Filter Bank Design for Multicarrier Transmission and Spectrum Sensing

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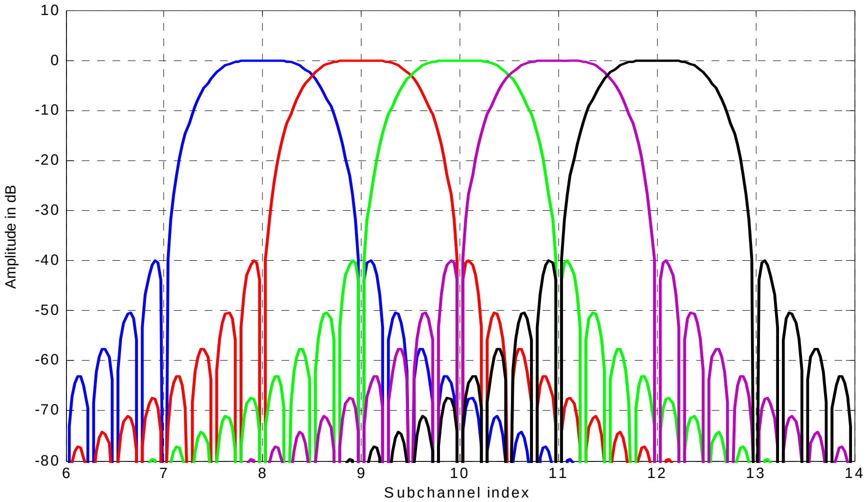
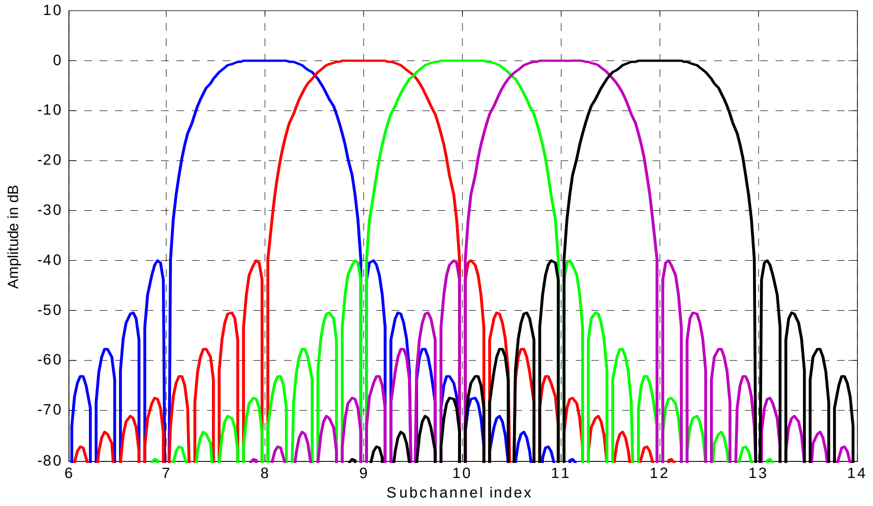
Filter bank structure

- We consider efficient uniform, modulation-based filter banks, where subchannel frequency responses are obtained as frequency-shifted versions of a prototype.



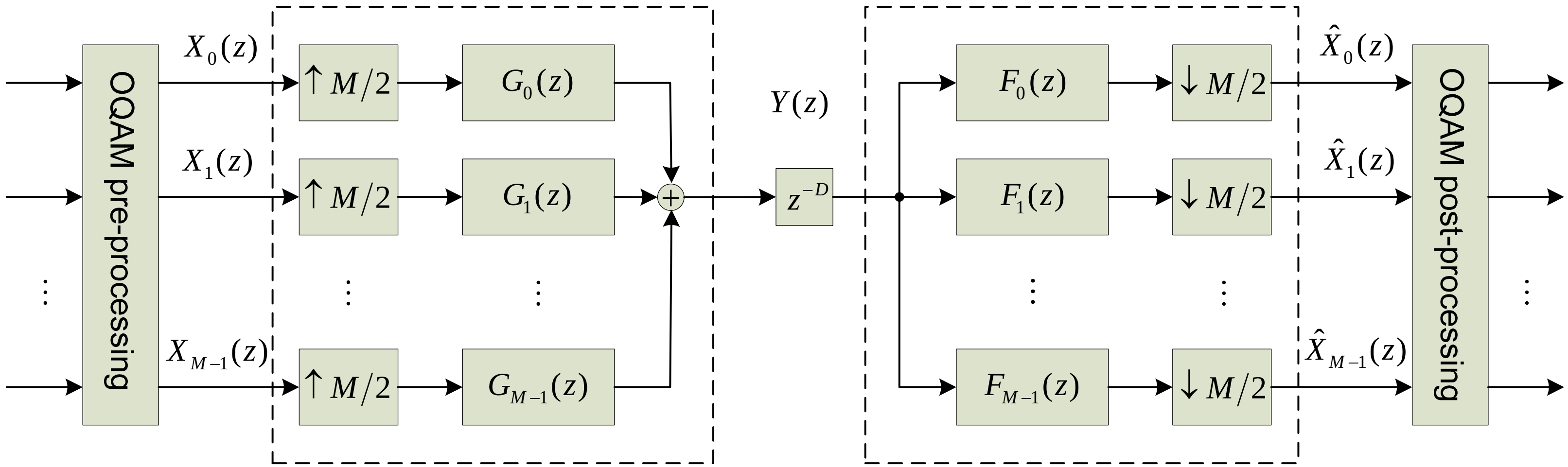
- In all designs, the overall subchannel bandwidth (with transition bands) is 2 x subchannel spacing (i.e., roll-off factor=1).
  - ➢ Only immediately adjacent subchannels are significantly interacting with each other.
  - ➢ One unused subcarrier is sufficient as a guard-band to isolate different groups of subcarriers.
- Reduced guardbands between users
- No CP's
  - ➢ Improved spectral efficiency

Filter bank structure



- The transmultiplexer system achieves nearly perfect reconstruction (with ideal channel).
  - ➢ Residual distortion is small compared to noise in the practical SNR range. (Perfect reconstruction is possible, but not interesting due to higher complexity.)

Transmultiplexer system model



Synthesis filter bank

Analysis filter bank

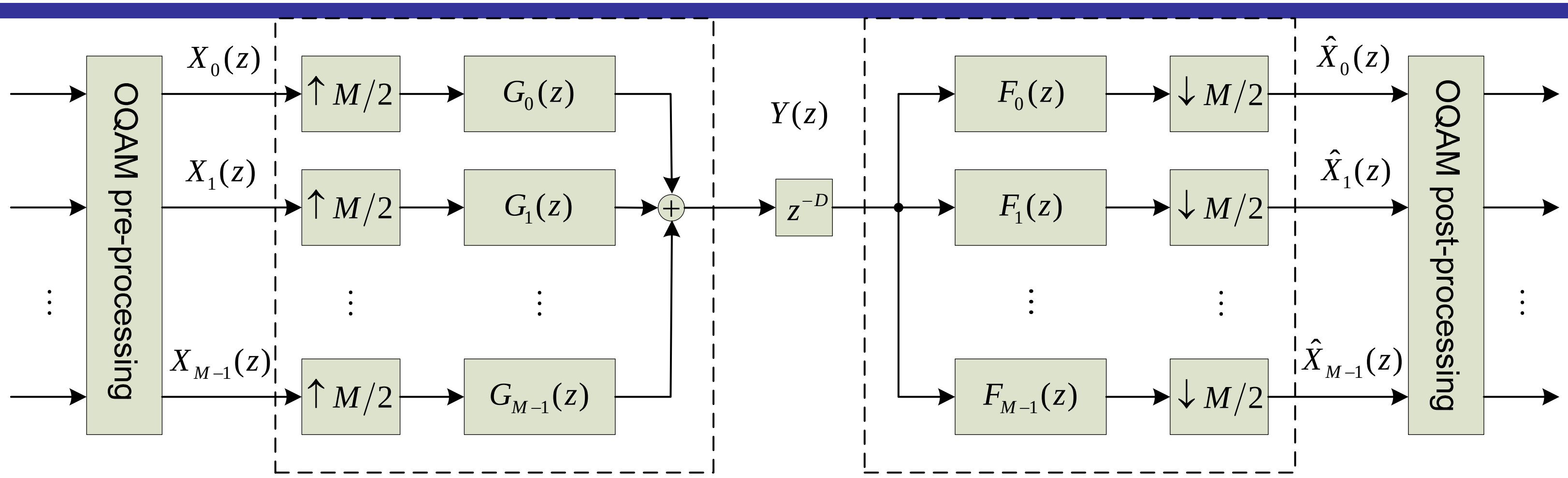
$$g_k[m] = p[m]\exp\left(j\frac{2\pi k}{M}\left(m - \frac{L_p - 1}{2}\right)\right)$$

$$\begin{aligned} f_k[m] &= g_k^*[L_p - 1 - m] \\ &= p[m]\exp\left(j\frac{2\pi k}{M}\left(m - \frac{L_p - 1}{2}\right)\right) \end{aligned}$$

Extra delay z^{-D} depends on the prototype filter length: $L_p = KM + 1 - D$

- For example: PHYDYAS initial prototype filter $L_p = KM - 1 \Rightarrow D = 2$

Transmultiplexer system model



Synthesis filter bank

Analysis filter bank

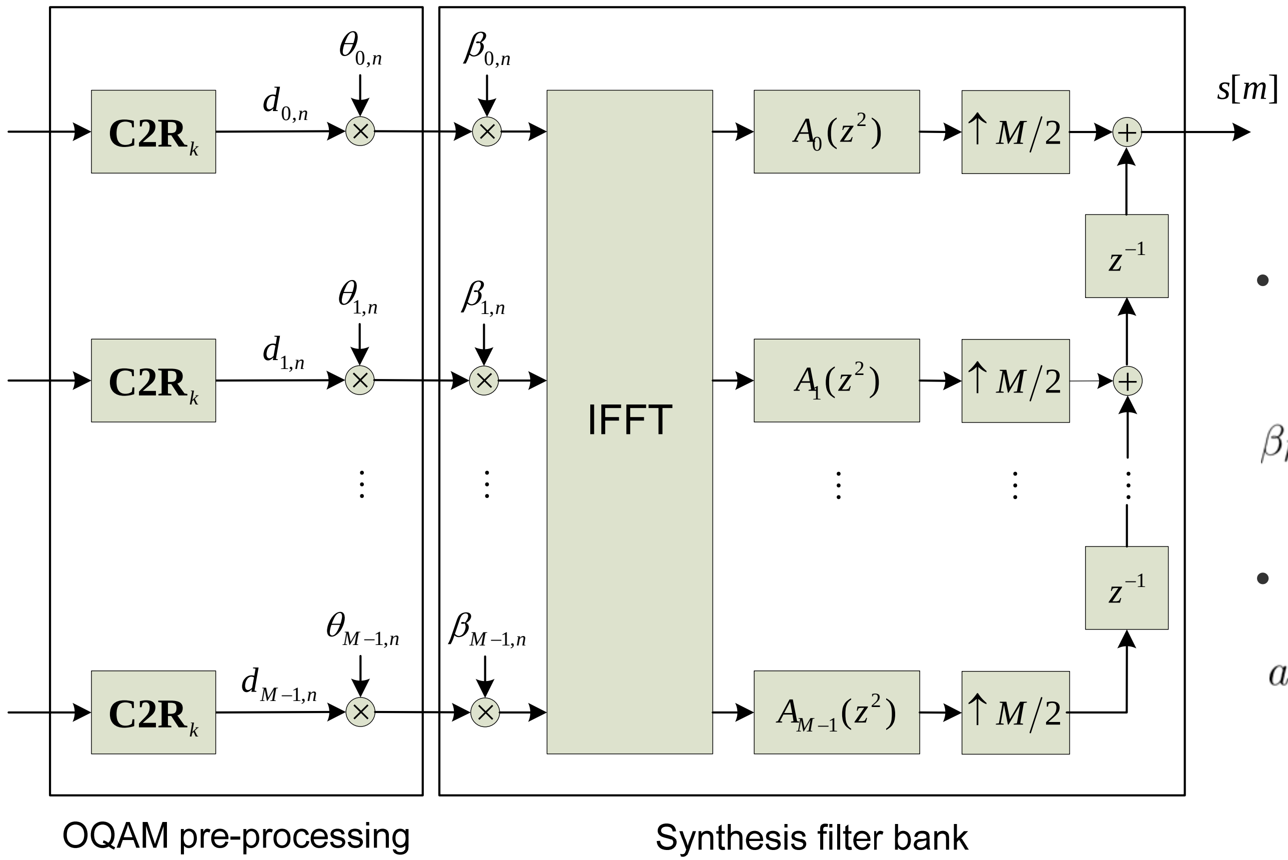
$$g_k[m] = p[m] \exp\left(j\frac{2\pi k}{M}\left(m - \frac{L_p - 1}{2}\right)\right)$$

$$\begin{aligned} f_k[m] &= g_k^*[L_p - 1 - m] \\ &= p[m] \exp\left(j\frac{2\pi k}{M}\left(m - \frac{L_p - 1}{2}\right)\right) \end{aligned}$$

To achieve orthogonality in a spectrally efficient manner, offset-QAM signal model is crucial.

- Each QAM symbol is mapped to two consecutive subcarrier samples.
- Subcarrier sample sequences are oversampled by a factor of 2.

Transmitter side: Efficient polyphase structure for synthesis filter bank



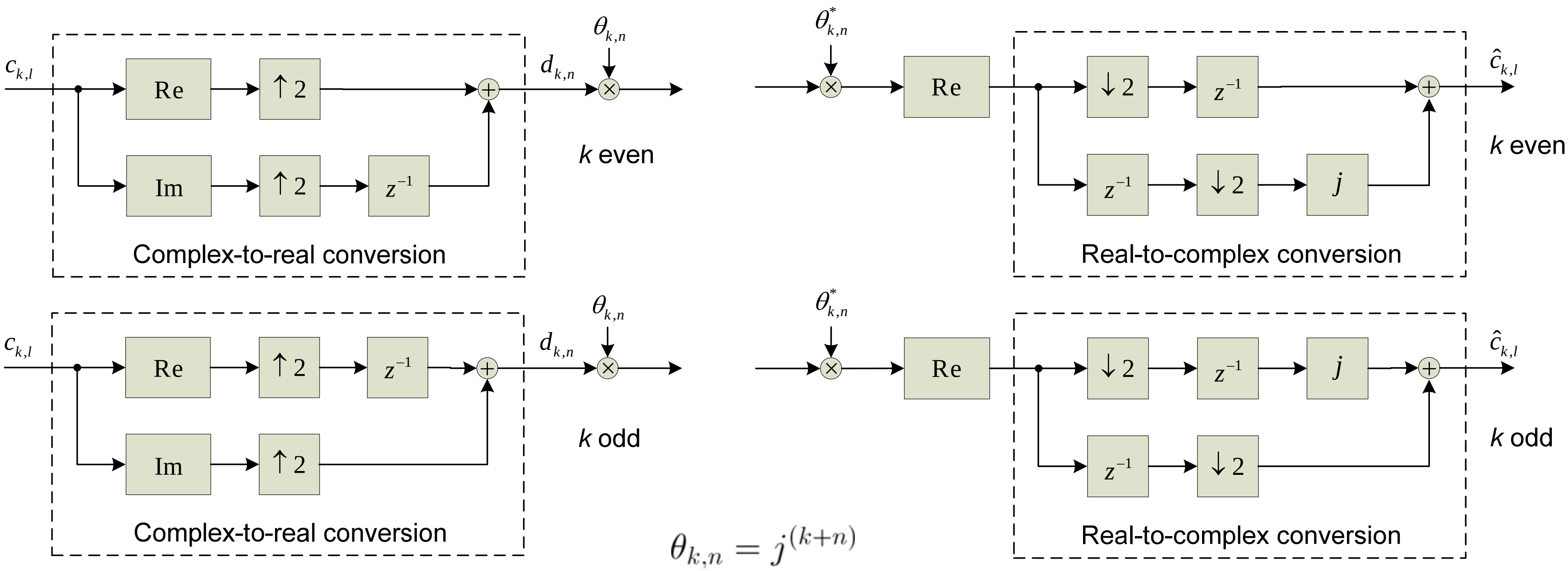
- Filter length dependent multipliers:

$$\beta_{k,n} = (-1)^{kn} \exp\left(-j\frac{2\pi k}{M}\left(\frac{L_p - 1}{2}\right)\right)$$

- Type-1 polyphase filters:

$$a_k[m] = p[k + mM]$$

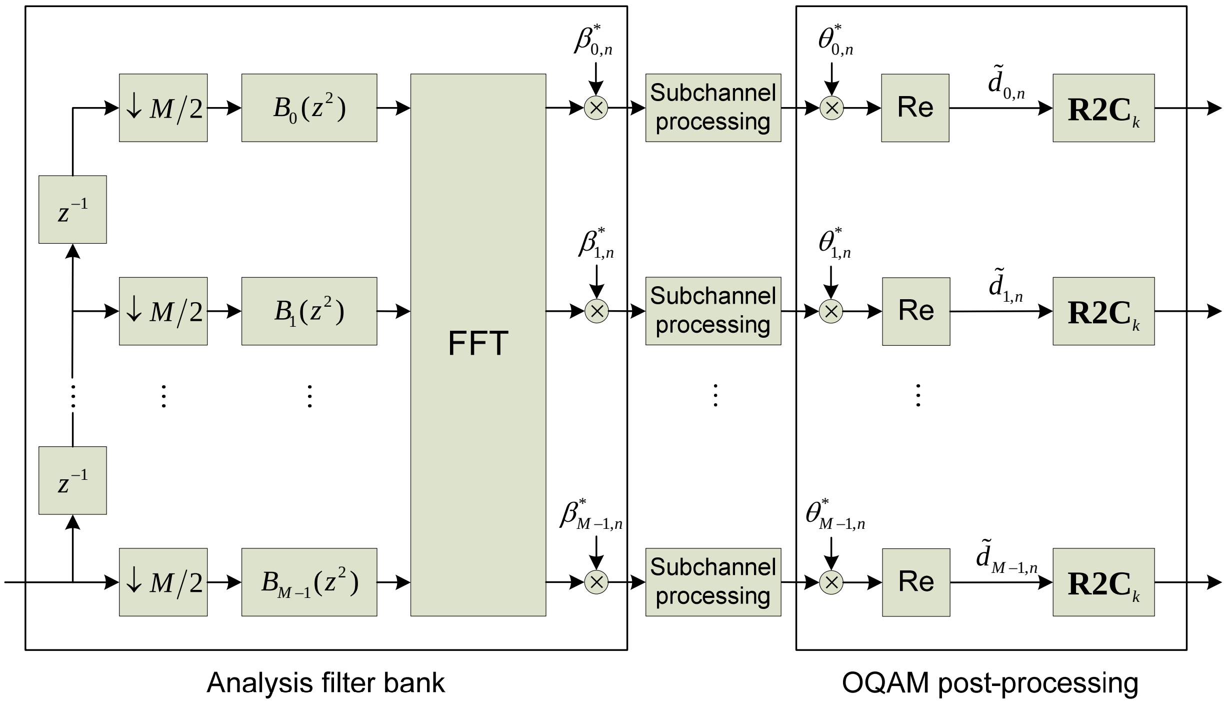
OQAM pre/post-processing sections



$$\theta_{k,n} = j^{(k+n)}$$

- Complex-to-real conversion increases the sample rate by a factor of 2
- Real-to-complex conversion decreases the sample rate by a factor 2

Receiver side: Efficient polyphase structure for analysis filter bank



- Filter length dependent multipliers:

$$\hat{\beta}_{k,n} = (-1)^{kn} \exp\left(-j\frac{2\pi k}{M}\left(\frac{L_p+1}{2}\right)\right)$$

- Type-2 polyphase filters:

$$b_k[m] = a_{M-1-k}[m] = p[M-1-k+mM]$$

Proper subchannel processing restores the orthogonality of subcarriers in case of frequency-selective channels.

- Synchronization & channel equalization
- 2x oversampling at subcarrier processing => Fractionally spaced equalization

Contents

Optimization of prototype filters

- **Design techniques**
  - Frequency sampling technique
    - Just one adjustable parameter in optimization
  - Windowing based techniques
    - A few adjustable parameters in optimization
  - Direct optimization of prototype filter coefficients
    - All coefficients optimized
- **Design criteria**
  - C1: Least-squares (LS) criterion: *minimized stopband energy*
  - C2: Minimax criterion: *maximizes stopband attenuation*
  - C3: Peak-constrained LS criterion
  - C4: Total filter bank structure based interference (ISI & ICI)

Frequency sampling technique in prototype filter

$$p[m] = \bar{P}[0] + 2\sum_{k=1}^{K-1}(-1)^k \bar{P}[k]\cos\left(\frac{2\pi k}{KM}(m+1)\right)$$

$$m = 0, 1, \ldots, KM-2$$

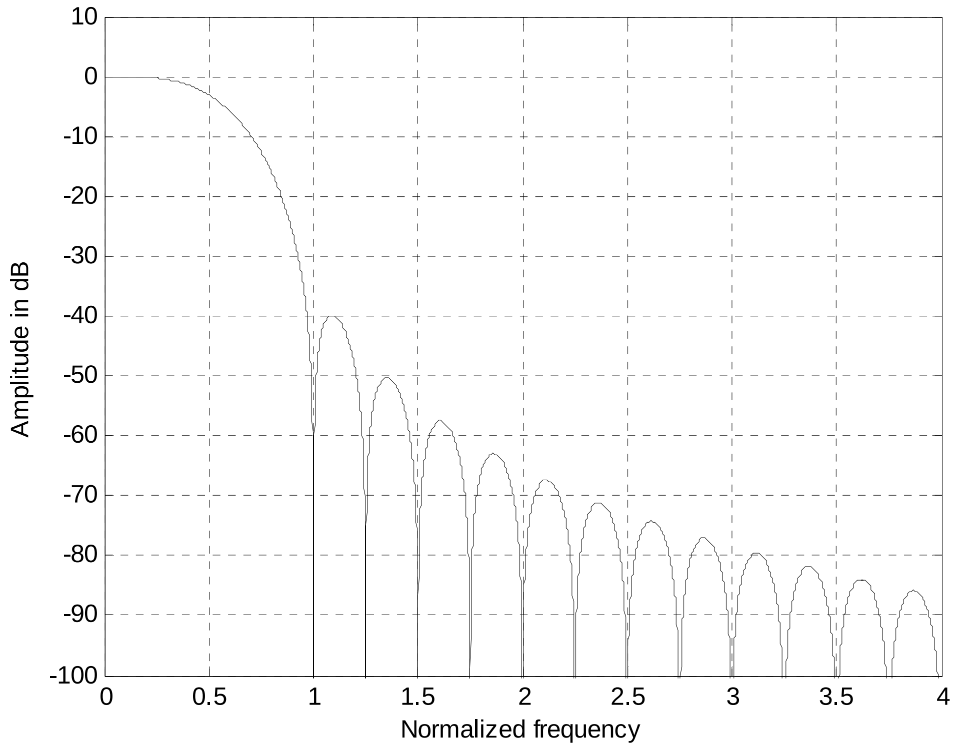
$$K = 4$$

$$\bar{P}[0] = 1$$

$$\bar{P}[1] = 0.97195983$$

$$\bar{P}[2] = 1/\sqrt{2}$$

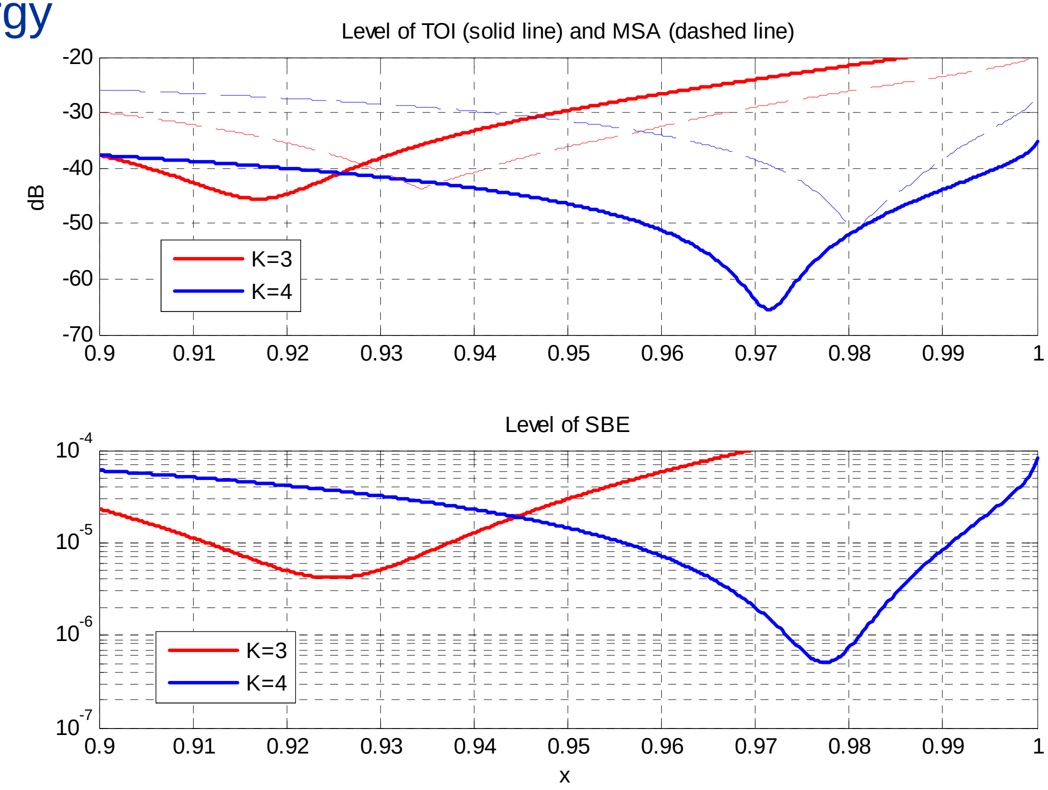
$$\bar{P}[3] = 0.23514695$$



- High frequency selectivity
- Exact stopband zeros
- The prototype filter length is $L=KM \pm 1$, where M is the number of subchannels and K is the overlaping factor.
- Mostly the overlapping factors $K=\{3, 4, 5\}$ are considered.

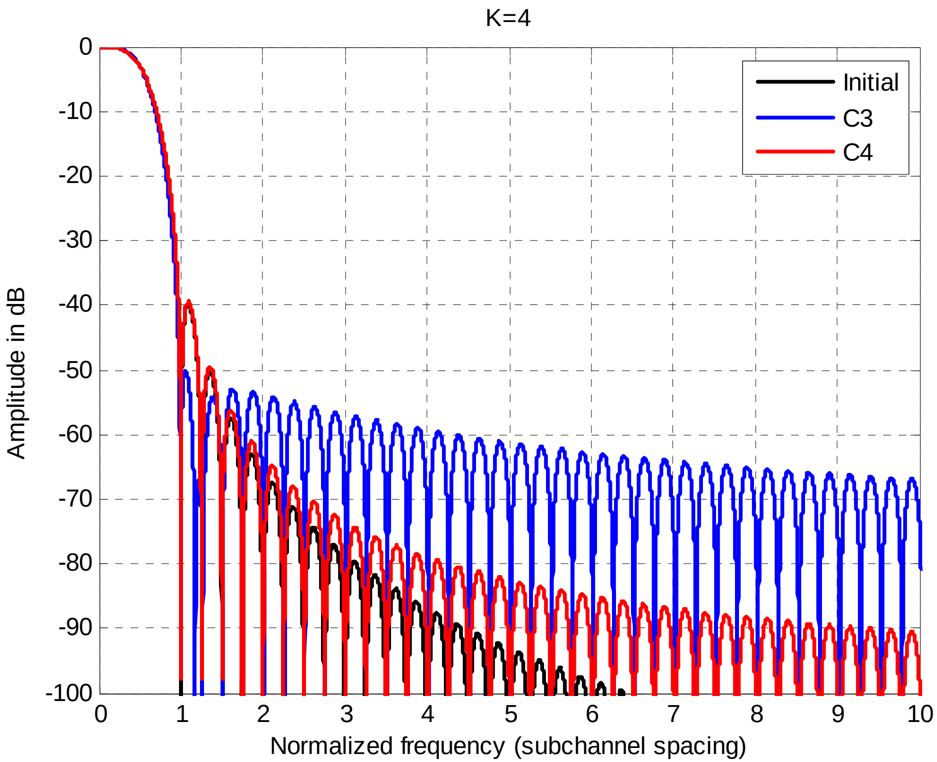
Optimization results: Frequency sampling technique

- Performance metrics vs. optimization parameters
  - MSA: minimum stopband attenuation, TOI: Total interference, SBE: stopband energy
    - ➢ Tradeoff between different criteria!



Optimization results: Frequency sampling technique

- Frequency responses with different criteria



Optimization results: Tradeoffs between optimization criteria

1. Frequency-sampling based design

	Minimum stopband attenuation dB	Stoband energy dB	Total interference dB
K=3 Initial	32.6	-50	-43.4
max MSA	**43.8**	-51.3	-35.8
min SBE	37.6	**-53.8**	-41.5
min TOI	34.3	-52.0	**-45.5**
K=4 Initial	39.9	-58.7	-65.2
max MSA	**51.7**	-60.9	-51.5
min SBE	45.7	**-63.0**	-55.1
min TOI	39.5	-58.2	**-65.5**
K=5 max MSA	**72.2**	-77.7	-63.6
min SBE	65.2	**-82.7**	-64.4
min TOI	56.2	-74.8	**-71.6**

Optimization results: Tradeoffs between optimization criteria

2. Frequency-sampling based design vs. direct optimization

	Minimum stopband attenuation dB	Stoband energy dB	Total interference dB
K=3 Initial	32.6	-50	-43.4
max MSA	**43.8** **48.7**	-51.3	-35.8
min SBE	37.6	**-53.8** **-56.8**	-41.5
min TOI	34.3	-52.0	**-45.5** **(-91.1)**
K=4 Initial	39.9	-58.7	-65.2
max MSA	**51.7** **57.3**	-60.9	-51.5
min SBE	45.7	**-63.0** **-68.0**	-55.1
min TOI	39.5	-58.2	**-65.5** **(-96.6)**
K=5 max MSA	**72.2** **75.7**	-77.7	-63.6
min SBE	65.2	**-82.7** **-84.9**	-64.4
min TOI	56.2	-74.8	**-71.6** **(-101.9)**

Contents

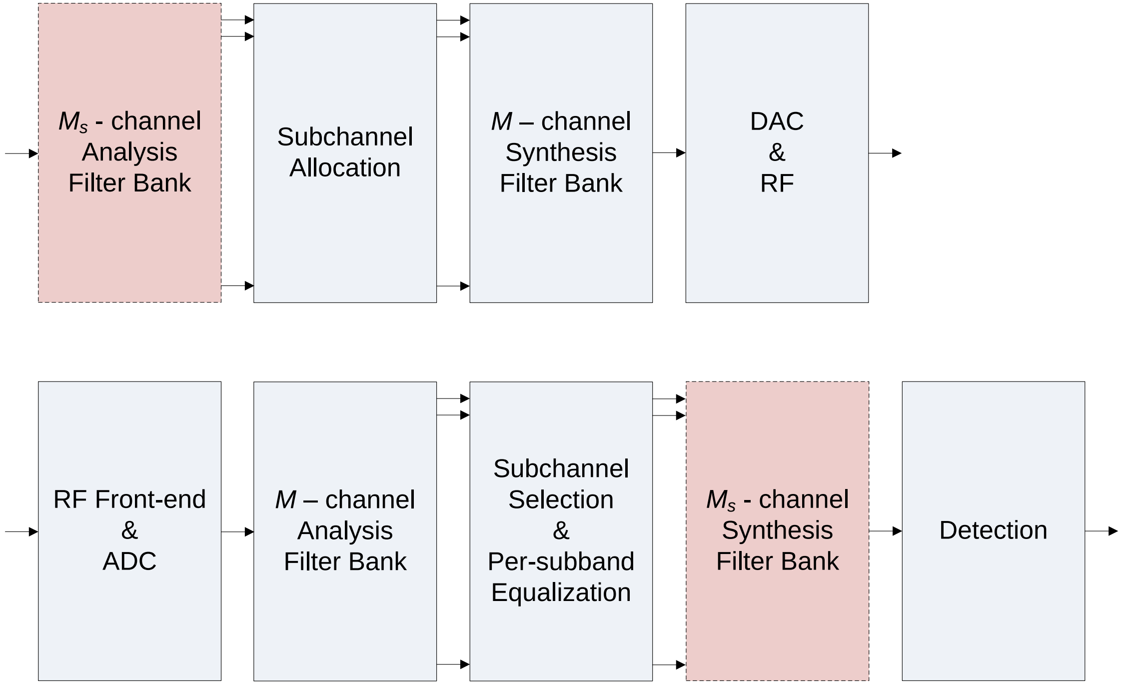
Mixing multicarrier and single-carrier transmission

DFT -spread OFDM Used in 3GPP LTE uplink

- Primary motivation: Reduced peak-to-average power ratio (PAPR)

FB-spread FBMC

- Can be easily combined with FBMC in the uplink
- Can achieve similar PAPR benefit as DFT-S-OFDM



Performance comparison: PAPR

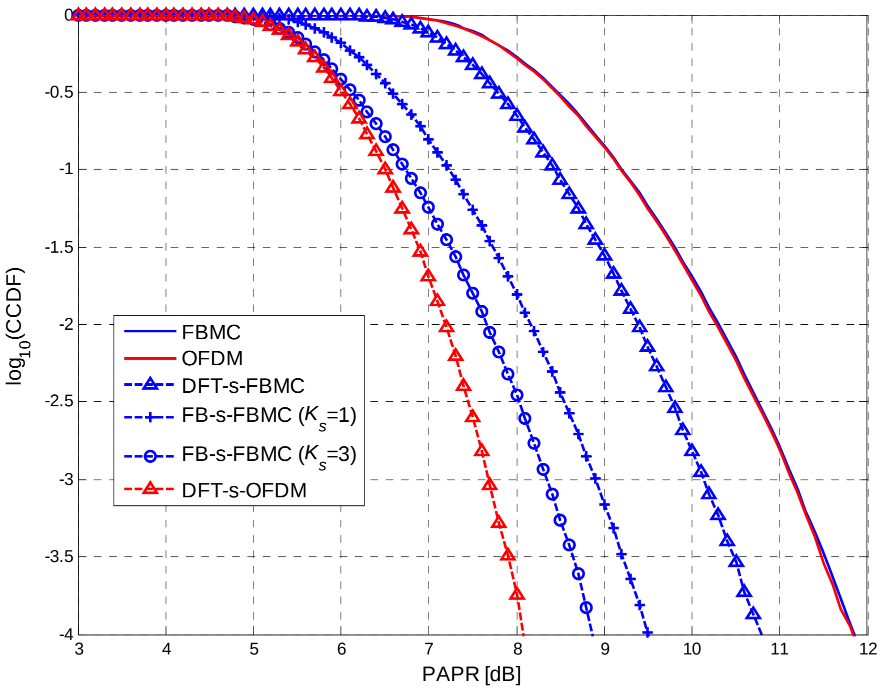
Comparison of OFDM and FBMC

- ➢ Prototype filter has only a minor effect on PAPR
- ➢ Characteristics of OFDM and FBMC are very similar

Comparison of single-carrier modes

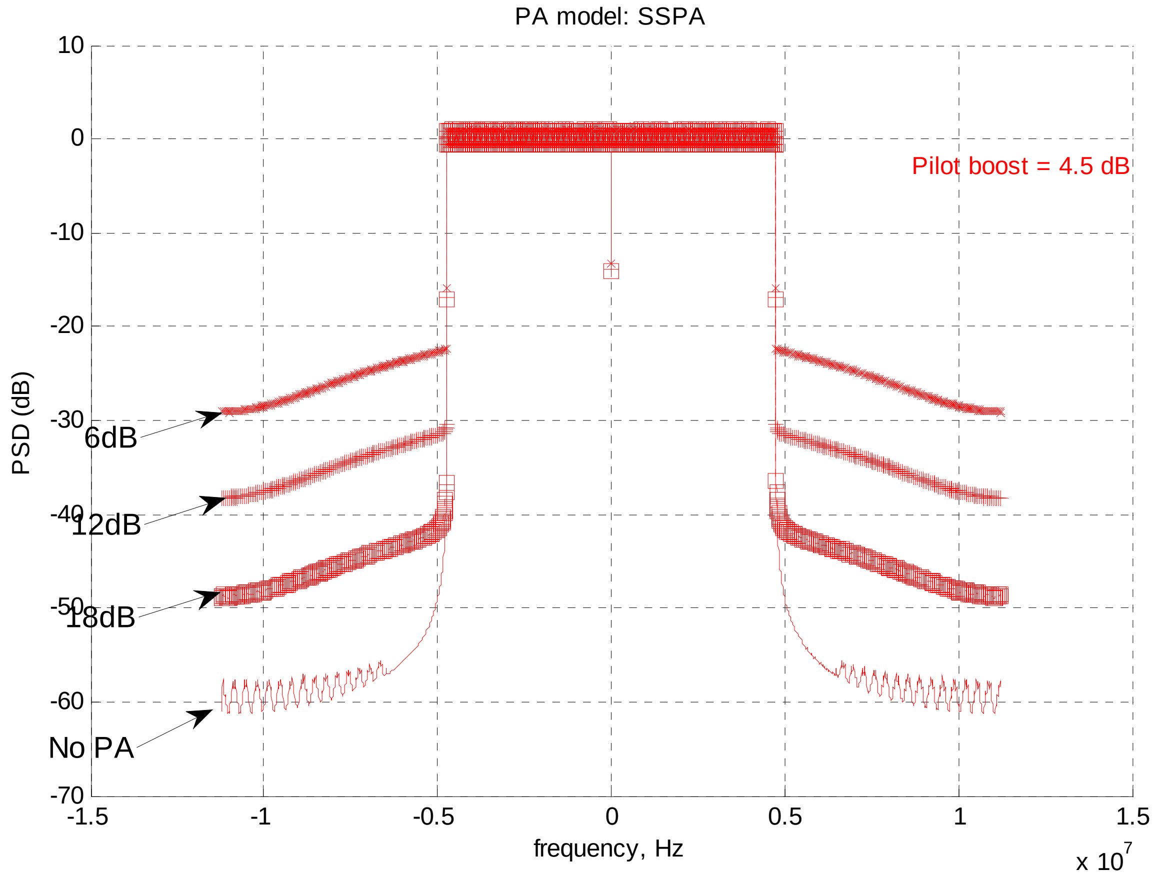
- DFT-S-OFDM
- DFT-S-FBMC
- FB-S-FBMC

- ➢ DFT spreading is not sufficient for FBMC
- ➢ With suitable prototype filters, it is possible to reach the PAPR performance of DFT-S-OFDM

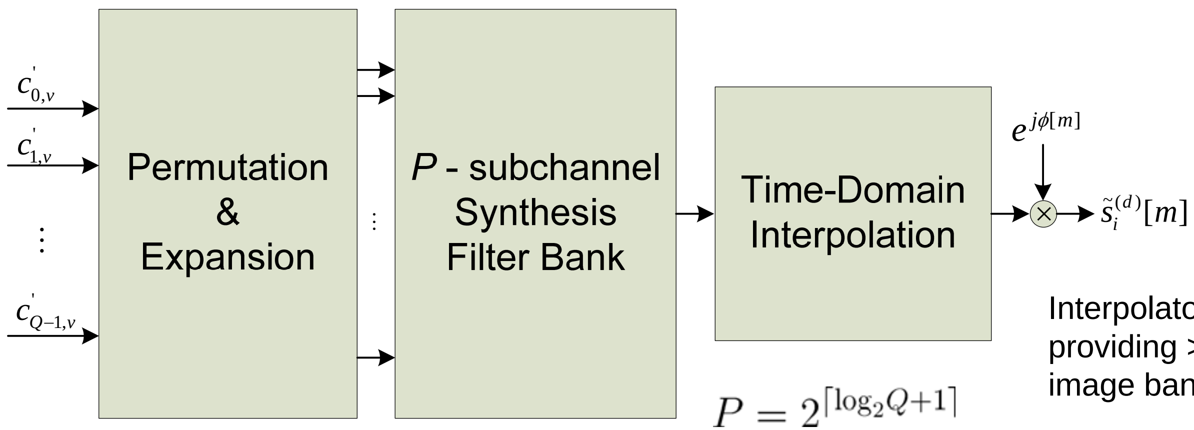


Spectral Regrowth due to PA nonlinearities

- Preliminary results for FBMC using basic PA models: SSPA model



Partial TMUX model



$$P = 2^{\lceil \log_2 Q + 1 \rceil}$$

Interpolator: A cascade of halfband filters providing >70 dB attenuation on the image band(s).

FBMC transmitter and receiver can be based on synthesis and analysis filter banks of different sizes.

- Focus on signals with contiguous narrowband subcarrier allocation (uplink).
- Instead of using full-size SFB, the scheme relies on a cascade of P-subchannel SFB ($P << M$), time domain interpolation, and a user-specific frequency shift.
  - It is easy to extend the idea to P-subchannel AFB (downlink case).
- In partial TMUX design, the signal quality is not compromised
  - EVM in -55…-66 dB range

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3. **Prototype filter design**
4. **Advanced filter bank techniques**
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   - Partial TMUX
5. **FBMC based cognitive radio physical layer**
6. **Spectrum sensing issues**
7. **Conclusion and outlook**

PHYDYAS: FBMC based cognitive radio physical layer

- **The idea of FBMC has existed since the 60'ies, but still there are signal processing and communication theoretic issues which are not mature enough for practical use:**
  - Synchronization
  - Channel estimation and equalization
  - Adaptation to multi-antenna & MIMO concepts
  - Multiple access specifics
  - etc.

- **PHYDYAS project is focusing on these open topics.**
  - WiMAX -like system concept as the starting point
  - Special focus on dynamic spectrum use and cognitive radio

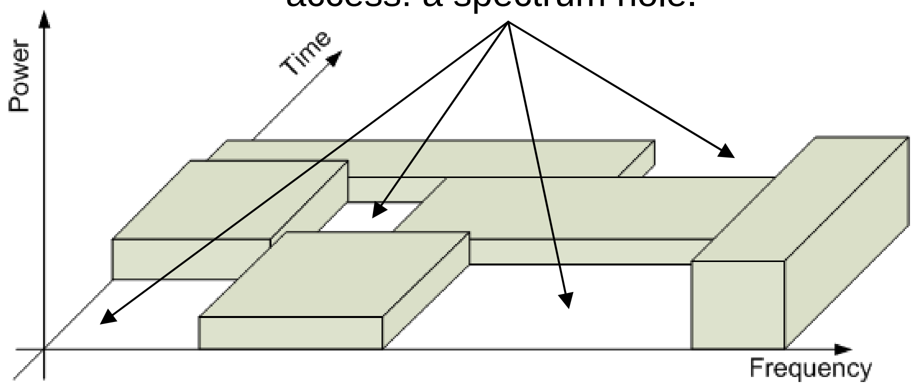
About spectrum sensing

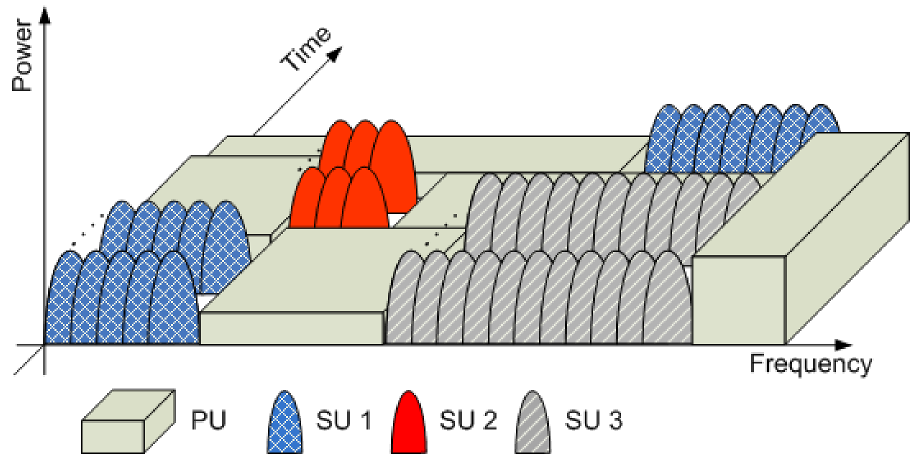
- **Spectrum sensing will be an important element in future networks.**
- **There is also need for devices which can be used for both sensing and data reception.**
  - Commonality of sensing and data reception functions is important.
  - Similar requirements for spectral agility.
- **Most of the spectrum sensing studies have assumed an idealized spectrum sensing filter.**
  - Basically, we need a highly configurable filter bank.
- **Multicarrier techniques can provide the needed commonality and configurability.**
  - OFDM is the common choice.
  - Filter bank based multicarrier (FBMC) techniques have some very interesting characteristics.
- Here the focus is on spectrum sensing using FBMC.

Motivation, problem area

- **Concepts of a spectrum hole and opportunistic spectrum sharing:**

Spectral opportunity for secondary access: a spectrum hole.

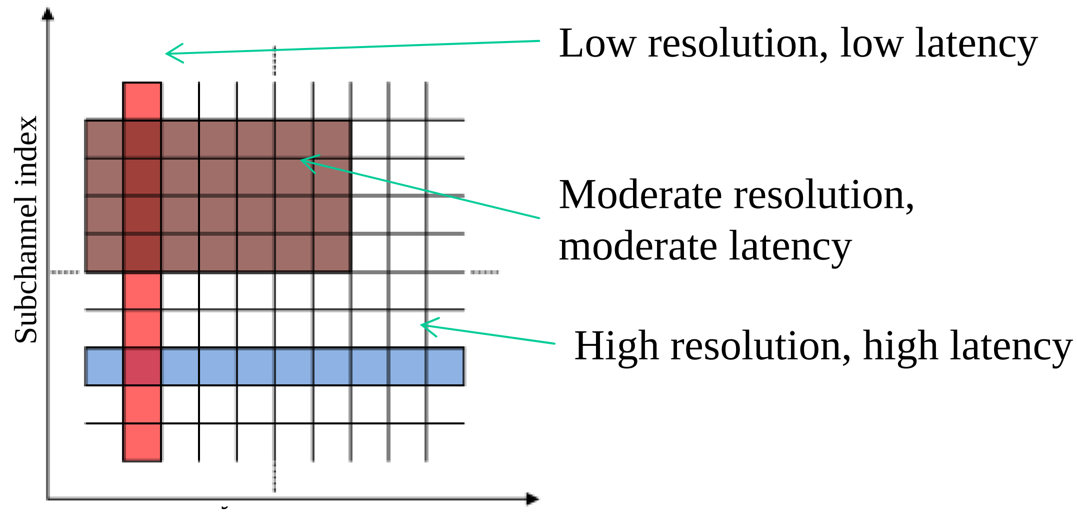




Concept of opportunistic spectrum sharing: secondary utilization of the identified spectrum holes.

Filter bank spectrum sensing

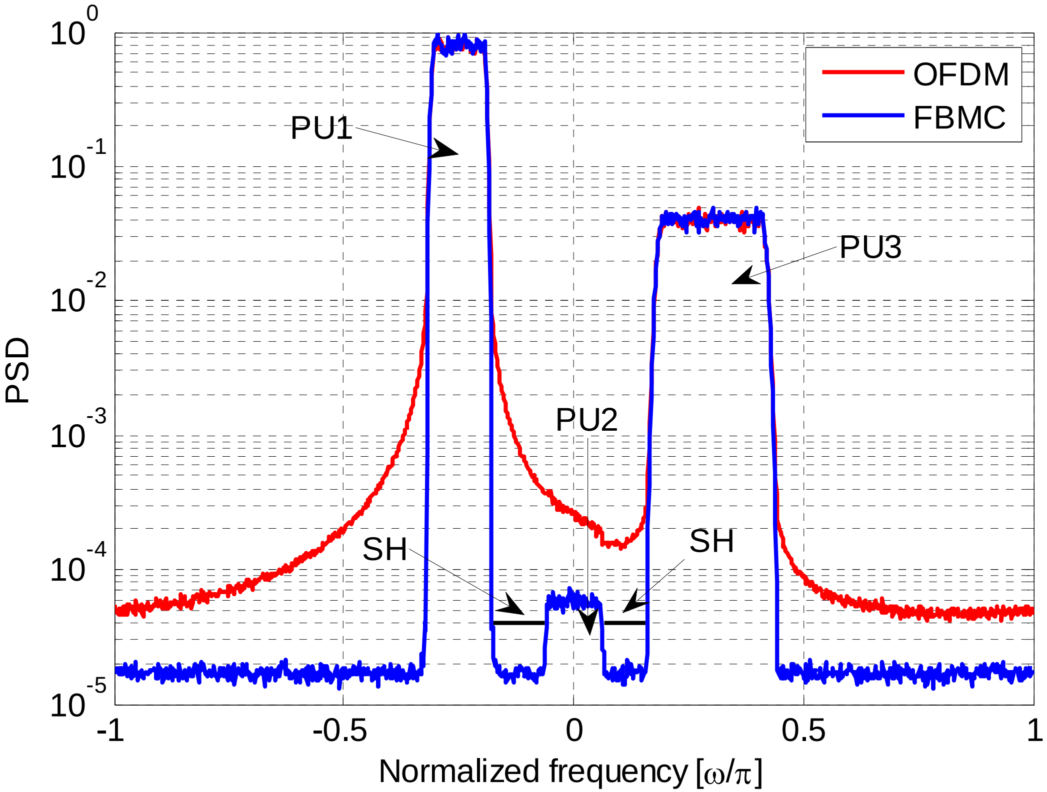
- **Resolution vs. latency trade-off:**



- **High flexibility:**
  - Energy measurements for each subcarrier symbol.
  - Summation of energy measurements over used time-frequency window(s).
  - Minimum window size determined by P_{FA} & P_{MD}.
- **Multiple-dwell approaches easy to implement using different window sizes:**
  - Fast reaction to new strong PU signals.
  - Fast detection of possible white spaces (i.e., grey spaces)
  - Longer integration to reach adequate P_{FA} & P_{MD}.

FBMC receiver as energy detector

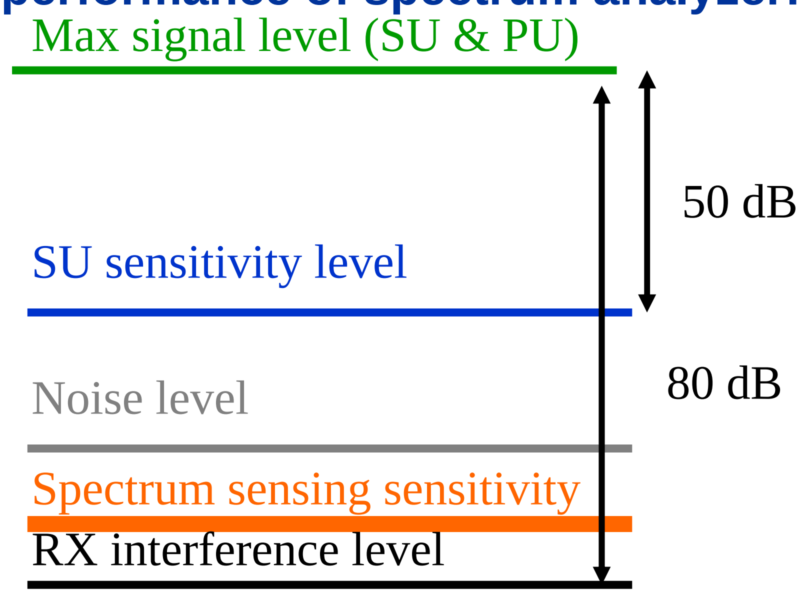
- Here, classical energy detection is considered.
- M = 1024 subchannels.
- FBMC receiver is not blinded by the presence of high level neighboring signals and is able to identify accurately the spectrum holes.



Spectrum sensing specifications

- **Frequency resolution: subchannel spacing**
  - smallest spectral hole
  - spectral granularity for transmission
- **Noise floor: thermal noise + interference**
- **Spectral dynamic range: > 50 dB**
- **Out-of-band interference rejection performance of spectrum analyzer: > 80 dB**
- **Sensing latency**

=> Criteria for filter bank design



Sensing time analysis

Sensing decision is a binary hypothesis testing problem:

$$z[l] = \begin{cases} n[l], & H_0 \text{ :noise only} \\ s[l] + n[l], & H_1 \text{ :signal present} \end{cases}$$

Test statistic:

$$Y = \frac{1}{N}\sum_{l=1}^{N} |z[l]|^2$$

Probability of false alarm:

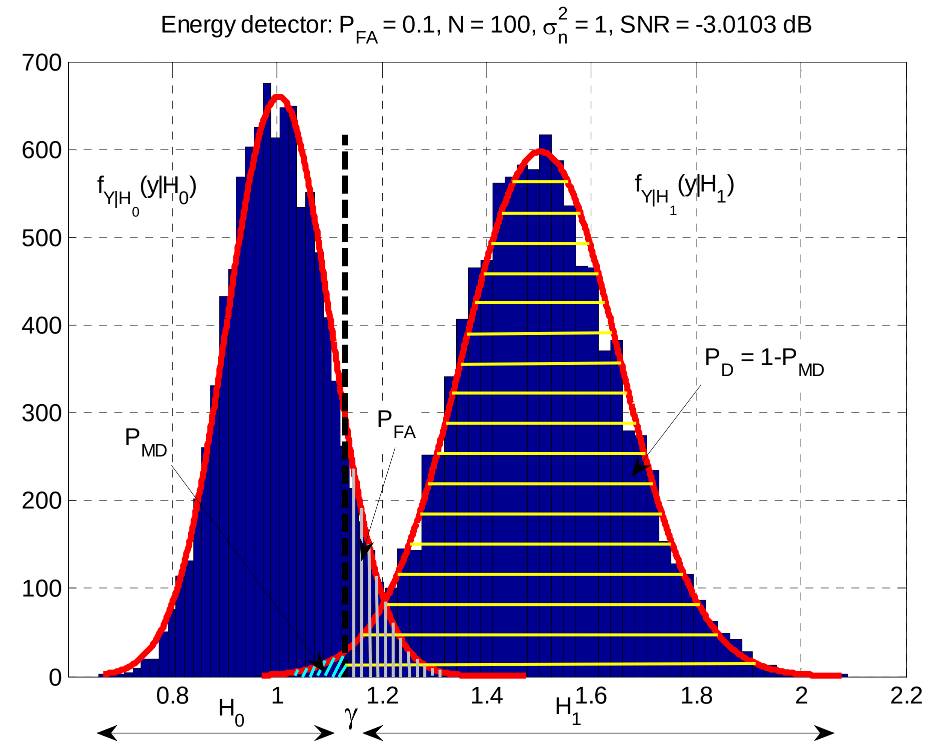
$$P_{FA} = P(Y > \gamma \mid H_0)$$

→ Lost secondary opportunity.

Probability of missed detection:

$$P_{MD} = P(Y < \gamma \mid H_1)$$

→ Interference to primary system.



Sensing in the presence of noise uncertainty

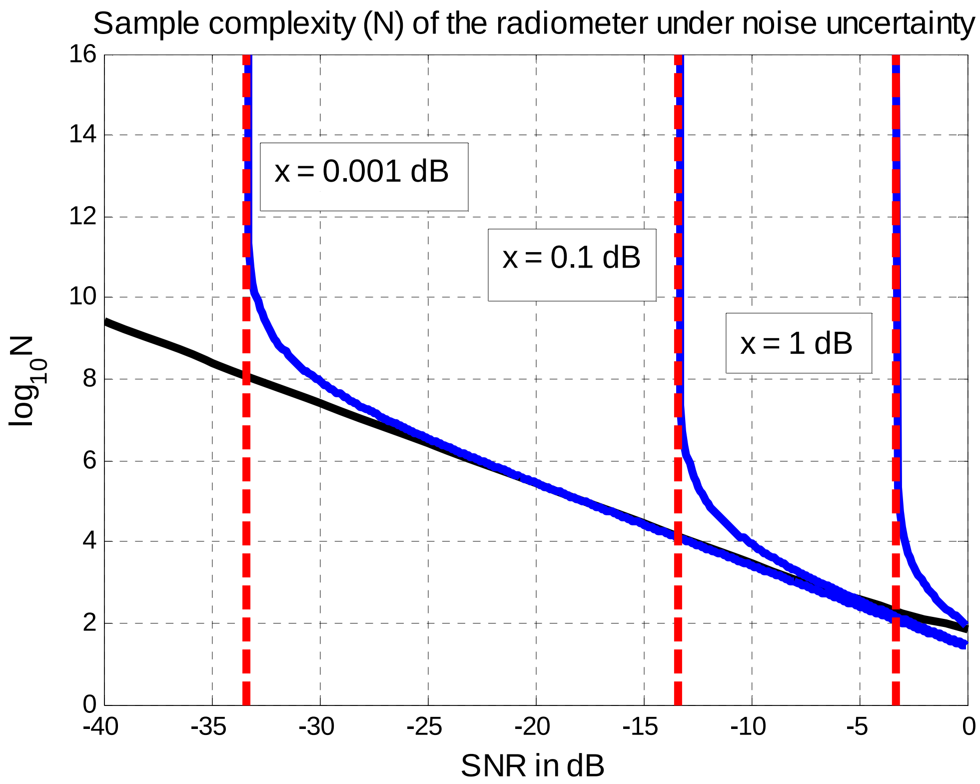
$$N = \frac{2[\Phi^{-1}(P_{FA}) - \Phi^{-1}(1-P_{MD})(1+SNR)]^2}{SNR^2}$$

$$N \approx \frac{2[\Phi^{-1}(P_{FA}) - \Phi^{-1}(1-P_{MD})]^2}{\left[SNR - (\rho - \frac{1}{\rho})\right]^2}$$

The sensing time depends on the primary signal SNR and the noise uncertainty ρ (x in dB units).

The noise uncertainty introduces an SNR wall in energy detection [1]:

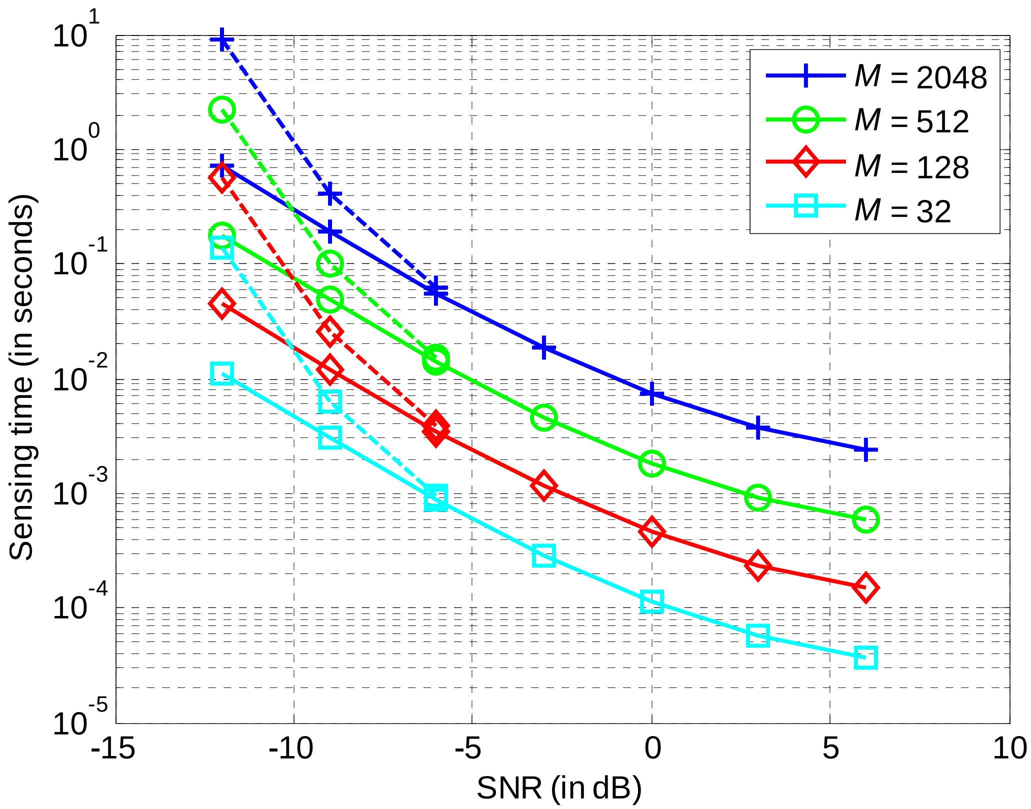
$$SNR_{wall}^{energy} = \frac{\rho^2 - 1}{\rho}$$



[1] R. Tandra and A. Sahai, "SNR Walls for Signal Detection," *IEEE J. Selected Topics in Signal Processing*, vol. 2, No. 1, Feb. 2008

Sensing time in FBMC systems

- **Sensing time in subcarrier -wise spectrum sensing in multicarrier systems:**



20 MHz overall bandwidth

$P_{FA} = 0.1$

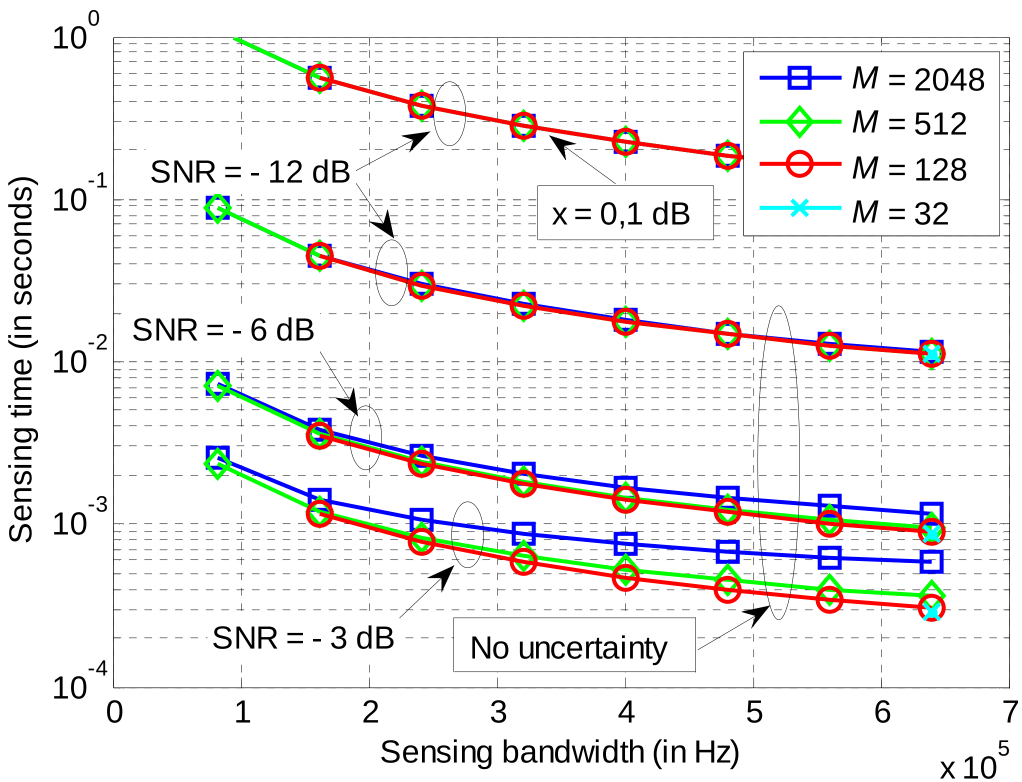
$P_{MD} = 0.01$

Dashed lines:
±0.1 dB uncertainty.
Solid lines:
Noise variance known.

- Sensing time is inversely proportional to sensing bandwidth (=subcarrier spacing).

Sensing time vs. sensing bandwidth

- Sensing time **as a function of bandwidth** for different primary signal SNR's:



$P_{FA} = 0.1$

$P_{MD} = 0.01$

- With higher SNR's, high bandwidths, and high number of subcarriers, the sensing time is only a few multicarrier symbols, and filter bank impulse response length becomes the limiting factor.

About the sensing bandwidth

1. **PU bandwidth and center frequency known**
   - Sensing time minimized when all subcarriers within the PU bandwidth are utilized in sensing.
   - In wideband cases, it may be sufficient to use only part of the subcarriers.
     - Frequency diversity useful in case of frequency selective channels.
2. **PU bandwidth known, center frequency unknown**
   - Test all possible center frequencies
   - Missed detection probability requirement satisfied.
   - Some uncertainty about the center frequency even if PU can be reliably detected.
     - Some edge subchannels as grey space.
3. **Free scenario: PU bandwidths and center frequencies unknown**
   - Subchannel spacing as the sensing bandwidth.

Simultaneous sensing and reception

The possibility of simultaneous sensing and reception would facilitate the coexistence of primary and secondary users.

- Fast reaction to reappearing primary users.
- Implementation: a single, highly frequency selective filter bank for sensing and reception.
- Techniques for spectrum monitoring:
  1. Reserved sub-channels or sensing blocks in time-frequency plane.
  2. Zero pilots could be used
     - Reduced overhead because guard space is not needed around pilots.
  3. Estimation of residual interference in pilots or detected data symbols.
     - No overhead in data transmission capacity due to sensing..
- In case 1, coarse time and frequency synchronization of SU's is sufficient.
- In case 2 and 3, the sensing device has to synchronize itself to the secondary transmissions.
  - Performance is degraded in case of significant multi-user interfrence between secondary users.

Summary: FBMC as cognitive radio physical layer

Advantages:

- Spectral efficiency: no CP's, one empty subcarrier is sufficient as a guard-band between different secondary users.
- The same filter bank can be used for receiver data signal processing and flexible, high-resolution spectrum sensing with high dynamic range.
- Spectrally efficient way to introduce silent blocks within secondary transmissions for spectrum sensing.

Challenges:

- Filter bank impulse response "tails" (i.e., time-domain overlap of subcarrier symbols) introduce overhead in tightly time-multiplexed operation.
- High linearity for transmitter power amplifier needed to maintain the clean spectrum provided by the synthesis filter bank.
- Analog RF performance is critical for implementing generic spectrum sensing with wide bandwidth and high dynamic range.

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