Design of Cognitive Receiver RF Front-End Control

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Content

- The (near) future (problem statement)
- Introduction to cognitive control
- Modeling of the spectrum
- Cognitive engine design
- Theoretical analysis
- Conclusion

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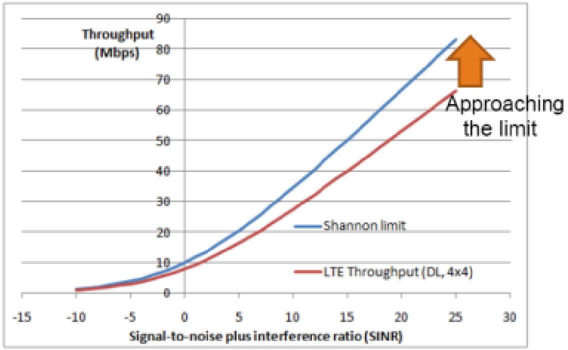
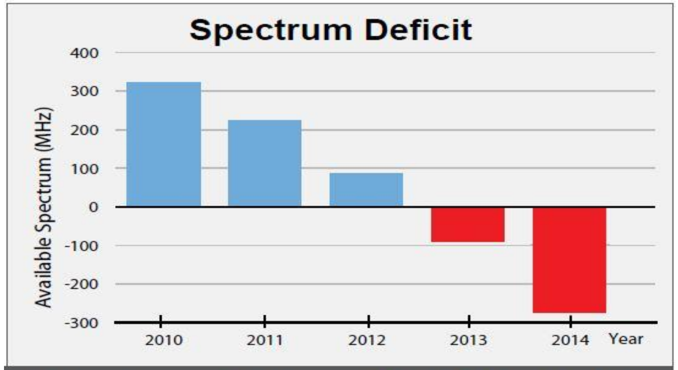
The (Near) Future: The Spectrum

- Already close to the limit to modulation and coding can provide
- Demand is increasing (a looming spectrum deficit)
- Efficient utilization of the spectrum is the remaining knob to increase capacity
  - Note that historical capacity gains come mainly from frequency re-use
- More energetic and unpredictable spectrum is expected
  - Less number of white spaces
  - W per Hz is expected to rise



Rupert **Baines**, “**The Best** That LTE Can Be**:** Why LTE Needs Femtocells”



The FCC projects a spectrum deficit by the year 2013

http://www.hightechforum.org/spectrum-deficit-disorder/

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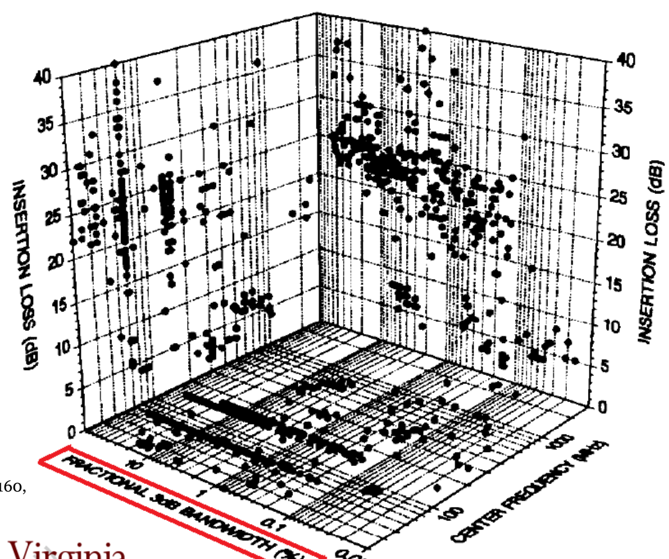
The (Near) Future: The Radio

- Both flexibility and selectivity are on demand
- Technological trade-off
  - **Flexible filters are not as selective**



A. Coon, "SAW filters and competitive technologies: a comparative review," *Proceedings of Ultrasonics Symposium, 1991,* pp. 155-160, 1991.

Technology	Frequency Range (GHz)	10-dB BW (%)	Max. IL(dB)	Size
BST	0.49 – 0.79 (1.62:1)	≈ 40	3.0	≈20 cm^2
BST	0.18 – 0.28 (1.56:1)	≈ 50	2.0	≈15 cm^2
BST	0.23 – 0.40 (1.73:1)	≈ 25	2.5	≈ 2 cm^2
Semiconductor	0.70 – 1.33 (1.90:1)	≈ 30	6.0	≈10 cm^2
MEMS	1.50 - 2.50 (1.67:1)	≈ 12	2.2	≈0.5 cm^2
Semiconductor	0.50 – 0.90 (1.80:1)	≈ 28	2.0	0.16 cm^2
Semiconductor	1.40 – 2.00 (1.42:1)	≈ 10	3.0	0.64 cm^2
MEMS	3.55 – 4.71 (1.32:1)	≈ 3	3.55	≈8 cm^2
MEMS	4.30 – 5.50 (1.28:1)	≈ 10	5.3	1.0 cm^3
MEMS	0.70 – 2.26 (3.23:1)	≈ 50	6.0	0.6 cm^2
MEMS (Switch)	1.50 – 2.50 (1.67:1)	≈ 20	8.0	0.7 cm^2
MEMS (Switch)	2.60 - 3.60 (1.37:1)	≈ 15	5.0	0.7 cm^2
MEMS (Switch)	3.70 - 5.40 (1.45:1)	≈ 15	12.5	1.2 cm^2
Semiconductor	0.95 – 1.48 (1.55:1)	≈ 13	4.0	1.87cm^2

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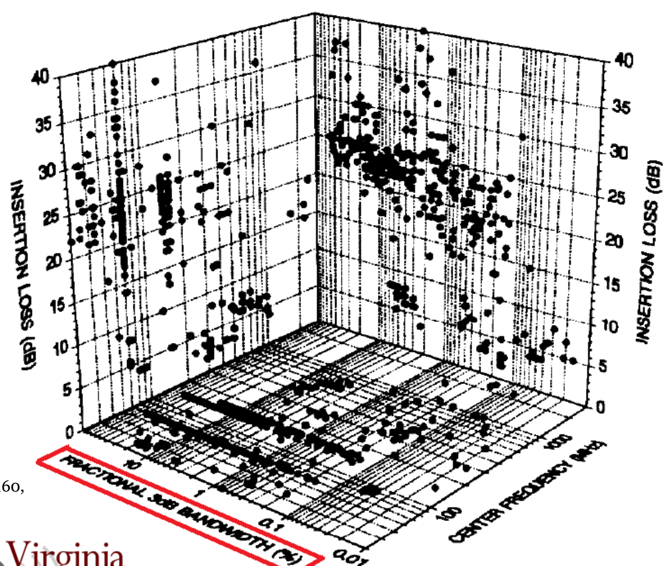

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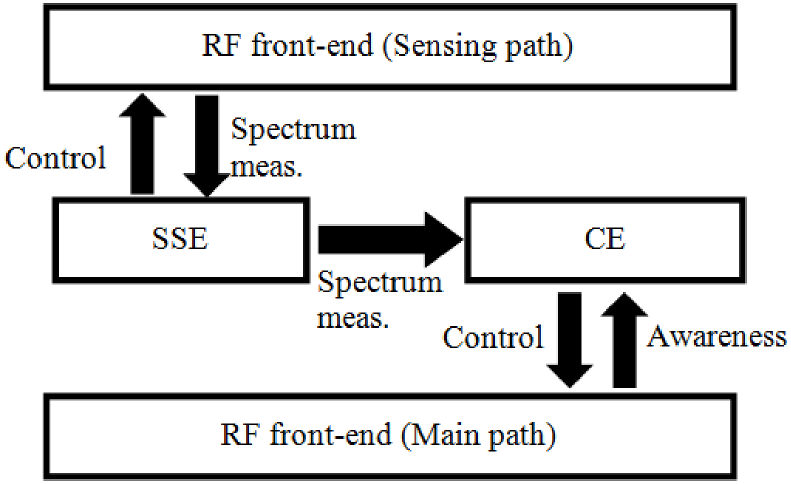
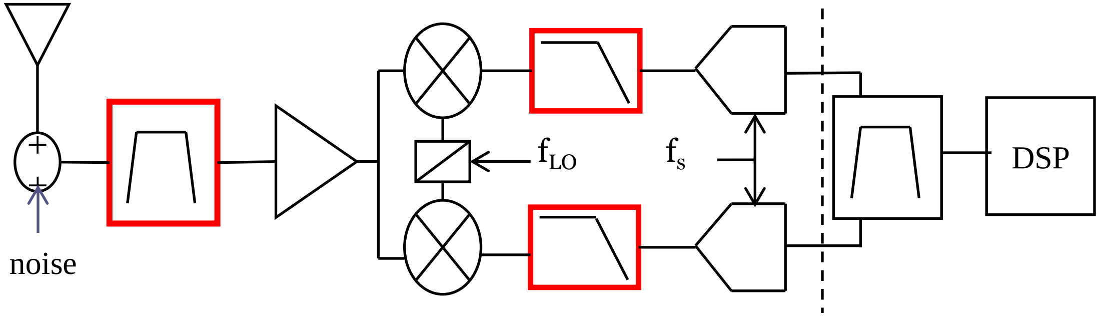
Proposed solution

- Use of cognitive control to reduce selectivity requirements of:
  - Pre-selector filter
  - Image rejection ration in the mixer
  - Anti-aliasing filter
  - LNA linearity



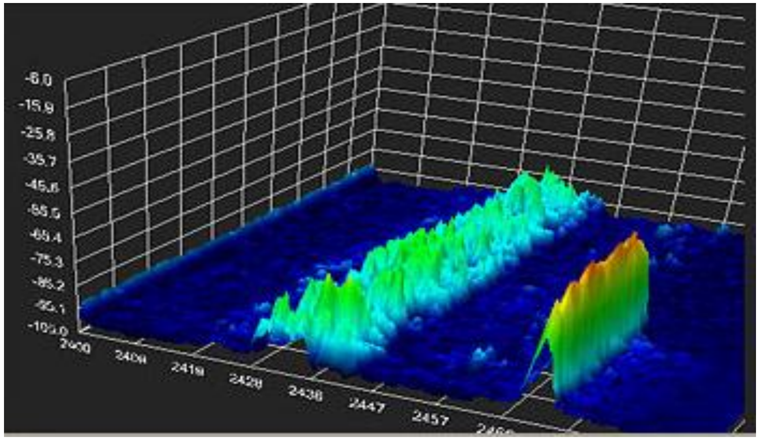
- This may relax the tradeoff between selectivity and flexibility of RF front-ends

- Sampling frequency and local oscillator frequency are controlled cognitively. The control employs:
  - Cognitive engine (CE)
  - Spectrum sensing engine (SSE)



Features of Proposed Cognitive RF Front-end Control

Sensing



Self-awareness

Intelligence

Exploiting experience

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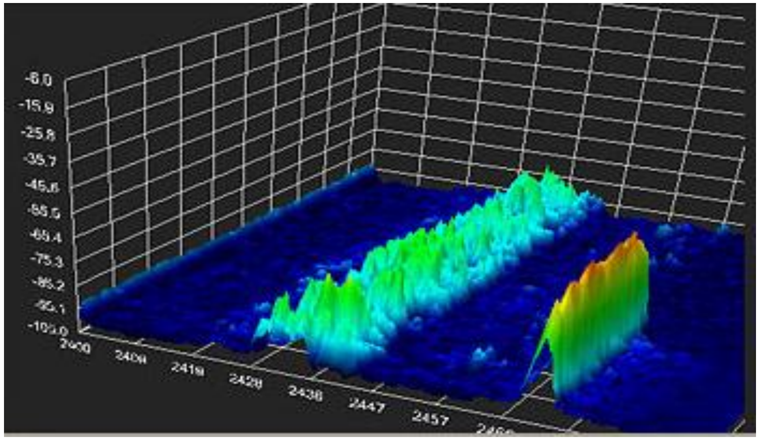

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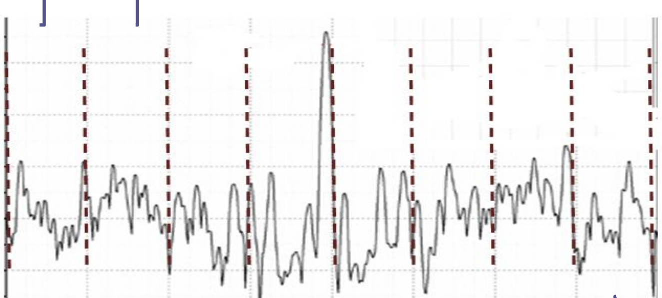
Modeling the Spectrum

- The spectrum is modeled by a vector representing the *power spectrum domain* of the signal

- *Power spectrum domain: <u>Average</u>* power contained in a given sub-band of the spectrum



RF spectrum

$$\underline{P} = \begin{bmatrix} p_0 \\ p_1 \\ \vdots \\ \vdots \\ p_{N-1} \end{bmatrix}$$

Note: For time-multiplexed communication systems, we show that each element of $\underline{P}$ follows Pareto distribution

$$f_P(P) = \begin{cases} \left(\dfrac{P_{min}^{2/n}}{1-\left(\frac{P_{min}}{P_{TX}}\right)^{2/n}}\right)\dfrac{2}{nP^{1+\frac{2}{n}}}, & P_{min} \le P \le P_{TX} \\ 0, & otherwise \end{cases}$$

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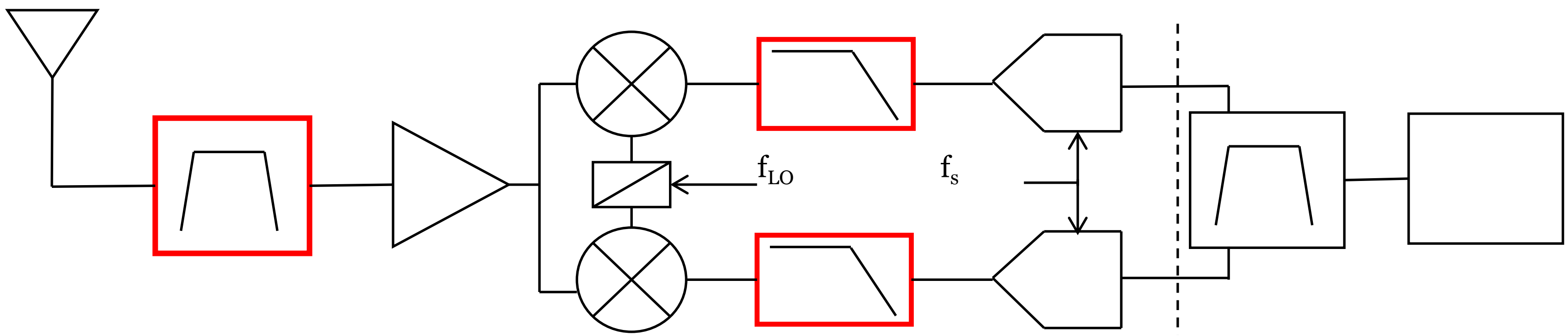
Self-Awareness (1/5)

- Each element of the RF front-end between the mixer and the ADC can be modeled as a matrix in the power spectrum domain
- This is valid under the assumption that signals in each sub-band are uncorrelated to each other



$$\underline{P} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ \vdots \\ p_M \end{bmatrix} \xrightarrow{\text{Complex mixer}} \underline{P}^{mix} = \begin{bmatrix} p^{mix}_{-K} \\ p^{mix}_{-K+1} \\ \vdots \\ \vdots \\ p^{mix}_{K} \end{bmatrix} \xrightarrow{\text{filter}} \underline{P}^{fil} = \begin{bmatrix} p^{fil}_{-K} \\ p^{fil}_{-K+1} \\ \vdots \\ \vdots \\ p^{fil}_{K} \end{bmatrix} \xrightarrow{\text{sampler}} \underline{P}^{adc} = \begin{bmatrix} p^{adc}_{-D_{fs}} \\ p^{adc}_{-D_{fs}+1} \\ \vdots \\ \vdots \\ p^{adc}_{D_{fs}} \end{bmatrix}$$

Self-Awareness(2/5)

- Mixer: $$p^{mix}(k;i_{LO}) = p(k+i_{LO}) + \beta \cdot p(k-i_{LO})$$

$$\underline{P}^{mix}(i_{LO}) = \underline{A}^{mix}(i_{LO}) \cdot \underline{P}$$

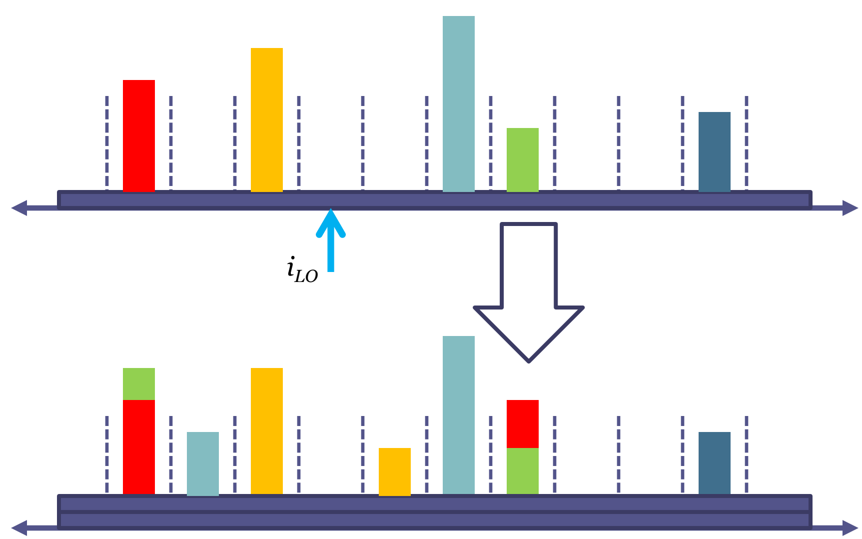
$$i_{LO} = 1,2,\ldots,M$$

i_{LO} : index of the sub-band containing LO frequency

β : image-rejection ratio of complex mixer

Example:
- M = 9
- i_{LO} = 3

$$\underline{A}^{mix}(3) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & \beta & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & \beta & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & \beta & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \beta & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & \beta & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ \beta & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



Self-Awareness(3/5)

- **Filter:** $$p^{fil}(l;i_{LO}) = p^{mix}(l;i_{LO})\left|H(l)\right|^2$$

H : represents frequency transform of the filter

$$\underline{P}^{fil}(i_{LO}) = \underline{A}^{fil} \cdot \underline{P}^{mix}(i_{LO})$$

Note: Filter is not non-linear. Hence, $\underline{A}^{fil}$ is a diagonal matrix

- **Sampler:** $$p^{adc}(d;i_{LO},l_{fs}) = \sum_{m=-\lfloor (K-d)/l_{fs} \rfloor}^{\lfloor (K+d)/l_{fs} \rfloor} Q_m p^{fil}(d - ml_{fs};i_{LO})$$

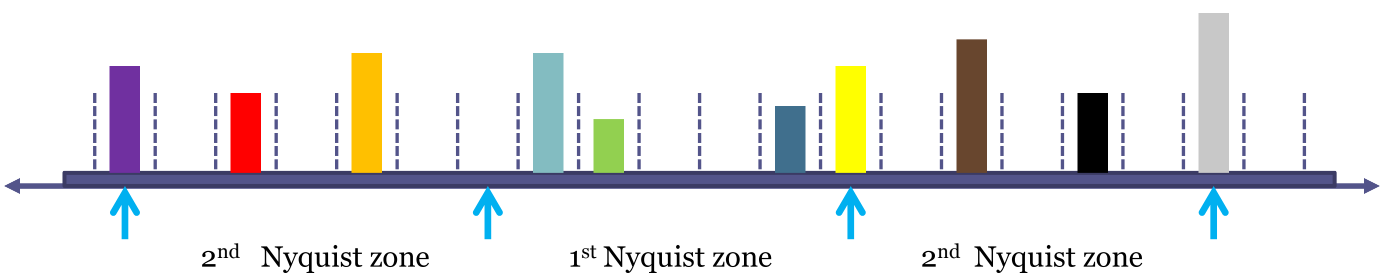
$$\underline{P}^{adc}(l_{fs},i_{LO}) = \underline{A}^{adc}(l_{fs})\underline{P}^{fil}(i_{LO})$$

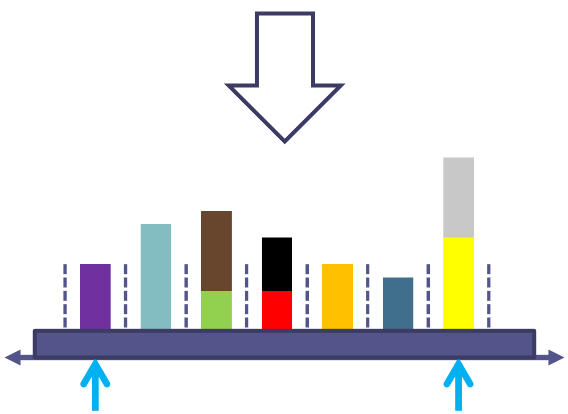
Q_m : represents filtering due to non-impulsive sampling
l_{fs} : sub-band containing sampling frequency

Note: Dimensions of $\underline{A}^{adc}$ are dependent on the sampling frequency

Self-Awareness(4/5)

- Example:





$$\underline{A}^{adc}(6)=\begin{bmatrix} Q_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & Q_2 & 0 \\ 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & Q_2 \\ 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Q_1 & 0 & 0 \end{bmatrix}$$

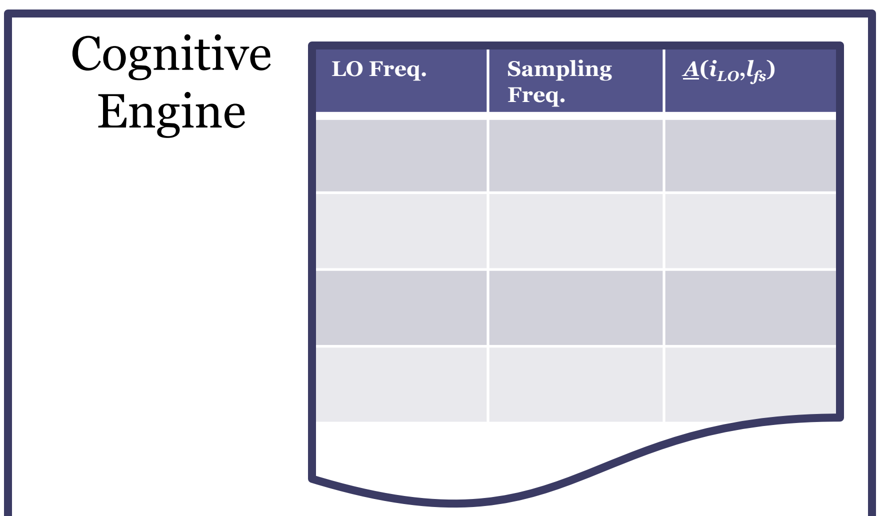
Self-Awareness (5/5)

- Model of the RF front-end:

$$\underline{A}(i_{LO}, l_{fs}) = \underline{A}^{mix}(i_{LO}) \cdot \underline{A}^{fil} \cdot \underline{A}^{adc}(l_{fs})$$

$$\underline{P}^{adc}(i_{LO}, l_{fs}) = \underline{A}(i_{LO}, l_{fs}) \cdot \underline{P}$$

- The CE is made “aware” of the RF front-end by storing $\underline{A}(i_{LO}, l_{fs})$ for every possible LO frequency and sampling frequency



Intelligence (1/2)

- The energy content of the overall signal is redistributed as it traverses through the RF front-end
- We propose the use of CE to select a the i_{LO} and l_{fs} which minimize the amount of undesired power that folds into the desired sub-band
- The CE is implemented as a simple search algorithm

Intelligence (2/2)

From spectrum sensing

$$\underline{P} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ \vdots \\ p_M \end{bmatrix}$$

$$\underline{\tilde{P}} = \begin{bmatrix} p_1 \\ \vdots \\ p_{i_d - 1} \\ p_{\min} \\ p_{i_d + 1} \\ \vdots \\ p_M \end{bmatrix}$$

$$\underline{\tilde{P}}_1^{ADC} = A_1 \underline{\tilde{P}} = \begin{bmatrix} p_{1,-D_{fs}} \\ \vdots \\ p_{1,d} \\ \vdots \\ p_{1,D_{fs}} \end{bmatrix}$$

$$\underline{\tilde{P}}_2^{ADC} = A_2 \underline{\tilde{P}} = \begin{bmatrix} p_{2,-D_{fs}} \\ \vdots \\ p_{2,d} \\ \vdots \\ p_{2,D_{fs}} \end{bmatrix}$$

$$\underline{\tilde{P}}_3^{ADC} = A_3 \underline{\tilde{P}} = \begin{bmatrix} p_{3,-D_{fs}} \\ \vdots \\ p_{3,d} \\ \vdots \\ p_{3,D_{fs}} \end{bmatrix}$$

Select k such that $p_{k,d} < p_{TH}$

Map k to LO frequency and sampling frequency

Exploitation

From spectrum sensing $\Rightarrow$ $\underline{P} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ \vdots \\ p_M \end{bmatrix}$ $\Rightarrow$ $\underline{\tilde{P}} = \begin{bmatrix} p_1 \\ \vdots \\ p_{i_d-1} \\ p_{\min} \\ p_{i_d+1} \\ \vdots \\ p_M \end{bmatrix}$ $\Rightarrow$ $\underline{\tilde{P}}^{ADC}_{k_{previous}} = A_{k_{previous}} \underline{\tilde{P}} = \begin{bmatrix} p_{k_{previous},-D_{fs}} \\ \vdots \\ p_{k_{previous},d} \\ \vdots \\ p_{k_{previous},D_{fs}} \end{bmatrix}$

If $p_{k_{previous},d} < p_{TH}$,

do not change the setting of the RF front-end (Exploit)

Else

search again(Explore)

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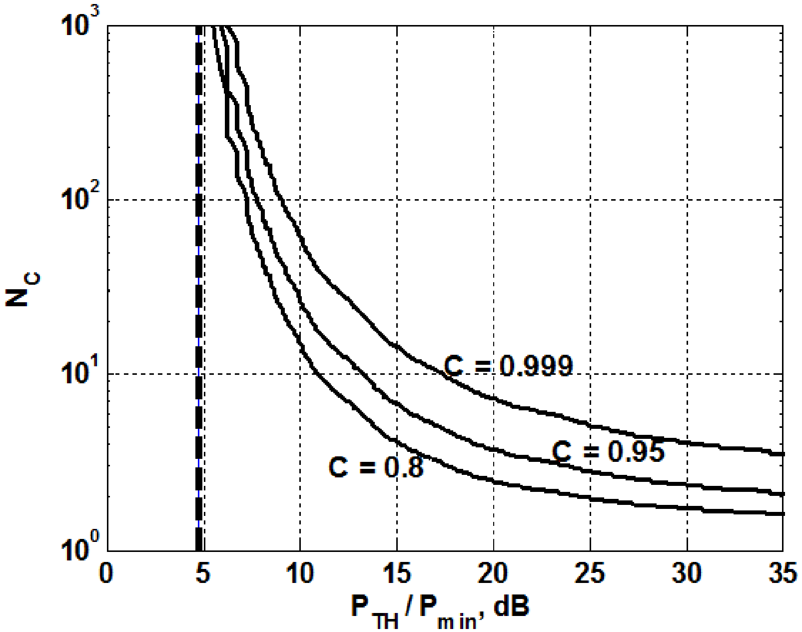
Theoretical Analysis (1/3)

- Feasibility of implementing the CE as a search algorithm was analyzed

$$N_C \approx \frac{\ln(1 - C)}{\ln\left(1 - p_s(P_{TH})\right)}$$

N_c: Number of independent trials the CE takes to find a solution with C degree of confidence
C: degree of confidence
$p_s(p_{TH})$: probability that the power of the signal in given sub-band in the spectrum is below p_{TH}



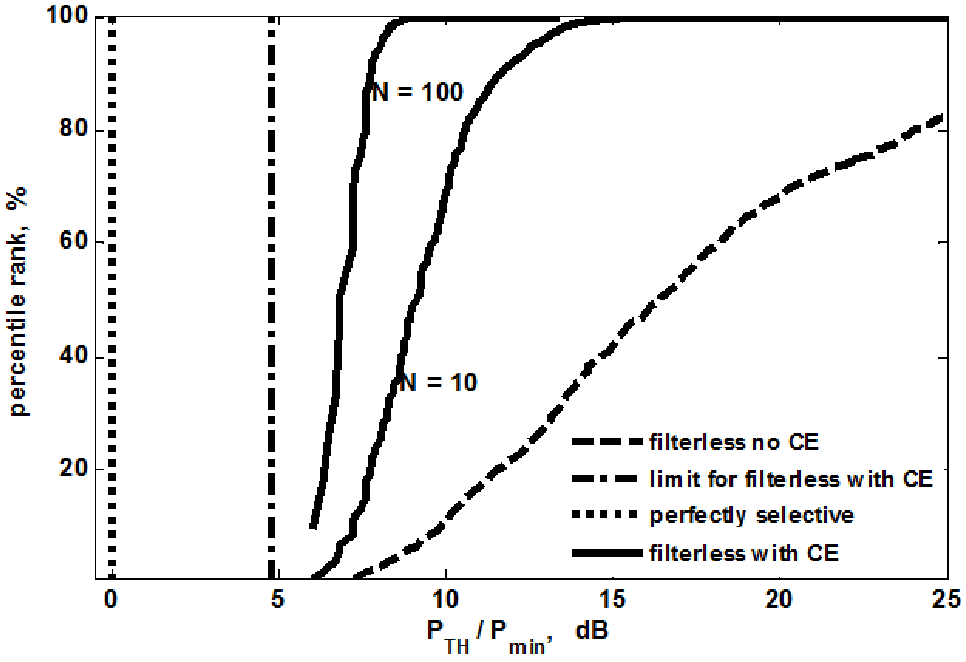
Theoretical Analysis (2/3)

- Comparing the performance of;
  - Perfectly selective RF front-end
  - Filter-less RF front-end
  - Cognitively controlled filter-less RF front-end

- Metric
  - Percentile of the ratio of the undesired power in the desired band with the power of the minimum detectable signal

Theoretical Analysis (3/3)

- Cognitive RF front-end control allows a filter-less RF front-end to behave similar to a highly selective RF front-end



Simulation (1/2)

- RF front-end is operational from 850 MHz to 950 MHz
- Width of each sub-band is 100 kHz
- No pre-selector filter
- 2nd order baseband Butterworth filter
- Maximum possible received power = 30 dBm
- Minimum detectable signal = -100 dBm
- Path-loss exponent = 4
- Probability of occupancy $\approx$ 0.8
- Sampling frequency varied from 200 kHz to 20 MHz in 200 kHz steps
- LO frequency varied from 900 MHz to 910 MHz in 200 kHz steps
- Simulation was re-run 100 times
- The average number of steps the CE takes to find a solution and the average of the sampling frequencies suggested by the CE are recorded

Simulation (2/2)

P_{TH}/P_{min} (dB)	With exploitation		Without exploitation			Theoretical Approximation
	Average N	Average sampling frequency (MHz)	Average N	Average sampling frequency (MHz)	$N_{0.95}$	
5.5	245	3.4	320	2.8	714	998
6.0	125	1.8	160	1.6	405	374
8.0	55	1.4	160	1.6	235	67
10.0	25	0.6	40	0.5	95	20
15.0	5	0.4	10	0.3	44	6
20.0	1	0.2	1	0.2	3	4
30.0	1	0.2	1	0.2	1	2

- Exploitation reduces number of steps by up to 30% at the expense of sub-optimal sampling frequency
- The theoretical approximation of the number of the CE takes to find its solution is accurate within an order of magnitude
- The CE finds solution in less than 100 steps, even for extreme P_{TH}/P_{min} values

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- In statistical sense, cognitive control potentially relaxes the selectively specification of the receiver RF front-end

- It is feasible to implement the CE as a simple search algorithm