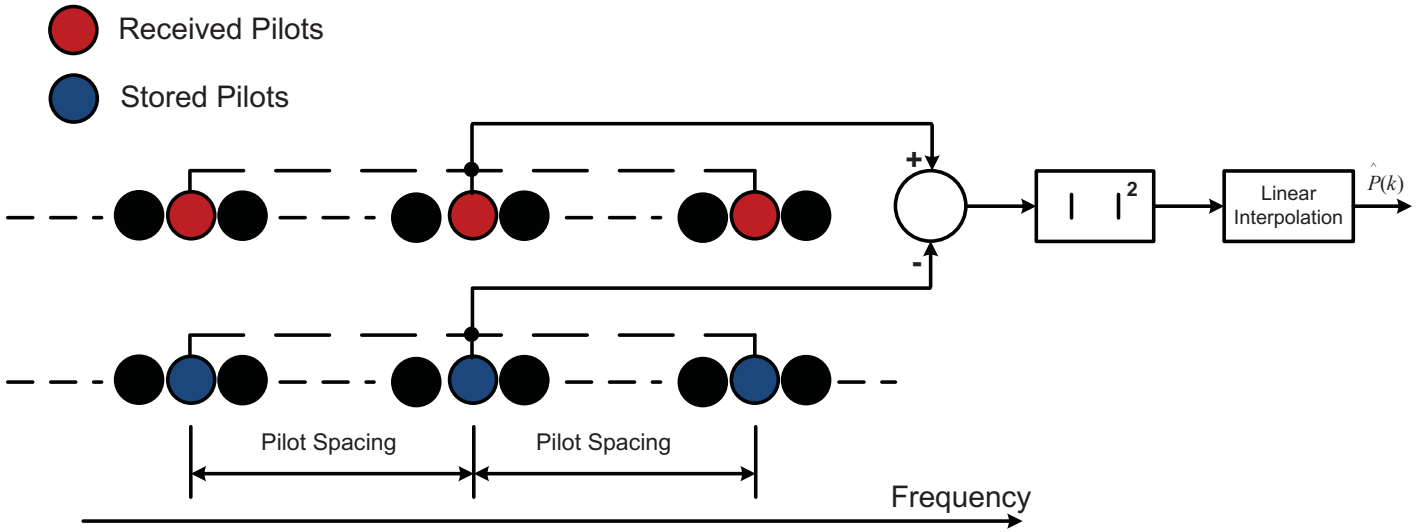
- Where $\breve{\sigma}_{lk}^2$ and $\tilde{\sigma}_{lk}^2$ represent the **instantaneous** noise power and the average noise power per OFDM sub-channel (or the noise **PSD**), respectively
- $\tilde{\sigma}_{lk}^2$ depends on l, the OFDM block index, as each OFDM block might belong to a different noise region

Proposed PLC/Wireless Combining



Instantaneous Noise Power Estimation

- As a simple technique to estimate the instantaneous noise power, we employ comb-type pilots inserted periodically within the data symbols
- We estimate the noise power in the pilot locations followed by linear interpolation to compute estimates over all symbols



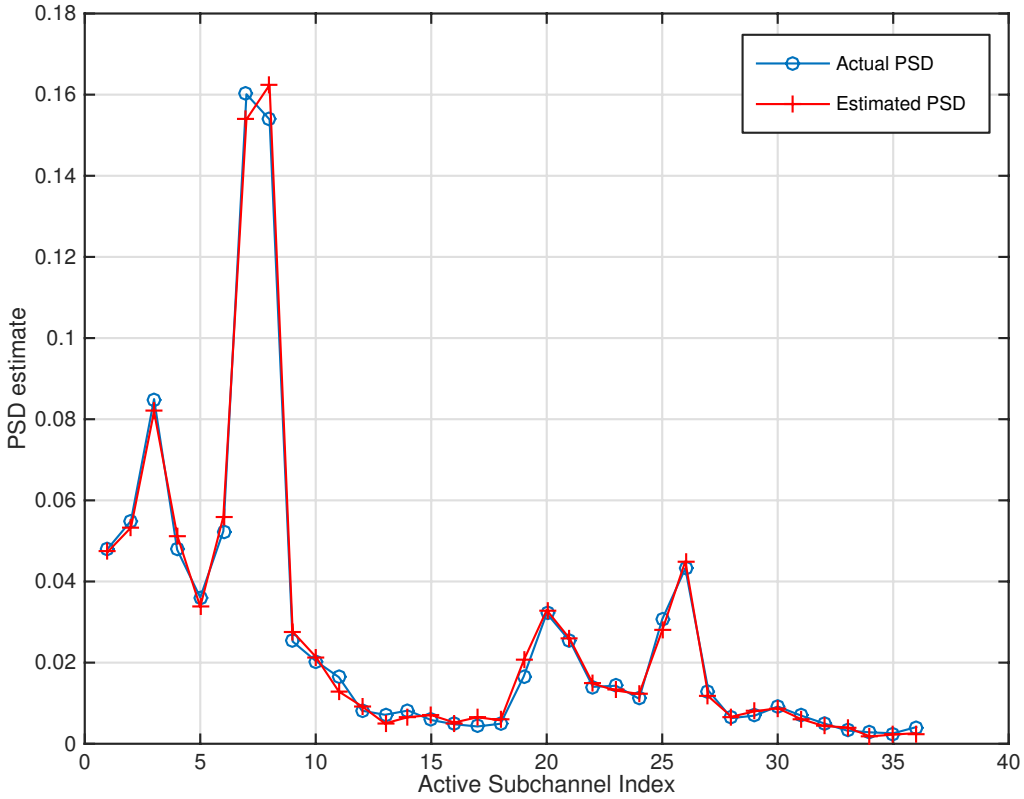
Noise PSD Estimation

- The noise PSD can be estimated by averaging the received signal power

$$\tilde{\sigma}_{lk}^2 = E\left[|Z_k^l|^2\right] = E\left[|Y_k^l|^2\right] - E\left[|H_k^l|^2\right]$$

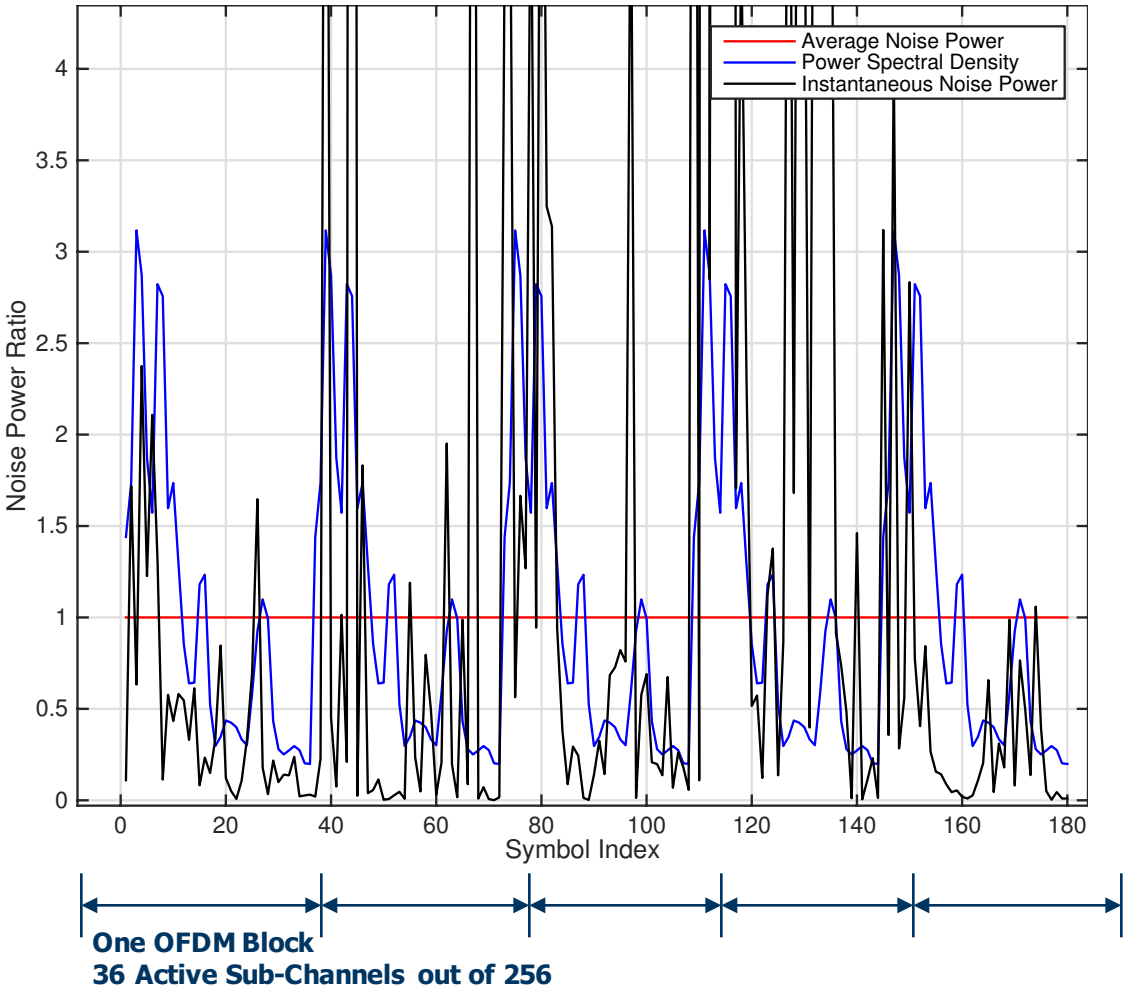
- Estimated PSD and actual PSD vs the active sub-channel indices (36 sub-channels in the CENELEC A band [35-91]kHz

- Averaging is performed over 512 OFDM Symbols



Combining Metrics Comparison

Noise Power Ratio = PLC Noise Power/ Wireless Noise Power



Noise over frequency sub-channels across multiple OFDM blocks

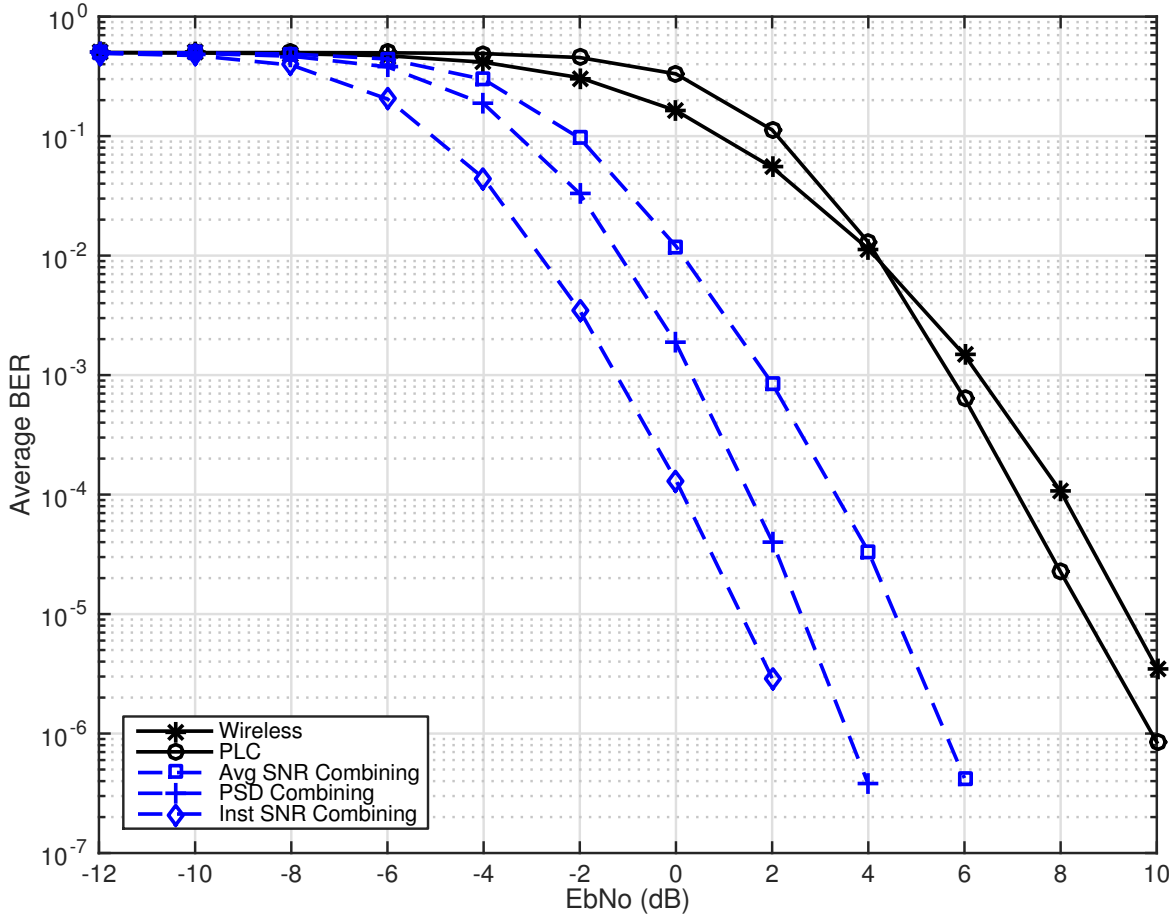
Simulation Parameters

- OFDM transmission with 256 sub-channels and BPSK modulation.
- 0.4 MHz sampling rate.
- CENELEC-A frequency band (35 kHz to 91 kHz).
- Rate 1/2 Convolutional Coding
- **Wireless Link Noise Model**: GM with two states $\alpha_0 = 0.98$, $\alpha_1 = 0.02$, $\sigma_0^2 = 0$ dB, and $\sigma_1^2 = 20$ dB
- **PLC Link Noise Model**:

	Region 1	Region 2	Region 3
Time Percentage	60 %	30 %	10 %
Power (dB)	-6.59	1.93	5.15

Performance Results

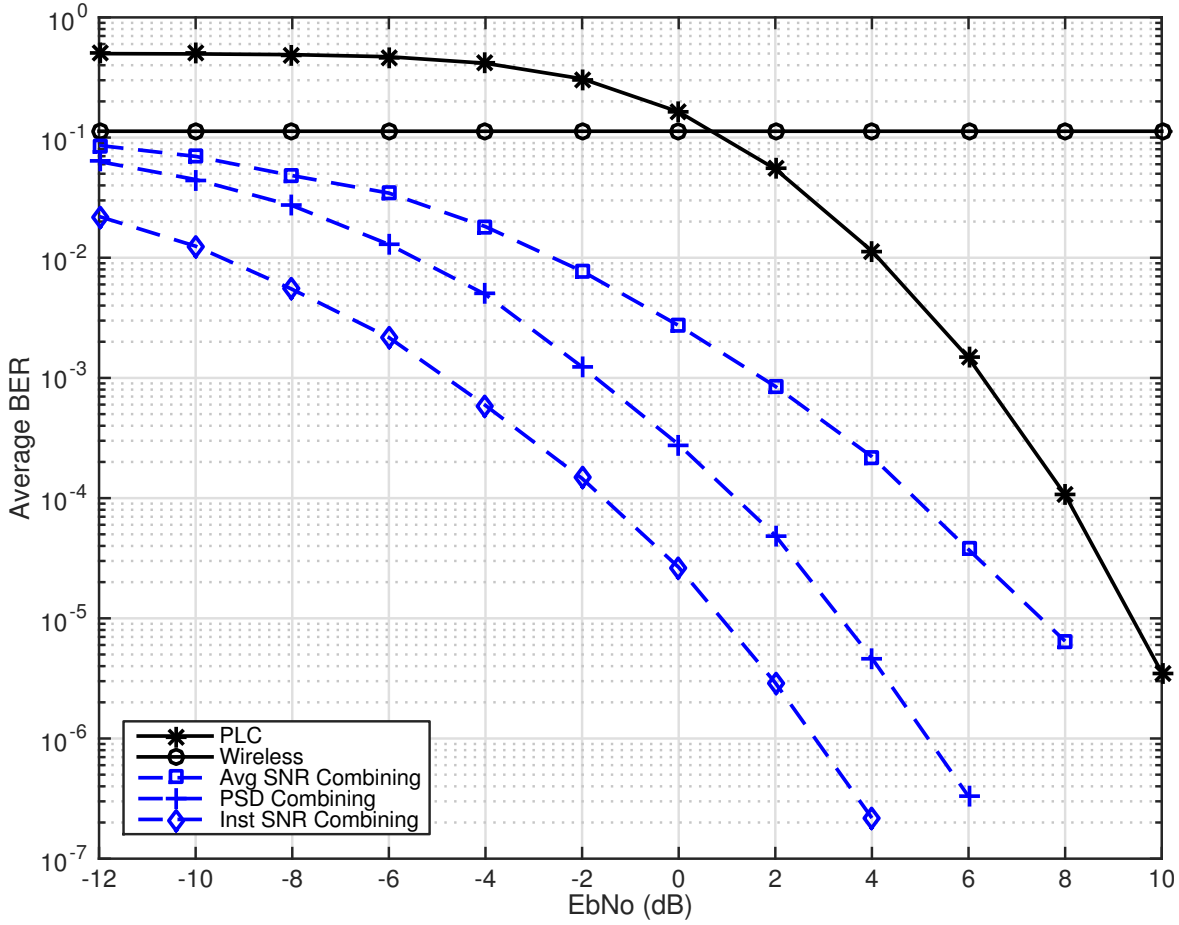
- Average BER vs Eb/No of both links (equal Eb/No) - PLC channel from measurements/Rayleigh channel for wireless



Performance Gain over one link only at 10^{-3}
Average SNR Combining
4 dB
PSD Combining
5.5 dB
Instantaneous SNR Combining
7 dB

Performance Results

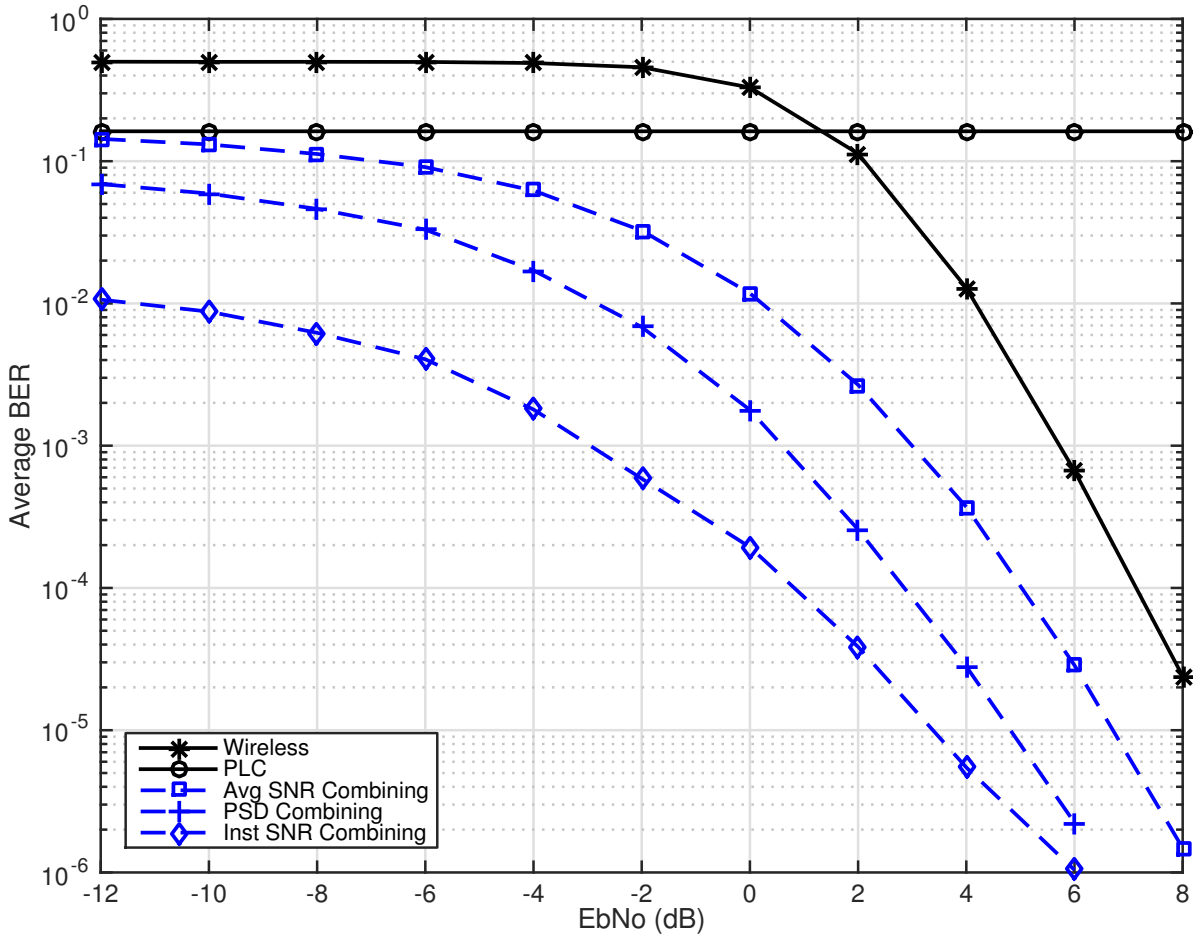
- Average BER vs Eb/No of the PLC link at Eb/No = 2 dB for the wireless link



Performance Gain over PLC only at 10^{-3}
Average SNR Combining
4.5 dB
PSD Combining
8 dB
Instantaneous SNR Combining
10 dB

Performance Results

- Average BER vs Eb/No of the Wireless link for Eb/No = 0 dB for the PLC link



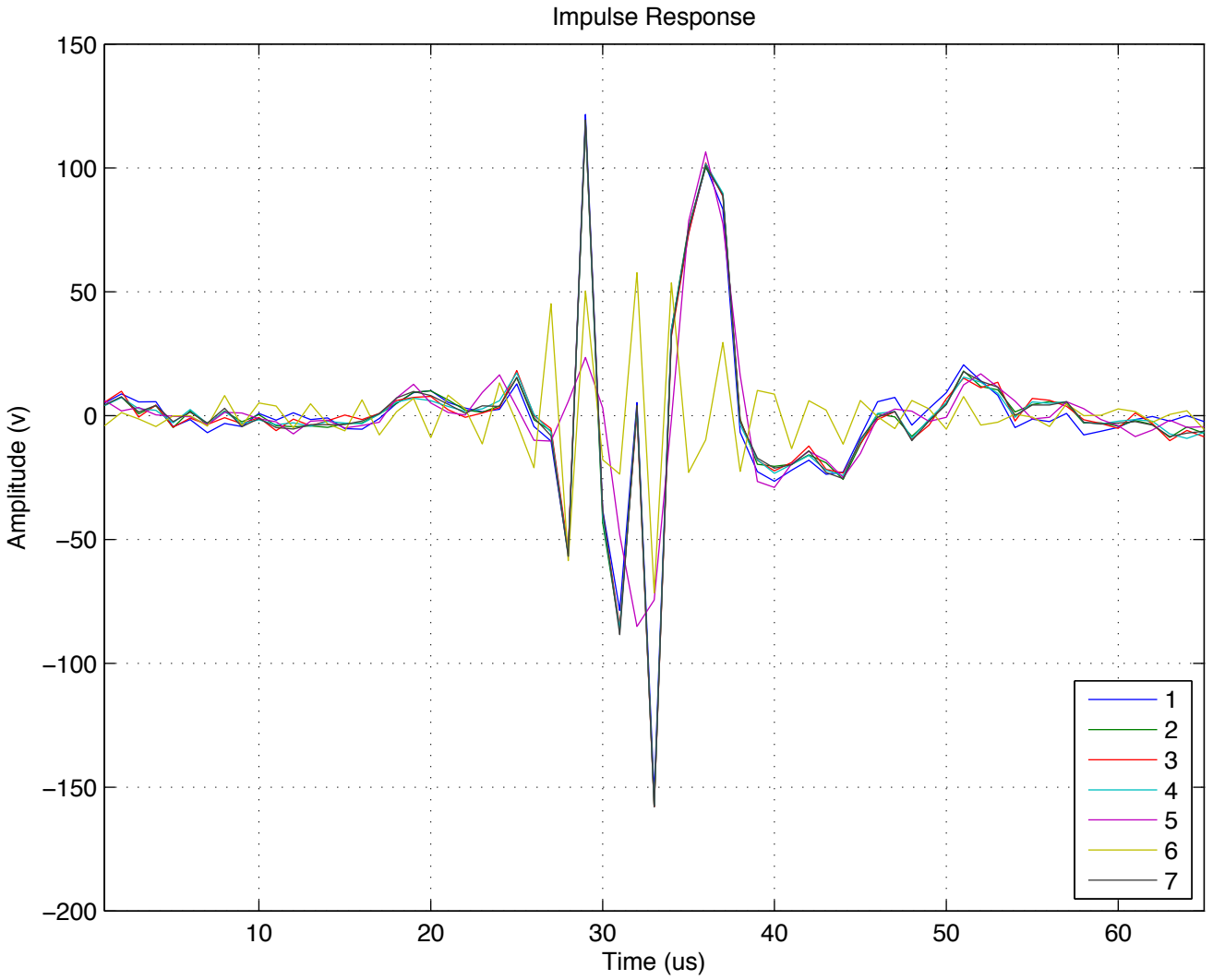
Performance Gain over Wireless only at 10^{-3}
Average SNR Combining
2.5 dB
PSD Combining
4.5 dB
Instantaneous SNR Combining
8 dB

Conclusion

- PSD combining provides the best performance /complexity tradeoff - better performance than average-SNR combining at lower complexity than instantaneous-SNR combining

- Our proposed PSD estimation method does not require pilot overhead while instantaneous-SNR combining requires high pilot overhead (resulting in data rate loss)

Back-up Slides



Back-up Slides