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Reappearing Primary User Detection in FBMC/OQAM Cognitive Radios

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Outline

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Introduction

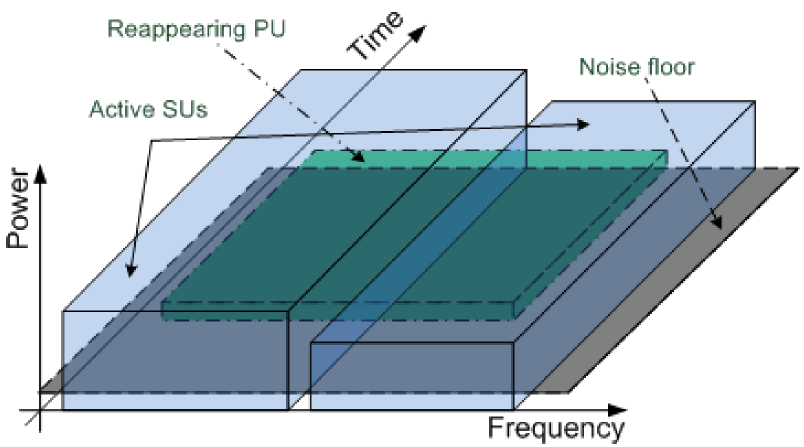
- From the physical layer point of view, cognitive radio (CR) has two key functionalities:
  - *Spectrum sensing* is utilized to identify spectrum holes and analyze the primary user (PU) spectrum occupancy
  - *Waveform adaption* (center frequency, bandwidth, modulation etc.) is required to respond to the dynamically changing operation environment
- In context of CR, multicarrier modulation techniques are strong candidates for the physical layer solution
  - Inherent ability to perform efficient spectrum sensing and flexible resource allocation

Introduction

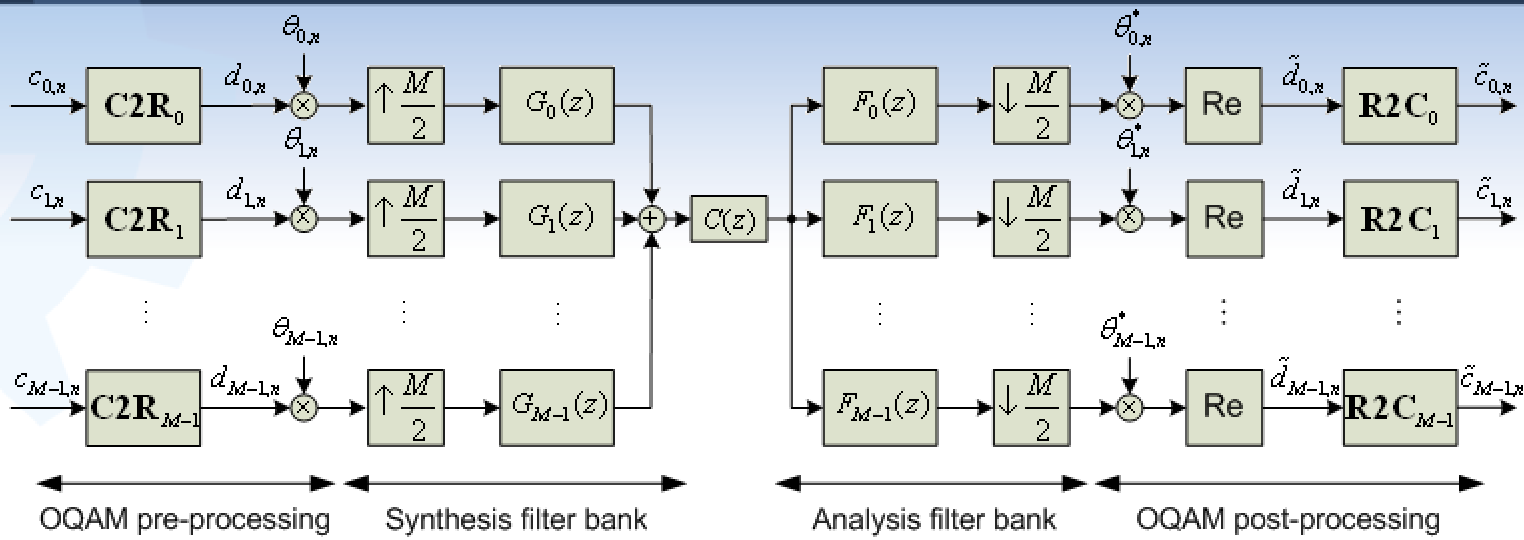
- Two modes of spectrum sensing
  1. Pre-transmission sensing that is targeted for spectrum hole acquisition
  2. Spectrum monitoring that takes place in parallel with ongoing secondary communication and its main target is to detect reappearing PU

- Typical approach is to perform periodic spectrum monitoring where secondary user (SU) transmission is switched off every once in a while to create a silent sensing interval

- Another idea is to leave narrow parts of the spectrum unused and allow them to be utilized for spectrum monitoring in a continuous manner



Critically sampled *M*-subchannel transmultiplexer



C2R_k :

$$d_{k,2n} = \begin{cases} \mathrm{Re}[c_{k,n}], & k \text{ even} \\ \mathrm{Im}[c_{k,n}], & k \text{ odd} \end{cases}$$

$$d_{k,2n+1} = \begin{cases} \mathrm{Im}[c_{k,n}], & k \text{ even} \\ \mathrm{Re}[c_{k,n}], & k \text{ odd} \end{cases}$$

Phase mapping:

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

R2C_k :

$$\tilde{c}_{k,n} = \begin{cases} \tilde{d}_{k,2n} + j\tilde{d}_{k,2n+1}, & k \text{ even} \\ \tilde{d}_{k,2n+1} + j\tilde{d}_{k,2n}, & k \text{ odd} \end{cases}$$

Synthesis and analysis filters:

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

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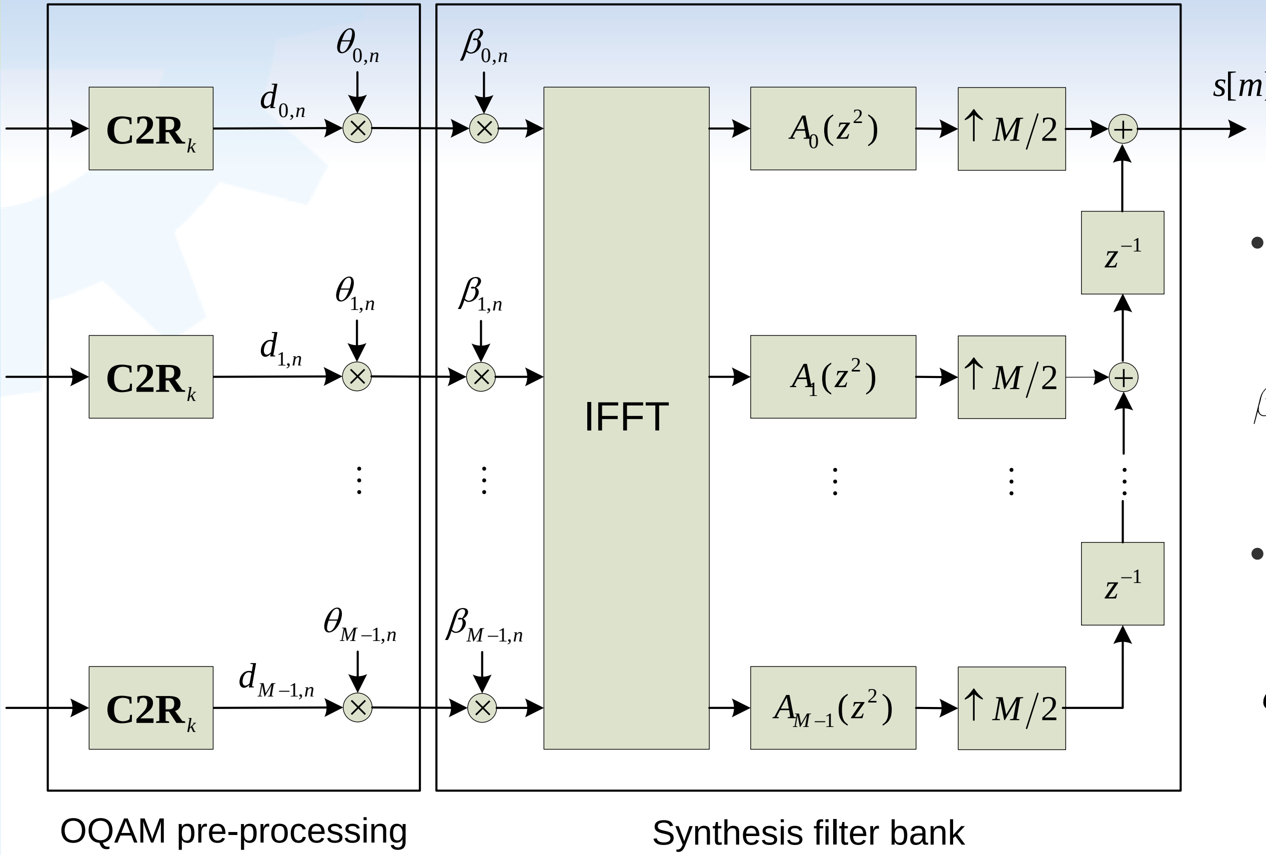
Efficient implementation of SFB



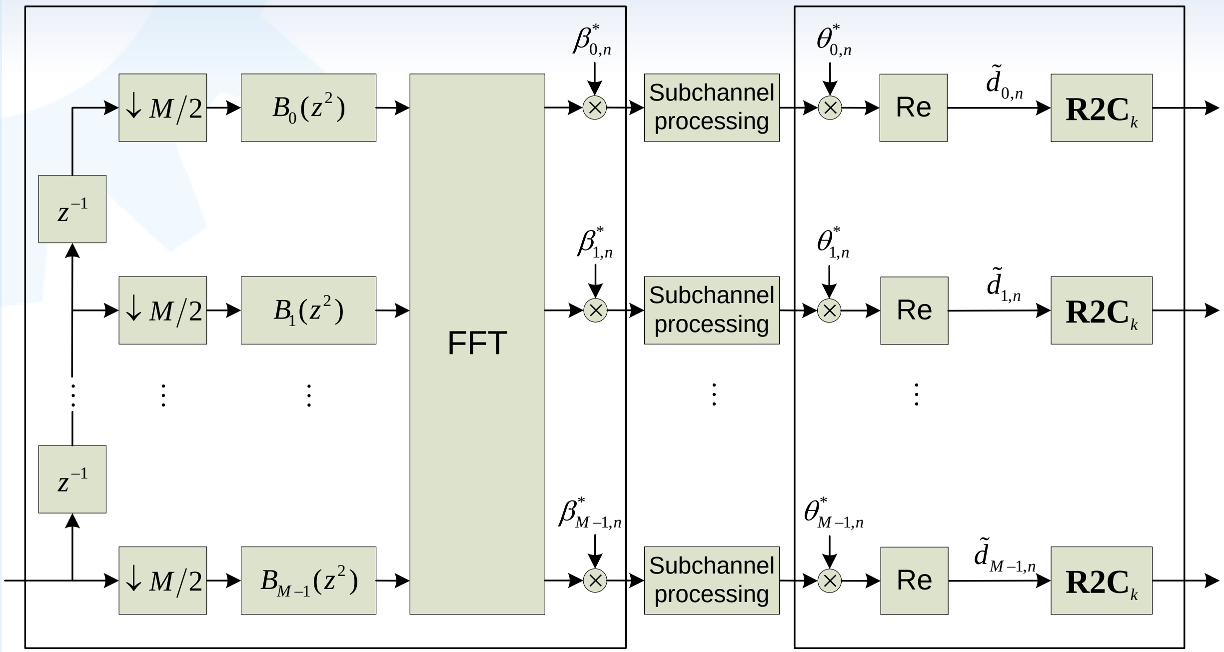
- Filter length dependent multipliers:

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

- Type-1 polyphase filters:

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

Efficient implementation of AFB



- 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:

$$\begin{aligned} b_k[m] &= a_{M-1-k}[m] \\ &= p[M-1-k+mM] \end{aligned}$$

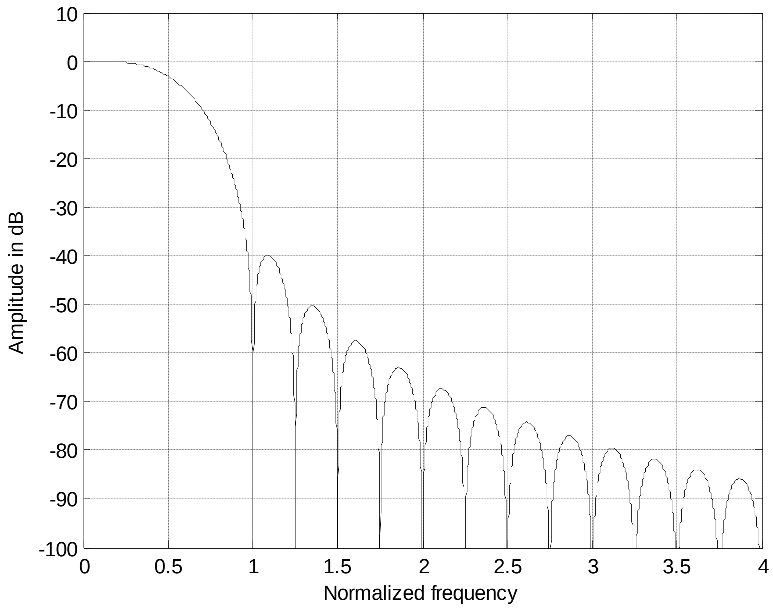
Prototype filter

- NPR prototype is designed using frequency sampling technique and it can be expressed using the following closed-form representation

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

$$m = 0, 1, \ldots, KM-2$$
$$K = 4$$
$$\bar{P}[0] = 1$$
$$\bar{P}[1] = 0.97195983$$
$$\bar{P}[2] = 1/\sqrt{2}$$
$$\bar{P}[3] = 0.23514695$$

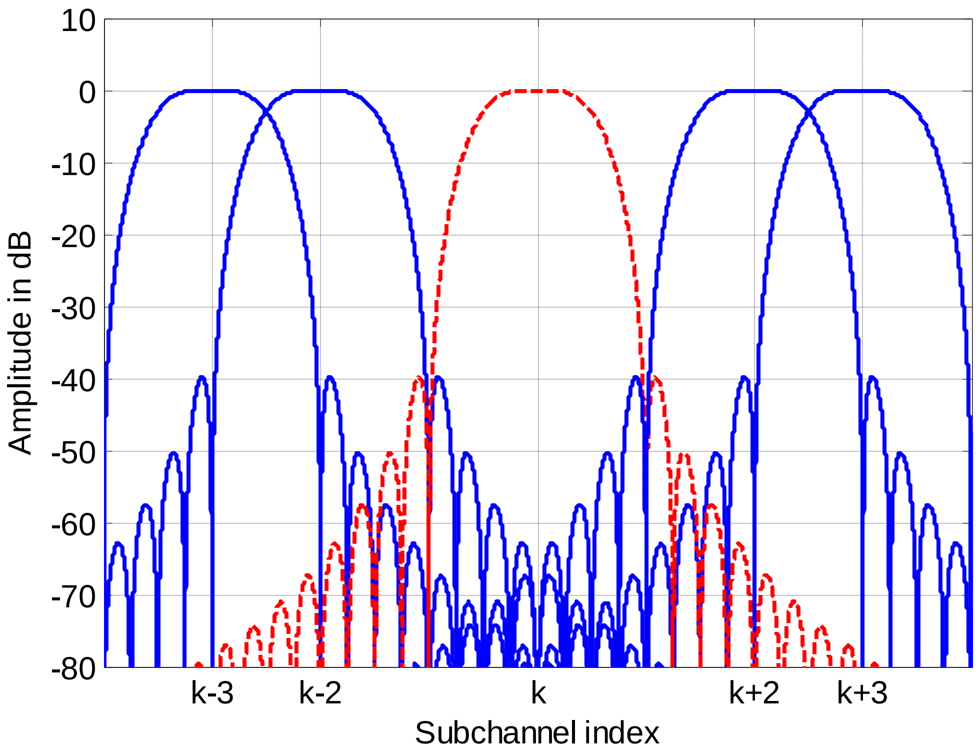
MSA = –39.8 dB	
TOI = –65.2 dB	



- High frequency selectivity

Spectrum monitoring in FBMC receivers

- In FBMC, one unused subchannel is sufficient to isolate a sensing subchannel from active data-carrying subchannels of the adjacent secondary systems

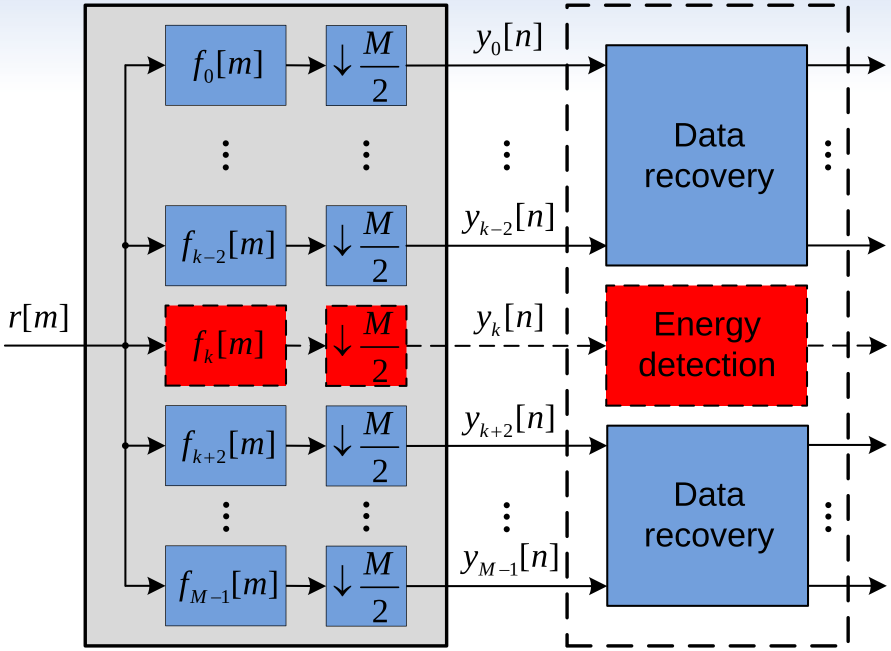


Spectrum monitoring in FBMC receivers

- Main baseband processing elements: 2x oversampled analysis filter bank and subchannel processing blocks
- Sequence $y_k[n] = \left[r[m] \star f_k[m]\right]_{\downarrow \frac{M}{2}}$ is utilized for spectrum monitoring
- Energy detection with test staticitic

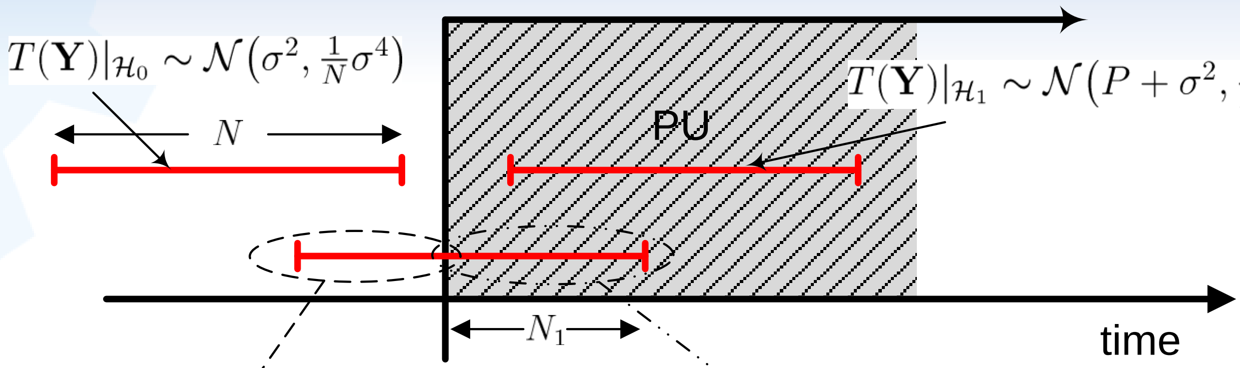
$$T(\mathbf{Y}) = \frac{1}{N}\sum_{n=0}^{N-1}\left|y_k[n]\right|^2$$

- Binary hypothesis testing
  - Gaussian distributions



Reappearing PU signal

- Distribution of the transient phase test statistic can be derived as follows:



σ^2 : noise variance

P : signal variance

$$\frac{N-N_1}{N}\mathcal{N}\left(\sigma^2, \frac{1}{N-N_1}\sigma^4\right) = \mathcal{N}\left(\frac{N-N_1}{N}\sigma^2, \left(\frac{N-N_1}{N}\right)^2 \frac{1}{N-N_1}\sigma^4\right)$$

$$\frac{N_1}{N}\mathcal{N}\left(P+\sigma^2, \frac{1}{N_1}(P+\sigma^2)^2\right) = \mathcal{N}\left(\frac{N_1}{N}(P+\sigma^2), \left(\frac{N_1}{N}\right)^2 \frac{1}{N_1}(P+\sigma^2)^2\right)$$

$\oplus$

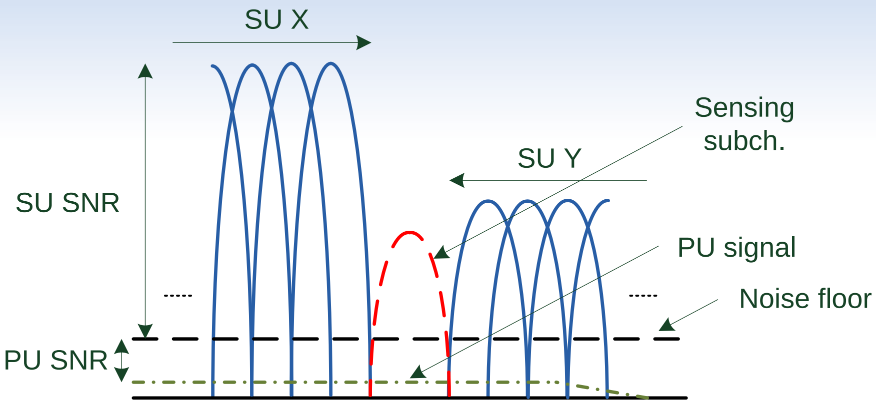
$$T(\mathbf{Y})|_{TR} \sim \mathcal{N}\left(\sigma^2 + \frac{N_1}{N}P, \frac{1}{N}\left(\left(1-\frac{N_1}{N}\right)\sigma^4 + \frac{N_1}{N}(P+\sigma^2)^2\right)\right)$$

Impact of the sensing filter

- It has been noticed that the sensing filter frequency response $F(j\omega)$ has the following effect on the both test statistics:
  - Means remain the same
  - Variances are multiplied by the factor $\beta = \frac{T}{2\pi}\int \left|F(j\omega)\right|^4 d\omega$
- In FBMC context, $F(j\omega)$ is the prototype filter frequency response
  - Our filter design results in $\beta = 0.8228$
- Needed sample complexity is reduced in subcarrier-wise sensing
  - N samples at subcarrier symbol rate and $2\beta N = 1.65N$ samples at 2x oversampled rate result in the same false alarm and misdetection probabilities

Effect of the power amplifier nonlinearity

- Subchannel-level signal model for an FBMC secondary device
  - Active secondary multiplexes SU X and SU Y
  - Sensing subchannel
  - SU/PU SNR: received SU/PU signal power relative to the noise floor



- PU SNR and SU SNR(s), jointly with the SU transmitter power amplifier (PA) characteristics, set the requirements for the energy detector

- In the simulations, noise variance is assumed to be perfectly known

Effect of the power amplifier nonlinearity

- Running the SU PA in its nonlinear operation region results in out-of-band spectral power leakage, which will increase the effective level of the noise experienced by the energy detector
- Effective PU SNR can be expressed as $P/\bar{\sigma}^2$, where the effective noise variance is given by

$$\bar{\sigma}^2 = \sigma^2 + \sum_{j=1}^{2} 10^{SNR_{dB}^j/10} \cdot \sigma^2 \cdot 10^{\alpha_{dB}^j/10}$$

  - SNR_{dB}^j power of the SU *j* with respect to the noise floor
  - α_{dB}^j PA back-off dependent (with respect to the SU signal power) level of the spectral regrowth component

Effect of the power amplifier nonlinearity

- Spectral regrowth characteristics of the considered realistic PA model

IBO (dB)	5.5	6.0	7.5	9.0	11.0	12.0	18.0	No PA
α^{j}_{dB}	–25.0	–26.7	–31.0	–35.5	–42.0	–45.1	–56.9	–61.5

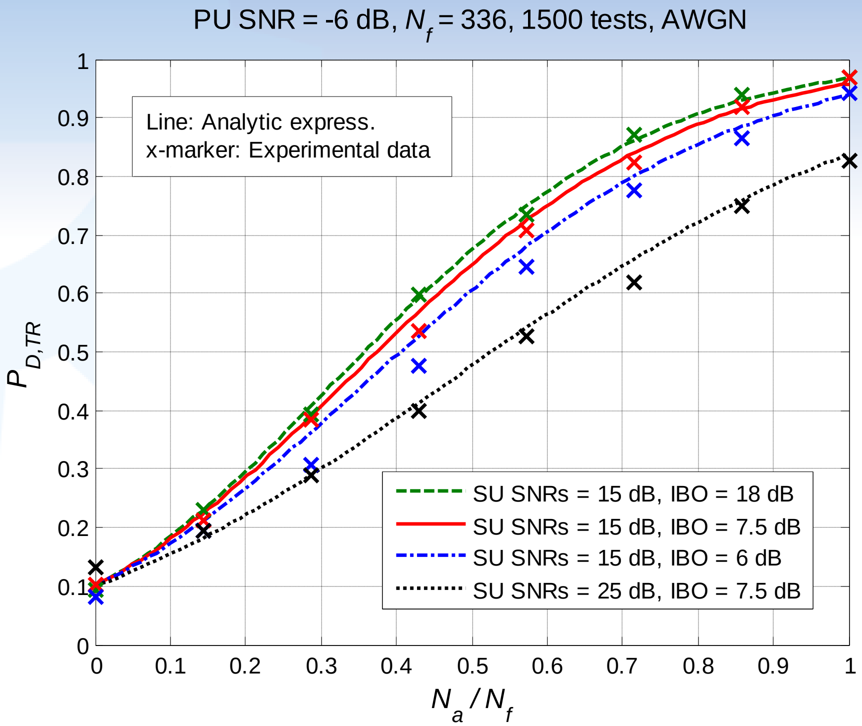
- Effect of spectral regrowth on effective PU SNR, nominal $\mathrm{PU\ SNR}|_{\mathcal{H}1} = -10\ \mathrm{dB}$

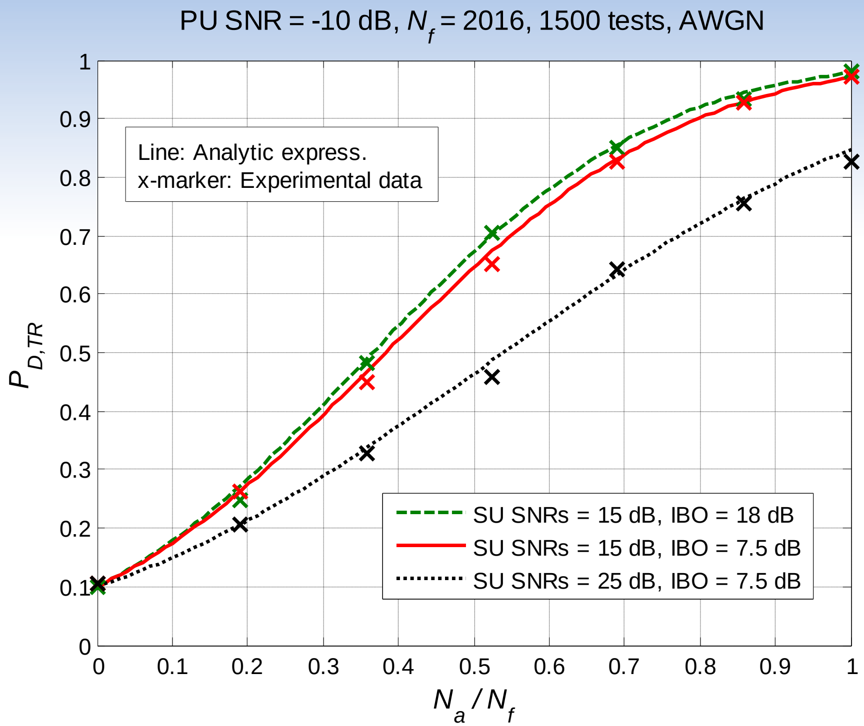
SU SNRs	**IBO 6.0 dB**	**7.5 dB**	**8.0 dB**	**12.0 dB**	**18.0 dB**	**No PA**
15 dB	–10.55	–10.21	–10.08	–10.01	–10.00	–10.00
25 dB	–13.71	–11.77	–10.71	–10.08	–10.01	–10.00
35 dB	–21.62	–17.80	–14.44	–10.76	–10.06	–10.02
45 dB	–31.34	–27.10	–22.75	–14.70	–10.53	–10.19
55 dB	–40.31	–37.02	–32.53	–23.13	–13.60	–11.61

Numerical performance evaluation

- Proposed monitoring scheme was analyzed by running energy detection at the dedicated sensing subchannel during active secondary data multiplexing
  - Sampling frequency of 1.4 MHz, filter bank size *M*=128, NPR prototype filter, AWGN channel, and perfect knowledge of $\bar{\sigma}^2$
- PU signal was modelled as a wideband (with respect to the bandwidth of the sensing subchannel) single-carrier signal with raised cosine pulse shaping
  - Sensing subchannel was located within the bandwidth occupied by the reappearing primary signal
- Performance metric: the probability of detecting the presence of a PU signal during the transient phase $P_{D,TR} = Pr(T(\mathbf{Y})\big|_{TR} > \gamma)$
  - N_a: number of fractionally-spaced post-reappearance samples
  - N_f: integration period in fractionally-spaced samples
  - γ : decision threshold designed to achieve $P_{FA} = 0.1$ with $N_a = 0$

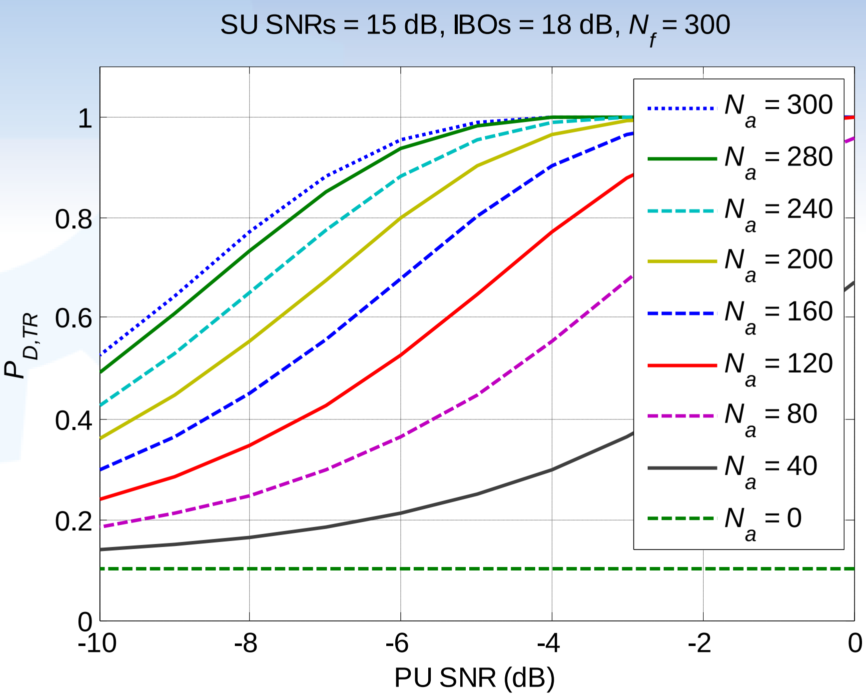
Transient phase detection probability as a function of a number of fractionally-spaced post-reappearance samples

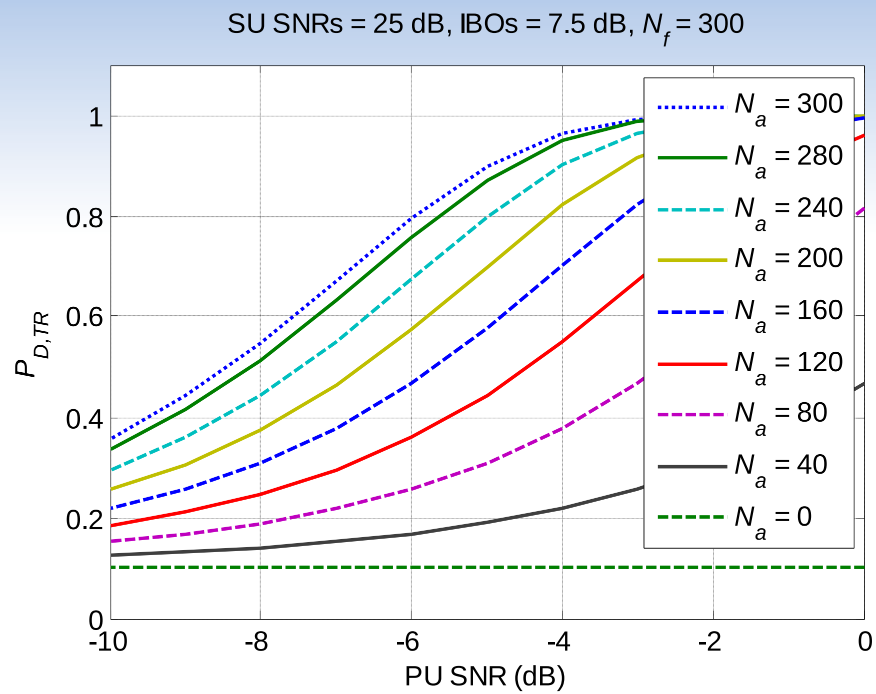




- Detection probability can be observed to gradually increase within the lower and upper limits of $Pr(T(\mathbf{Y})|_{\mathcal{H}_0} > \gamma) = P_{FA}$ and $Pr(T(\mathbf{Y})|_{\mathcal{H}_1} > \gamma) = P_D$
- Experimental performance matches fairly accurately with that of the analytical model for different levels of SU SNRs and PA nonlinearity (SU IBOs)

Analytic transient phase detection probability as a function of the nominal PU SNR





- Comparing the performance curves, the reduction in the effective PU SNR due to the increased spectral regrowth is evident
- In order to keep up with the performance achieved with linear PA (or with high back-off values), the integration time should be increased accordingly

Conclusions

Main points of our paper:

- Idea of silent sensing subchannel based spectrum monitoring technique to be applied in data-receiving FBMC secondary devices
- Derivation of the distribution of the test statistic to characterize the energy detector performance in the transient phase where reappearing PU signal falls arbitrarily within the integration window
- Verification of the analytical model using experimental data obtained from an FBMC/OQAM testbed
- Analysis of the sensitivity of the proposed monitoring scheme to nonlinear power amplifier induced spectral regrowth

Thank you for your attention!