Spectrum Sensing Technique using Polyphase DFT Filter Bank for Opportunistic Cognitive Radios

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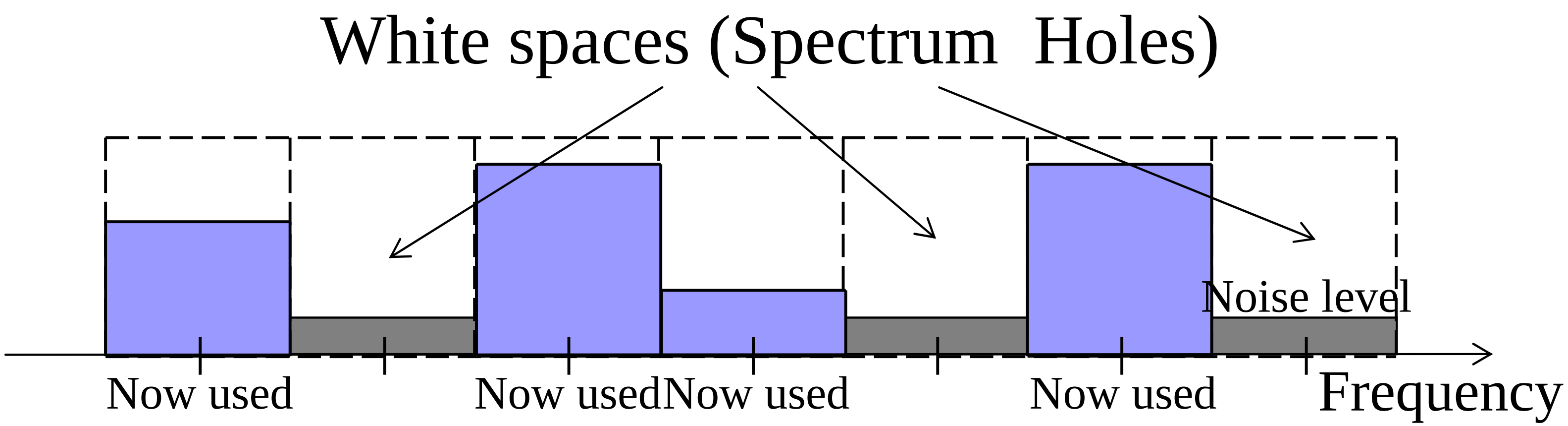
Background

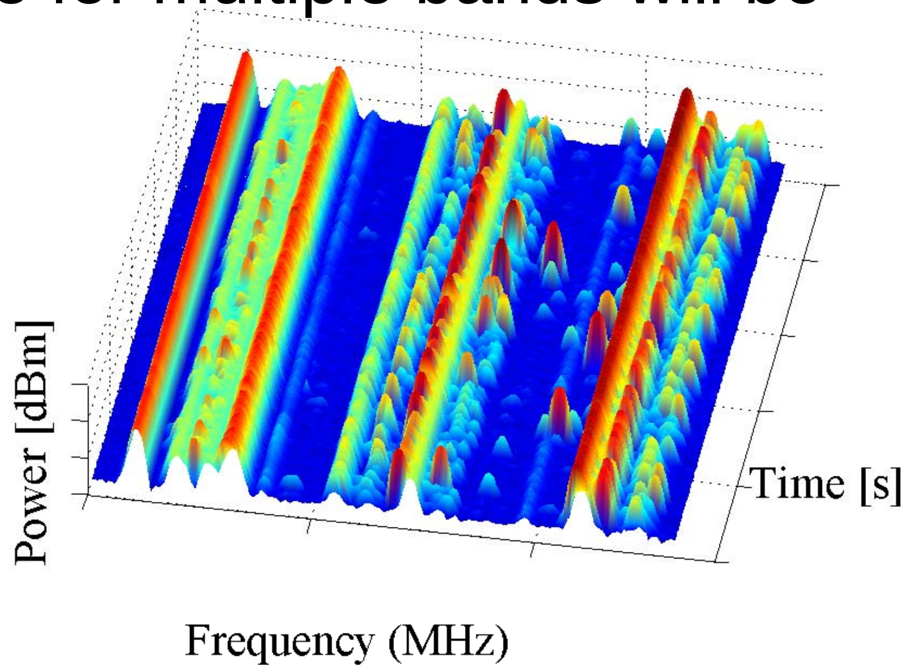
- Cognitive Radio (CR) offers to solve spectrum underutilization problem
- Spectrum sensing is an essential task to realize CR
- The challenges of spectrum sensing:

  Reliability & Efficiency
- Opportunistic use of inactive sub-bands (white spaces)

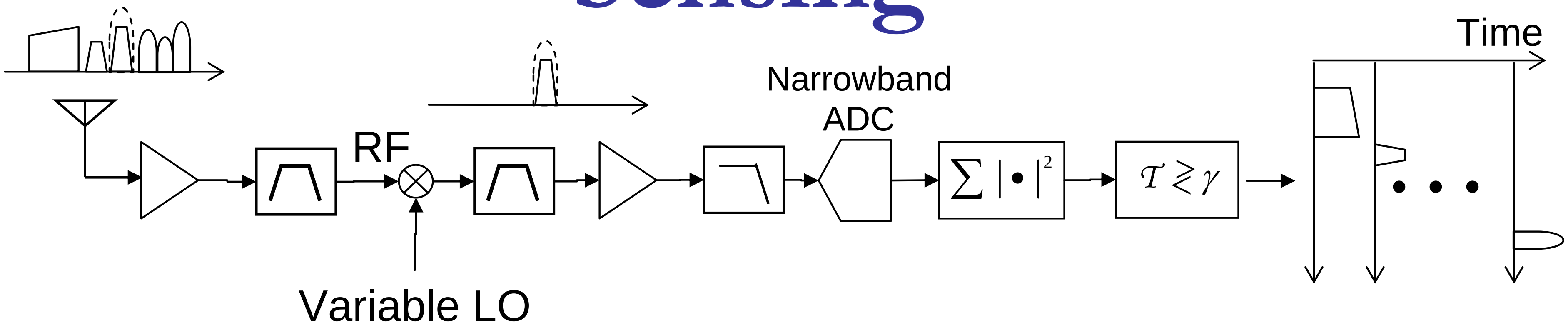


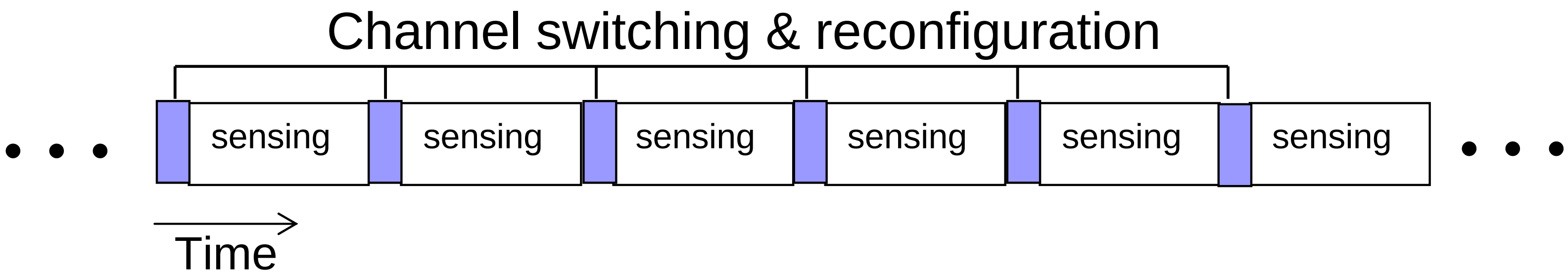
Spectrum Dynamic

- Spectrum usage is dynamically changed in time and frequency domain simultaneously
- How to detect the white spaces for opportunistic cognitive radios is the main concern
- Frequency scanning is not suitable as the sensing measurements become stale
- Wideband sensing scheme for multiple bands will be required for efficient use of spectrum dynamic



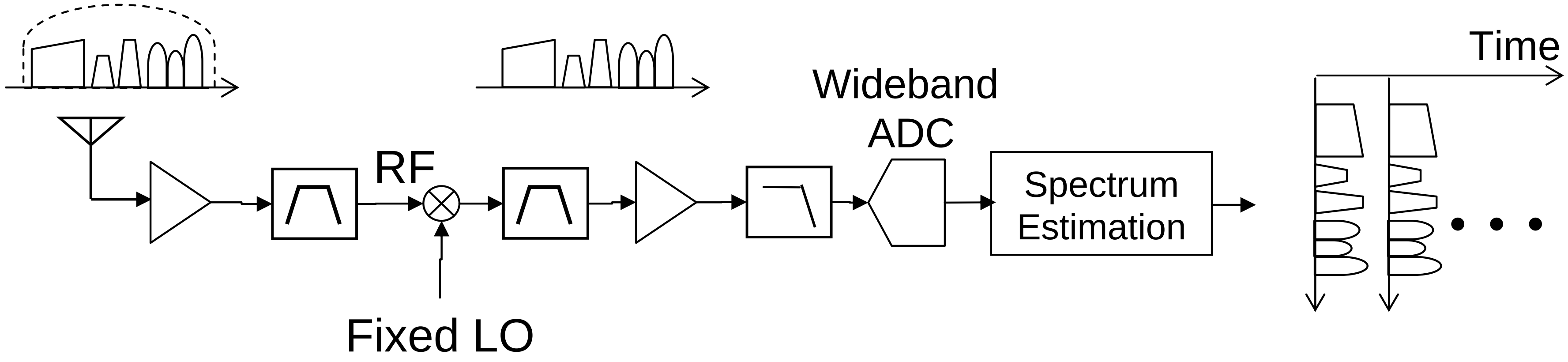
Time Domain Narrowband Sensing





- Wideband RF front-end with wideband tuning function
- Settling time for channel switching is necessary
- Each band cannot be detected at the same time

Frequency Domain Wideband Sensing



- Search multiple unused sub-bands (white spaces) within wide frequency band continuously
- No frequency sweeping → Simultaneous spectrum sensing
- Wideband ADC is necessary to sample wider band
- Dynamic range problem → ADC resolution
- How to estimate the power spectrum density (PSD) efficiently?

Periodogram Spectrum Estimator (PSE)

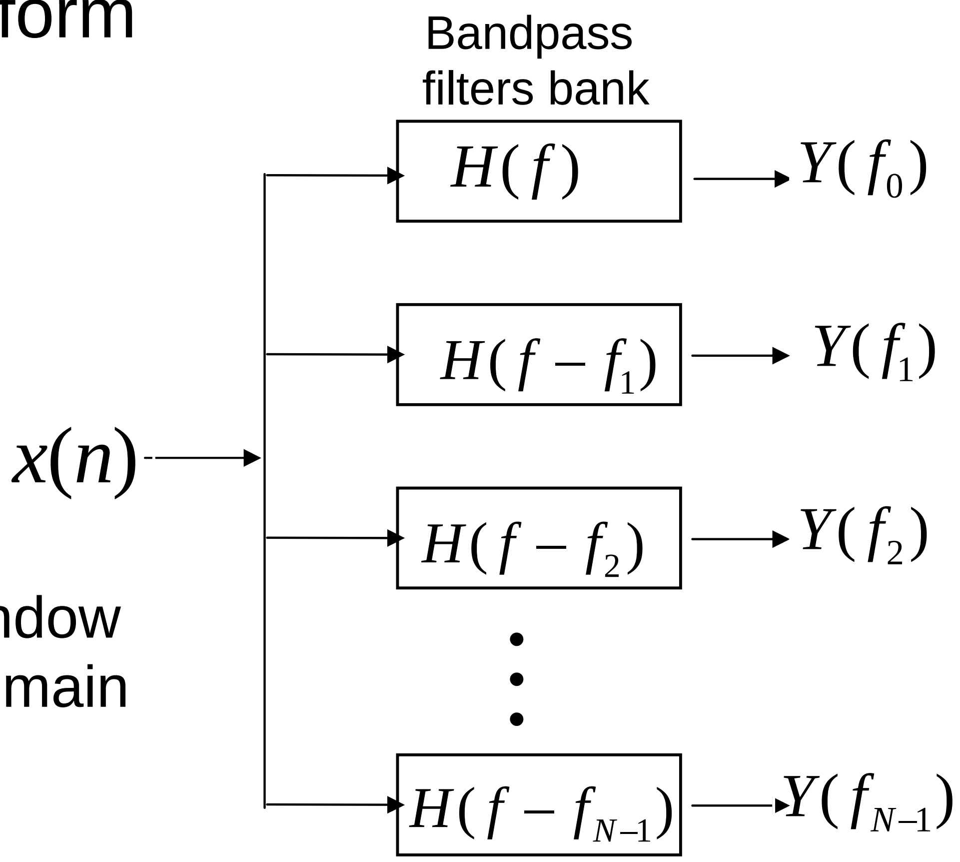
- Most basic non-parametric spectrum estimator
- Apply discrete Fourier transform

$$Y(f) = \left| \sum_{k=0}^{N-1} h(k) x(n-k) \right|^2$$

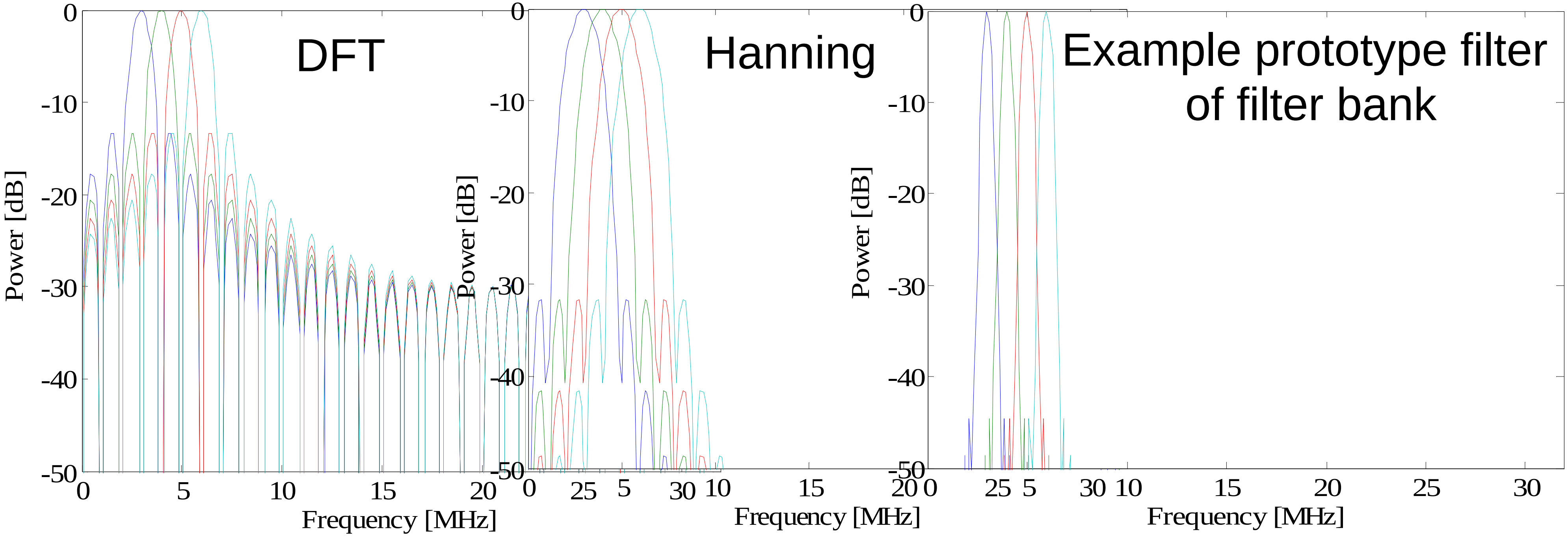
$$h(k) = \frac{1}{\sqrt{N}} e^{-j2\pi fk}$$

Modulated Rectangular Window
→ Sinc response in freq. domain

$$Y(f) = \left| \frac{1}{\sqrt{N}} \mathrm{DFT}\{x(k)\} \right|^2$$

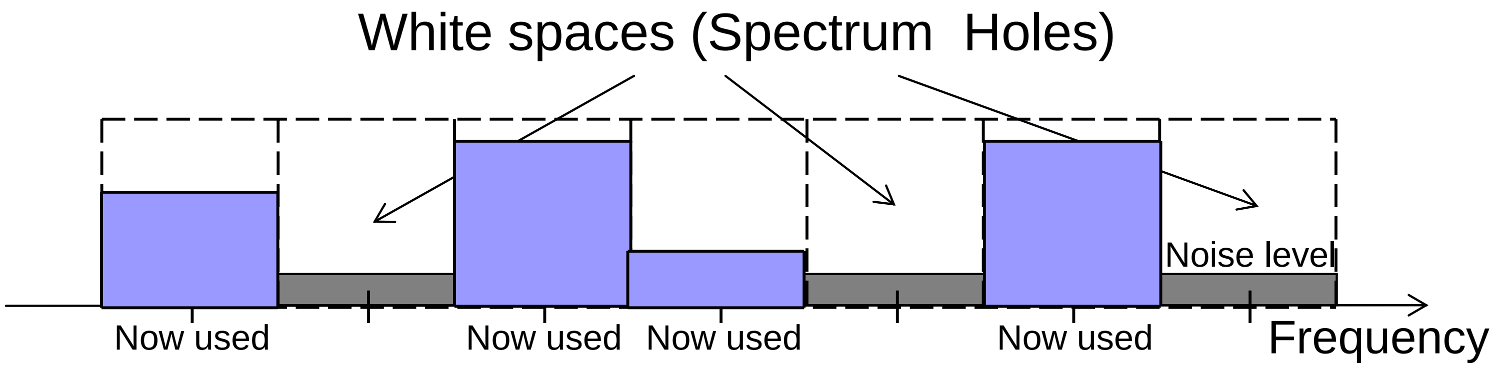


Dynamic Range & Resolution

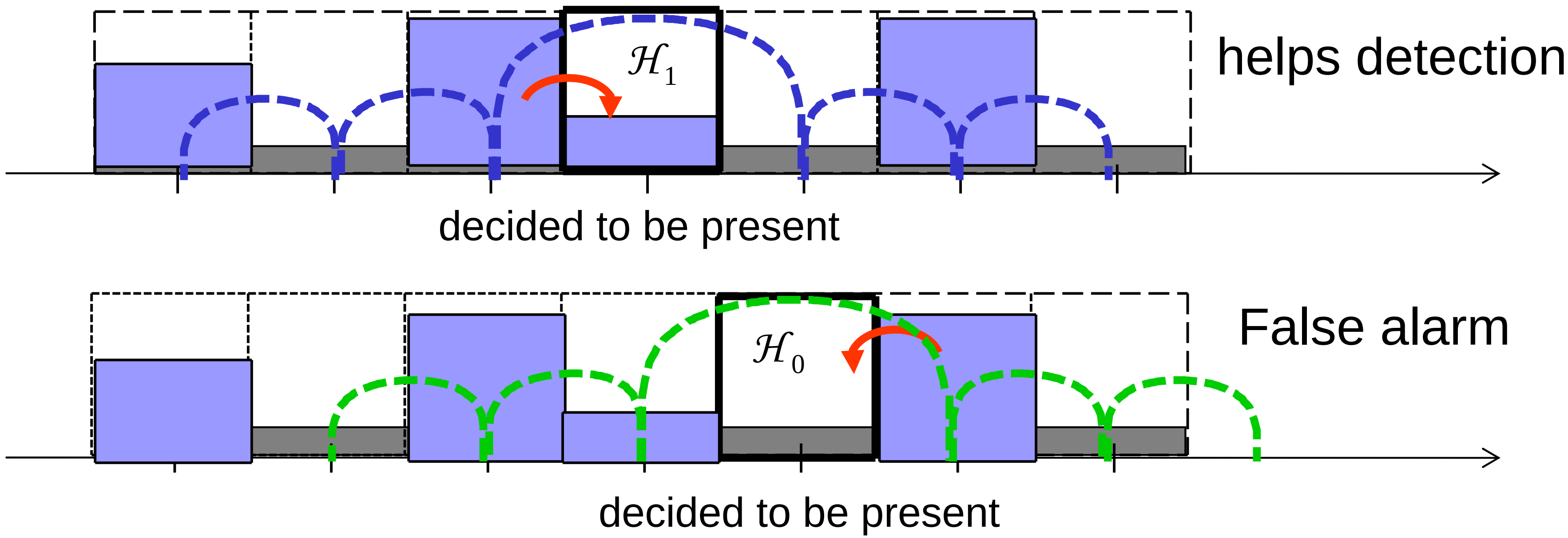


- Conventional periodogram spectral estimator (PSE) by DFT filter has large sidelobe. The significant leakage of spectral power among different bands.
  → Limit spectral dynamic range
- Sidelobes can be decreased at the cost of wider main lobe by using windowing. Reduction of leakage among different bands is traded at the cost of a lower resolution in frequency
- Filter bank provides best performance to minimize the leakage power (best spectral dynamic range) keeping the frequency resolution. Prototype filter can be optimally designed

Spectrum Sensing Problems in Multiple Sub-channels

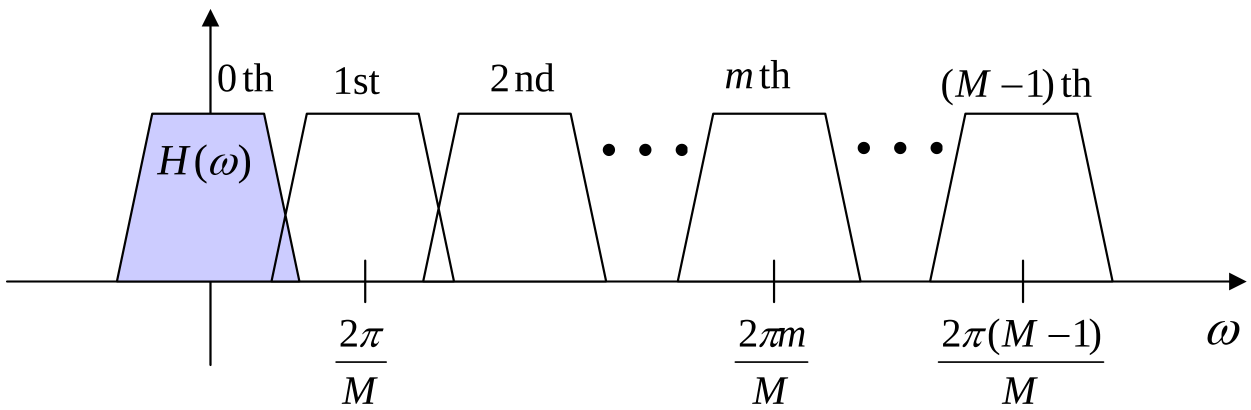


Power leakage from neighboring subbands



Poly-phase DFT Filter Bank

- M bandpass filter array where each bandpass filter is the frequency-shifted version of a low pass filter *H(w)* with impulse response of a prototype filter
- Filter bank can provide efficient bandpass filter implementation with low spectrum power leakage (good false alarm performance)



Poly-phase DFT Filter Bank

- Analysis filter bank
- Bandpass filters for each sub-band

$$h_m(n) = h(n) \cdot W_M^{-mn} \qquad W_M = e^{-j\frac{2\pi}{M}}$$

- Output spectra

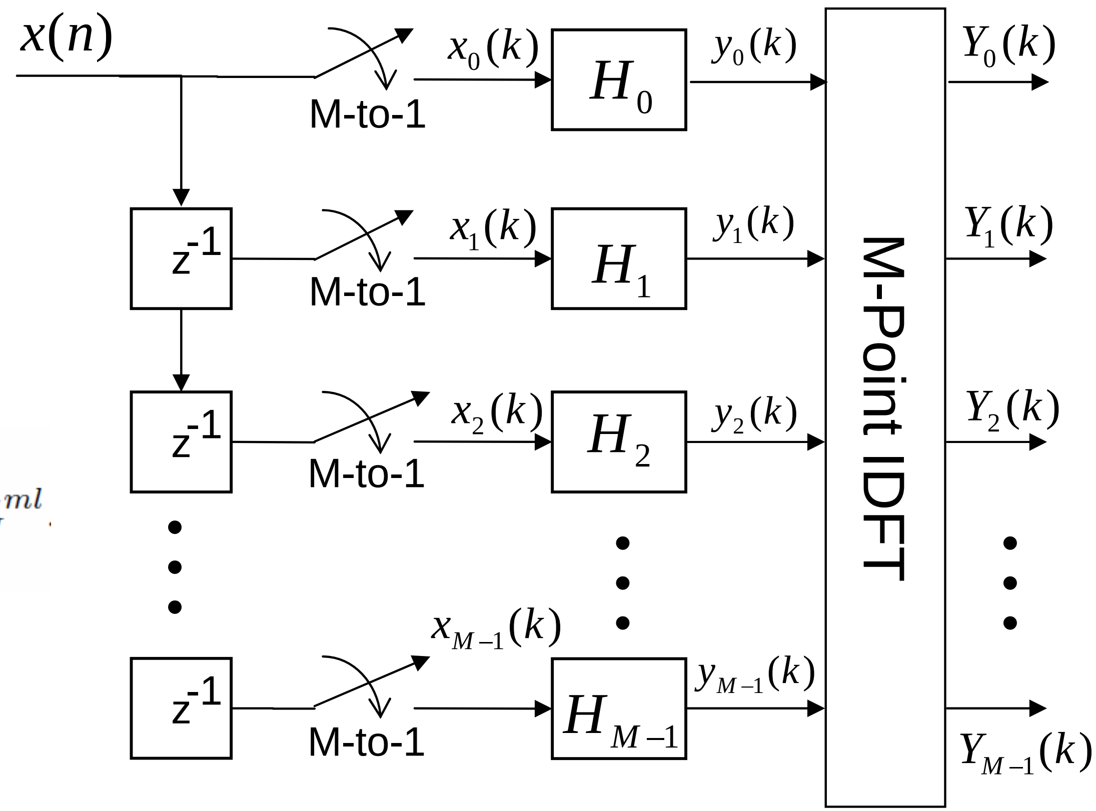
$$\begin{aligned} Y_m(n) &= \sum_{i=0}^{L-1} h_m(i) \cdot x(n-i) \\ &= \sum_{i=0}^{L-1} h(i) \cdot W_M^{-mi} \cdot x(n-i) \end{aligned}$$

- Polyphase decomposition

$$Y_m(n) = \sum_{l=0}^{M-1} \sum_{p=0}^{P-1} h(pM+l) \cdot x(n-pM-l) \cdot W_M^{-ml}.$$

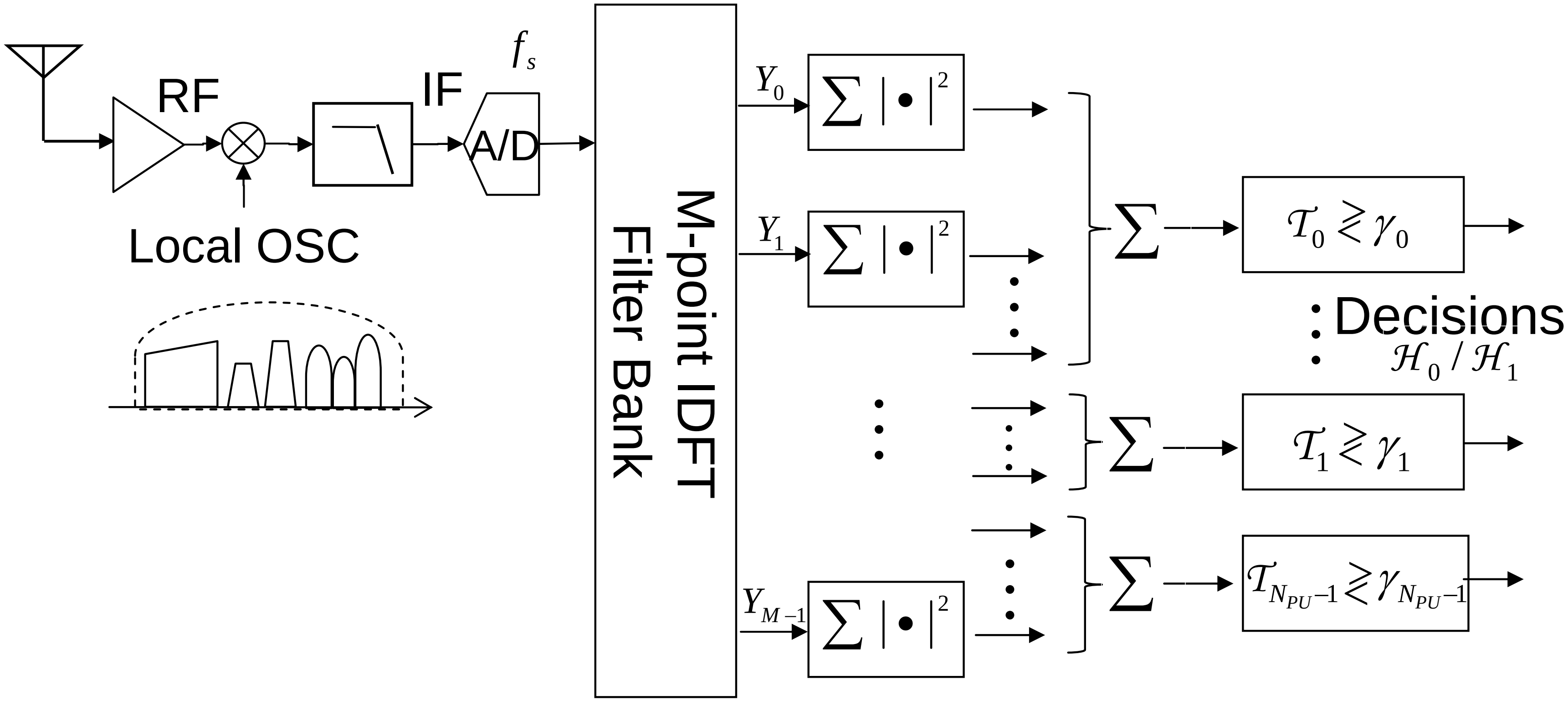
- Discrete Fourier transform

$$\begin{aligned} Y_m(k) &= \sum_{l=0}^{M-1} \sum_{p=0}^{P-1} h_l(p) \cdot x_l(k-p) \cdot W_M^{-ml} \\ &= \sum_{l=0}^{M-1} y_l(k) \cdot W_M^{-ml}, \end{aligned}$$



$$\begin{aligned} h_l(k) &= h(n)|_{n=kM+l}, \\ x_l(k) &= x(n)|_{n=kM+l}. \end{aligned}$$

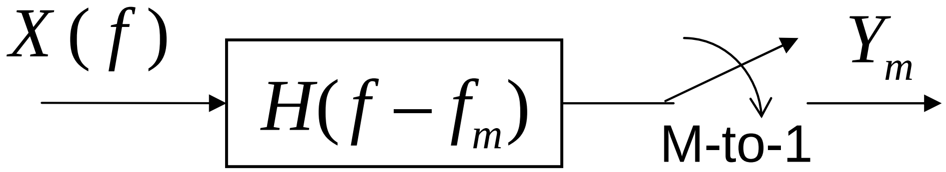
Filter Bank Sensing



- The composite signal of multiple PU (primary user) sub-channels is down-converted into IF frequency. Then, the passband signal is sampled by wideband ADC and fed into the filter bank processing block.
- The original idea is the minimum complexity design where the user sub-channels correspond exactly to the sub-bands (*M=(Npu+1)/2*).
- Energy detector is followed by filter bank output and hypothesis test is performed.

Energy Detection

- Sub-band can be thought equivalently as



- Test statistics for m-th sub-band

$$\mathcal{T}_m = \sum_{k=0}^{\bar{N}-1} \left| Y_i(k) \right|^2 \qquad \bar{N} = \frac{N}{M}$$

M: # of sub-bands

$$\eta \sim \chi^2_{2\bar{N}}$$

$$\mathcal{T}_m = \eta G \frac{\sigma_n^2}{2} \quad : \mathrm{H}_0 \qquad G = \sum_{l=0}^{L-1} h^2(l)$$

Filter gain

- Test statistics for m-th primary user with S_p sub-bands

$$\left(\because S_p = u_p - l_p + 1 \right)$$

$$\mathcal{T}_p = \sum_{i=l_m}^{u_m} \sum_{k=0}^{\bar{N}-1} \left| Y_i(k) \right|^2$$

$$\mathcal{T}_p \sim \mathcal{N}\left(S_p \bar{N} G \sigma_n^2, S_p \bar{N} G^2 \sigma_n^4 \right)$$

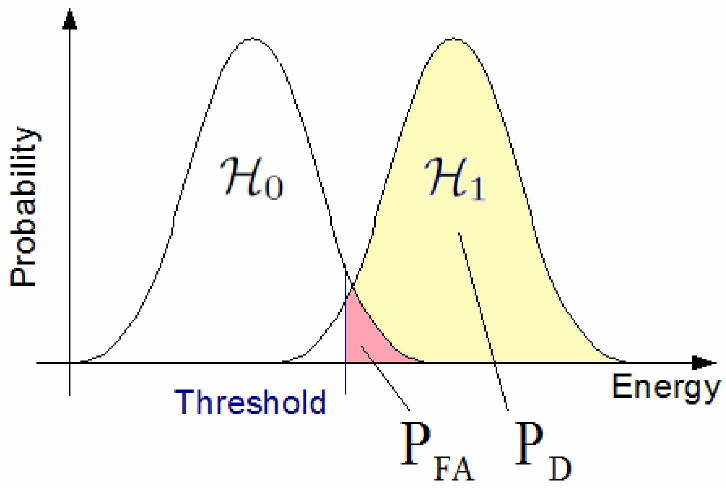
Energy Detection (2)

- False alarm probability for p-th primary user

$$P_{\mathrm{FA},p} = Q\left(\frac{\gamma_p - S_p \overline{N} G \sigma_n^2}{\sqrt{S_p \overline{N} G \sigma_n^2}}\right)$$

- Threshold level is determined by

$$\gamma_p = \left\lfloor Q^{-1}\left(P_{\mathrm{FA},p}\right)\sqrt{S_p \overline{N}} + S_p \overline{N} \right\rfloor G \sigma_n^2$$



- Detection probability for p-th primary user

$$P_{\mathrm{D},p} = Q\left(\frac{\gamma_p - S_p \overline{N} G\left(\sigma_n^2 + \sigma_s^2\right)}{\sqrt{S_p \overline{N} G\left(\sigma_n^2 + \sigma_s^2\right)}}\right)$$

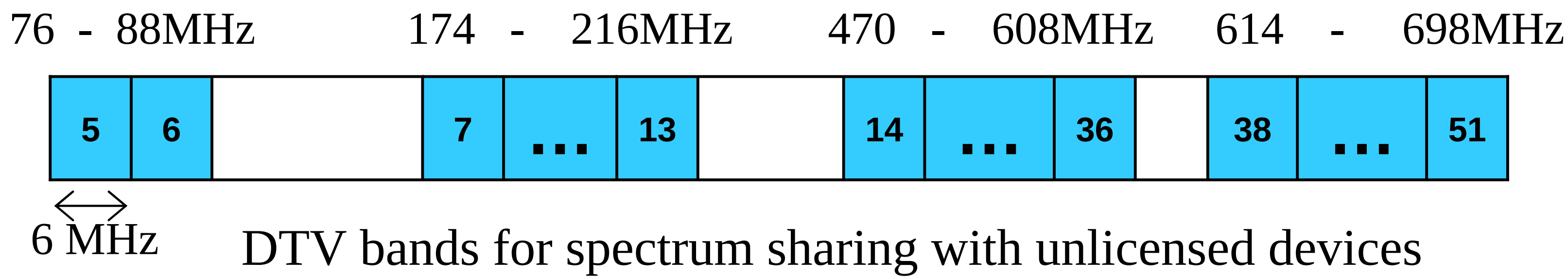
$$= Q\left(\frac{Q^{-1}\left(P_{\mathrm{FA},p}\right)\sqrt{S_p \overline{N}}\sigma_n^2 - S_p \overline{N} \sigma_s^2}{\sqrt{S_p \overline{N}}\left(\sigma_n^2 + \sigma_s^2\right)}\right)$$

Signal is supposed to be Gaussian process as well

Wideband Sensing Framework

- Filter bank can provide efficient bandpass filter implementation with low spectrum power leakage (good false alarm performance)
- Multi-channel sensing architecture based on poly-phase DFT filter bank followed by energy detector with minimum complexity
  - Sub-channels have the same bandwidth (single resolution)
  - Wideband RF frontend

    → license free radio using DTV bands in US (76-88, 174~216, 470~608, 614~698MHz)



DTV bands for spectrum sharing with unlicensed devices

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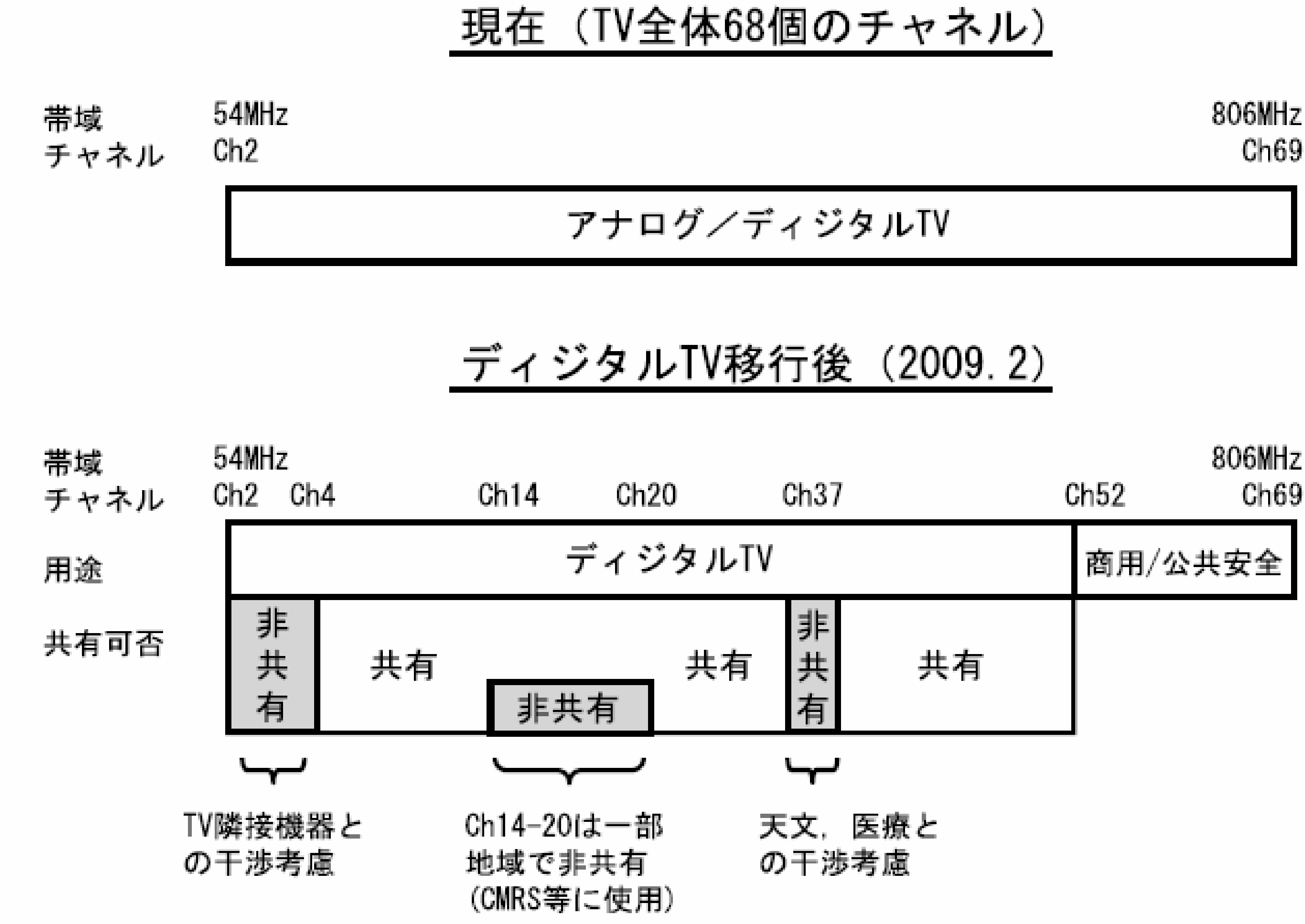

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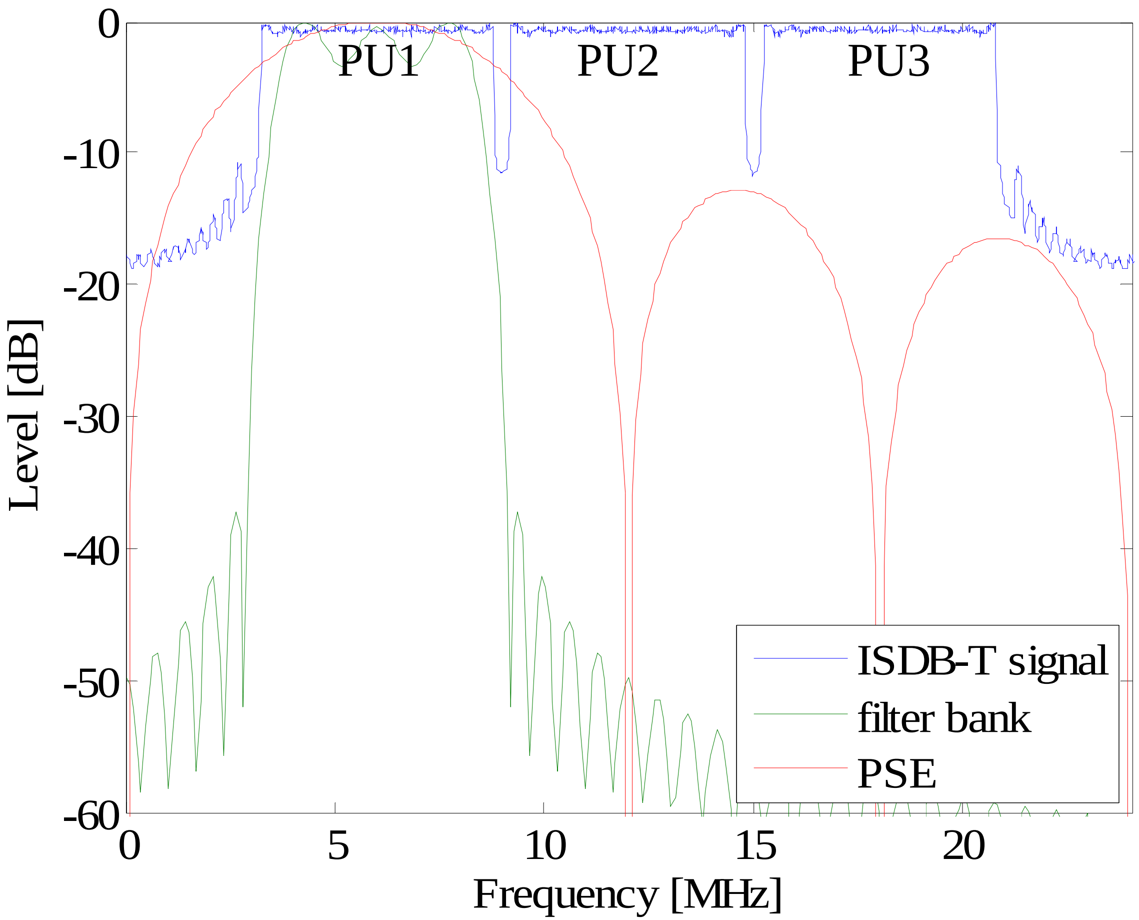
Wideband Sensing Framework

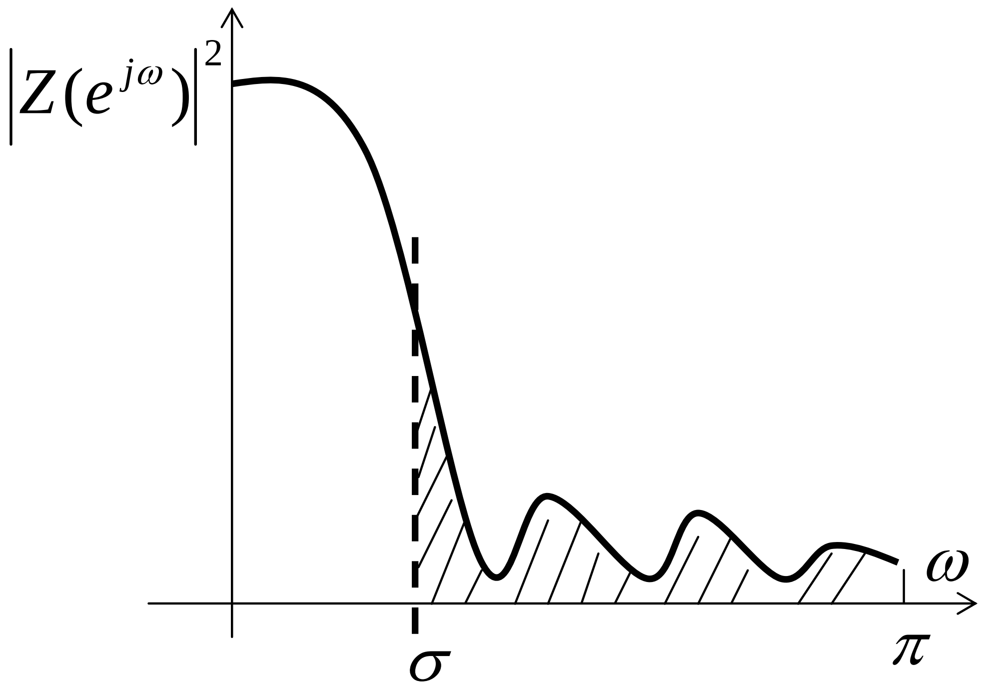
- In case of DTV channel, the sampling rate at about 1.3GHz is necessary
- Prototype filter :
  Energy in passband is maximized (Prolate sequence filter)



- RF signal BW : 18 MHz (=6MHz x 3)
- The composite RF signal with 3 PU sub-channels is down-converted into IF centered at 12MHz (=*fs/4*).
- Processing with passband signal（Real signal）

Prolate Sequence

- "Prolate spheroidal" or "Prolate" or "Slepian" sequence
- Real sequence of finite length and unit energy with the minimum energy in the specified region
- Two parameters : Length L and σ



$$\text{Maximize } \Phi = \frac{1}{\pi}\int_0^{\sigma} \left|Z(e^{j\omega})\right|^2 d\omega$$

$$\text{subject to } \frac{1}{\pi}\int_0^{\pi} \left|Z(e^{j\omega})\right|^2 d\omega = 1$$

$$\text{Maximize } \Phi = \mathbf{Z}^{-1}\mathbf{P}\mathbf{Z}$$

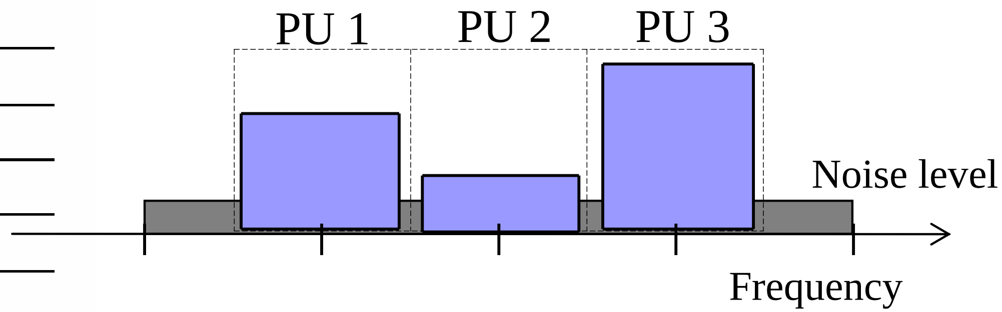
$$\text{subject to } \mathbf{Z}^{-1}\mathbf{Z} = 1$$

$\mathbf{Z}$ is the eigenvector corresponding to max eigenvalue

Simulation Specifications

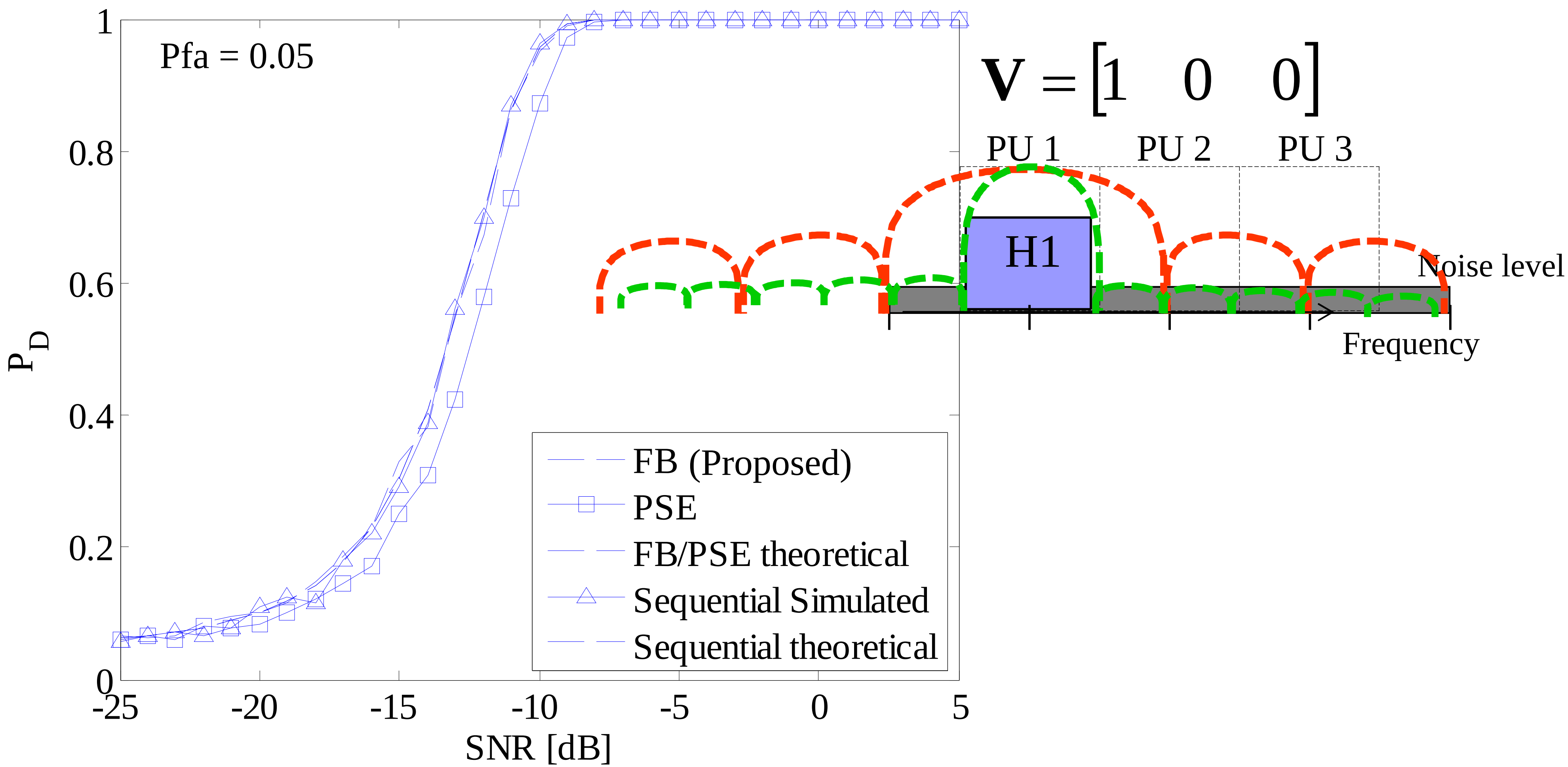
TABLE I
SIMULATION PARAMETERS.

Signal	ISDB-T mode 3
No. of primary users, N_{PU}	3 channels
Carrier modulation	64 QAM
Number of subcarriers	5,617
Carrier spacing	0.992 kHz
Channel bandwidth	5.57 MHz
Guard band	0.43 MHz
Guard interval	126 μs
Symbol period	1,008 μs
Sampling frequency	48 MHz
Prototype filter	prolate sequence filter ($L = 64$)
FFT points, M	8
Signal length, N	10,000 samples
False alarm rates (P_{FA})	0.05
SNR	$-25 \sim 5$ [dB]
Trials	1,000



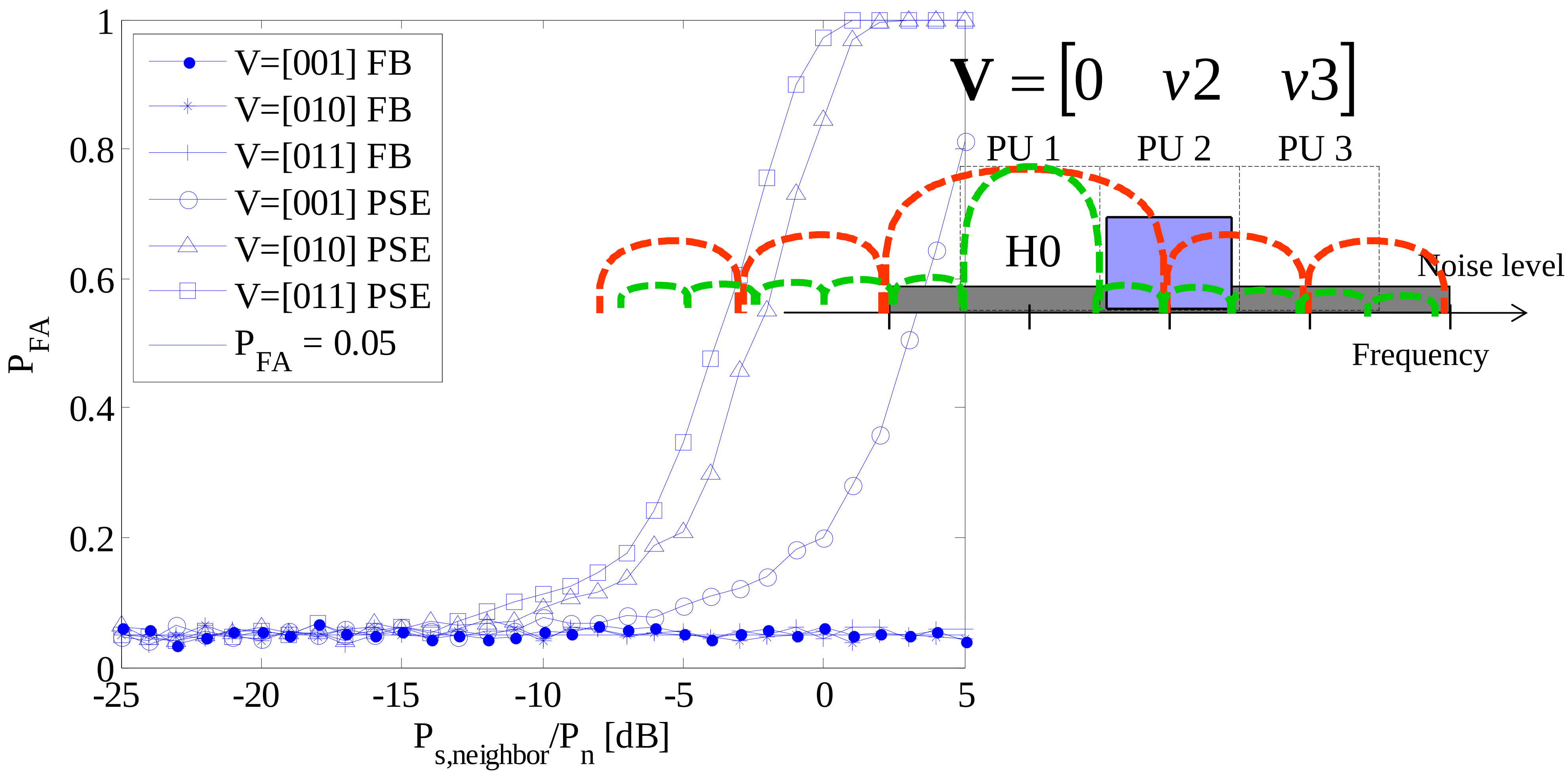
- RF signal BW : 18 MHz (=6MHz x 3)
- The composite RF signal with 3 PU sub-channels is down-converted into IF centered at 12MHz (=*fs/4*).
- Processing with passband signal

Prob. Detection (Pd)



- 理想的(サブバンド分離が完全)にはどの手法も同一性能になる
- PSEの隣接ユーザチャネルのノイズを拾ってしまうため，性能が劣化している(隣接ユーザチャネルは空いている場合)
- フィルタバンクは理論性能に近い

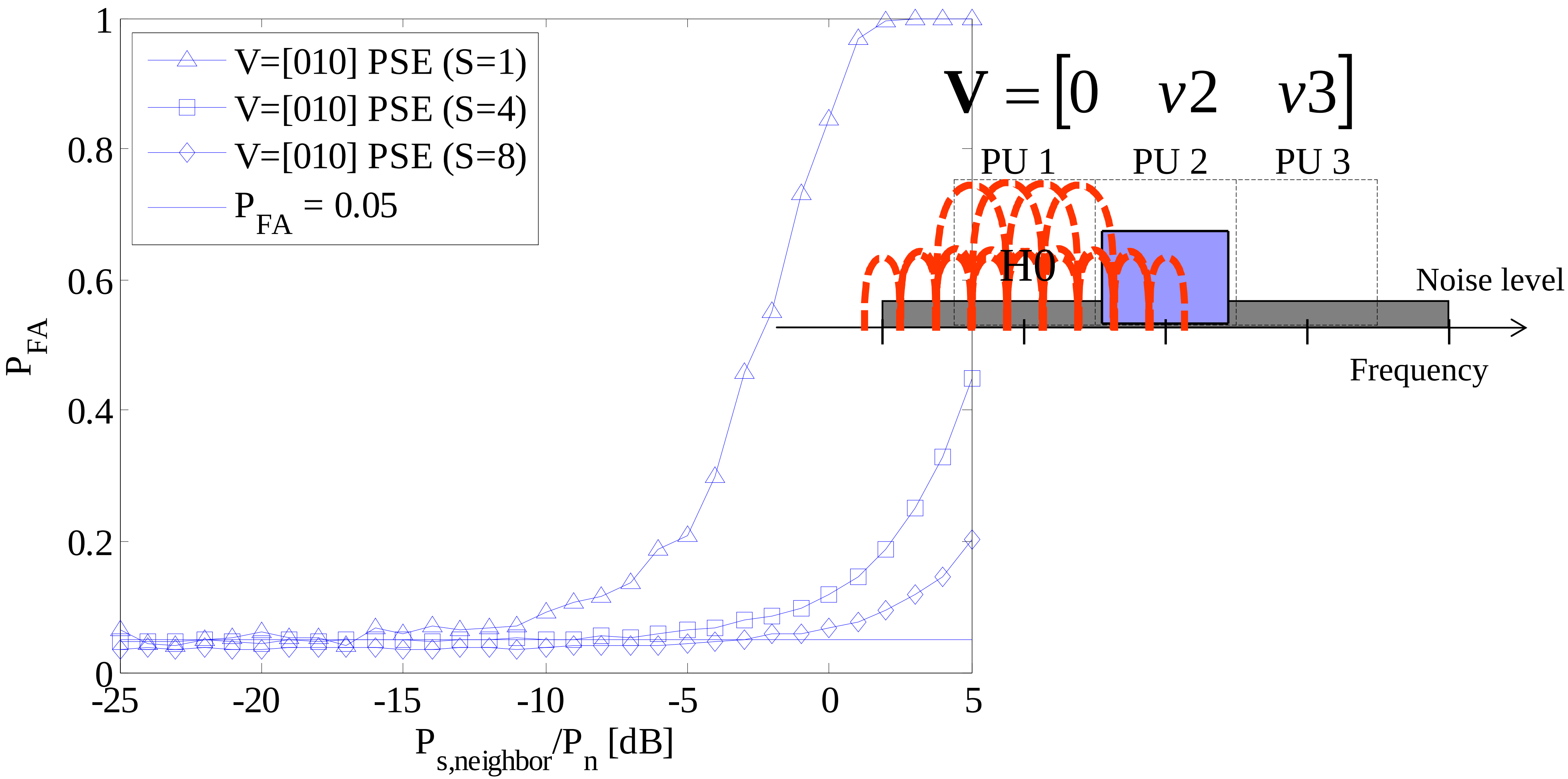
Prob. False Alarm（Pfa）



■ PSEの場合，隣接ユーザチャネルの信号電力を拾ってしまうため，隣接ユーザチャネル電力が大きくなるに連れて誤警報確率が高くなってしまう

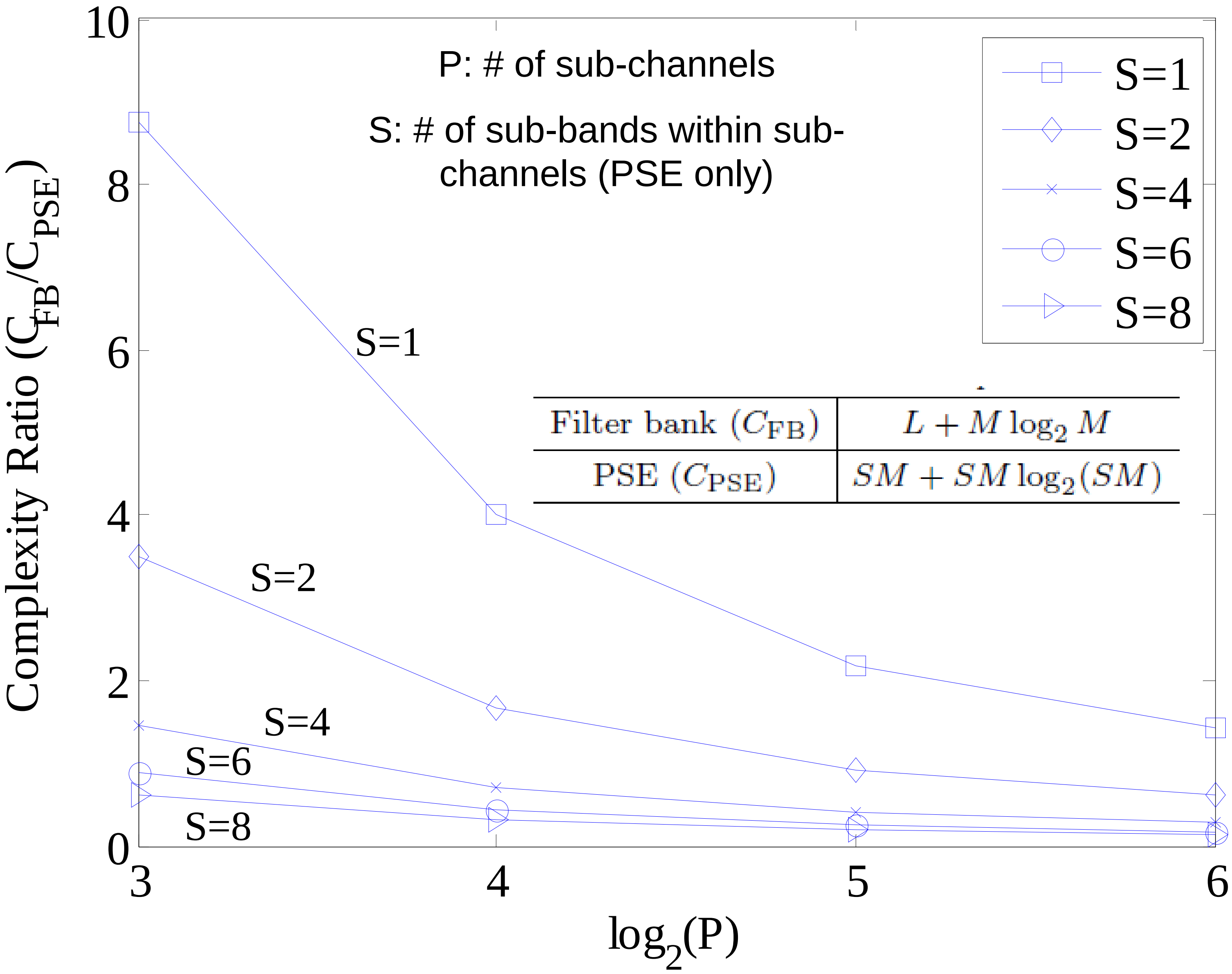
■ フィルタバンクの場合，性能劣化無し

Prob. False Alarm (Pfa) (2)



■ PSEの分解能を向上し，隣接ユーザチャネルの影響を抑えることはある程度可能であるが，計算負荷が増加する

Complexity



Filter bank (C_{FB})	$L + M \log_2 M$
PSE (C_{PSE})	$SM + SM \log_2(SM)$

Summary

- Efficient wideband sensing scheme for multiple sub-channels proposed
- By using poly-phase DFT filter bank, optimal bandpass filter can be implemented
- Practical scenario (DTV in US)
- Future works
  - Optimum filter design
  - Assessment in practical environment
  - Dynamic range
  - Optimum sensing strategy