Opportunistic Spectrum Access Learning Proof of Concept

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Presentation outline

- Cognitive radio equipment
- Decision making for cognitive radio
- Example of an Opportunistic Spectrum Access scenario
- Real experiments results for OSA
- Conclusion

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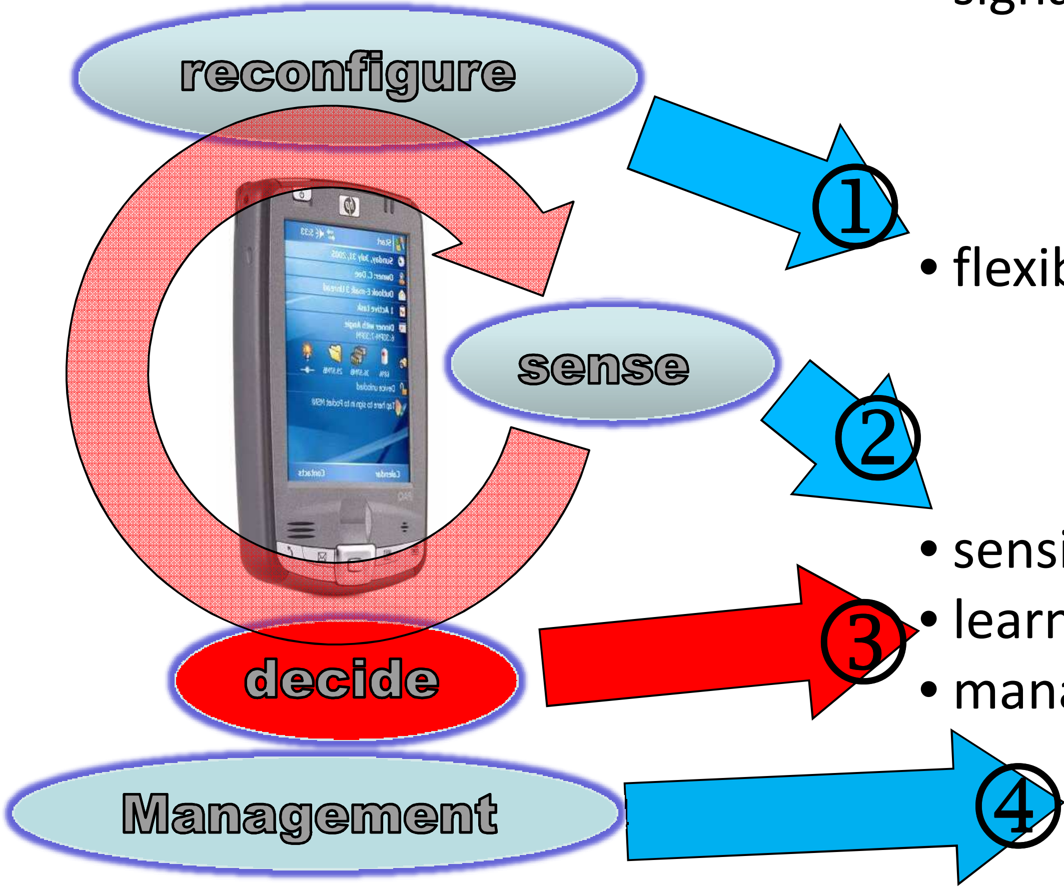
Cognitive radio equipment

- **Simplified cognitive cycle**



A cognitive radio equipment is made of

- signal processing
    - radio for PHY layer
    - also any other layer processing
- flexible platform and processing
    - multi-processing
    - heterogeneous (DSP, FPGA…)
    - adaptive signal processing
- sensing signal processing
- learning & decision making processing
- management architecture (HDCRAM)
    - reconfiguration management
    - cognitive management

③ Learning and decision making

- **Reinforcement learning**
  - try and evaluate approach
  - exploration vs exploitation paradigm
- **Multi-Armed Bandit (MAB) approach for decision making & learning**
- **Upper Confidence Bound - UCB**
  - Context of high uncertainty – no a priori knowledge
  - very simple implementation
  - UCB for opportunistic spectrum access (OSA)
  - UCB in the context of sensing errors

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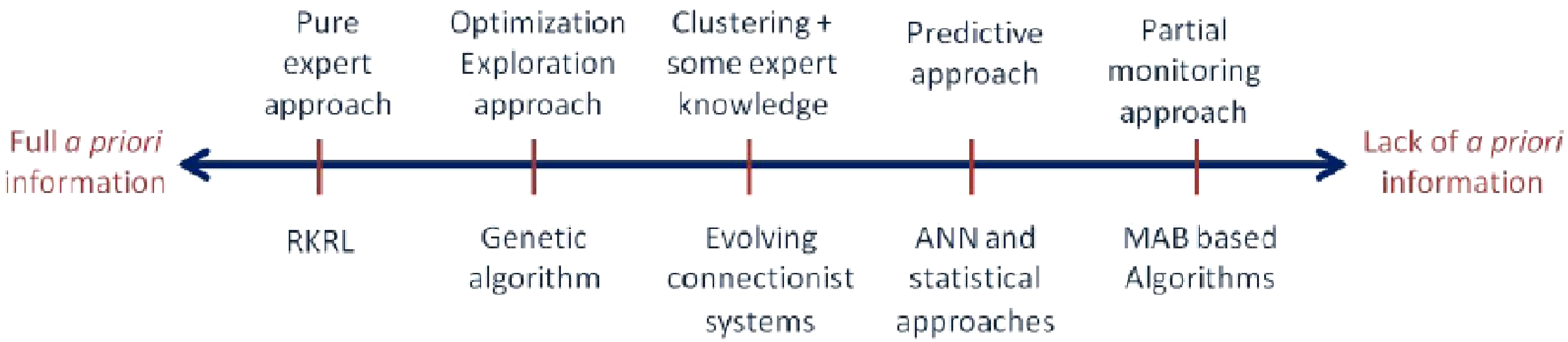
Decision making - classification

- **Depending on the degree of knowledge, different decision making solutions may be worth analyzing**
  - the more *a priori* knowledge ➔ left
  - the more uncertainty➔ right



[1] Wassim JOUINI, Christophe MOY, Jacques PALICOT, "On decision making for dynamic configuration adaptation problem in cognitive radio equipments: a multi-armed bandit based approach," 6th Karlsruhe Workshop on Software Radios, WSR'10, Karlsruhe, Germany, March 2010

Decision making for OSA

- **OSA: opportunistic spectrum access**
- **A secondary user (SU) may access the spectrum dedicated to a primary user (PU)**
- **Hardest case: SU has no *a priori* knowledge of channel occupancy when starting**
- **Learning issue is**
  - which is the best channel choice next time I will try to access the channel?
- **Some kind of prediction**
  - channel which has the maximum of probability to be vacant in the next instants?

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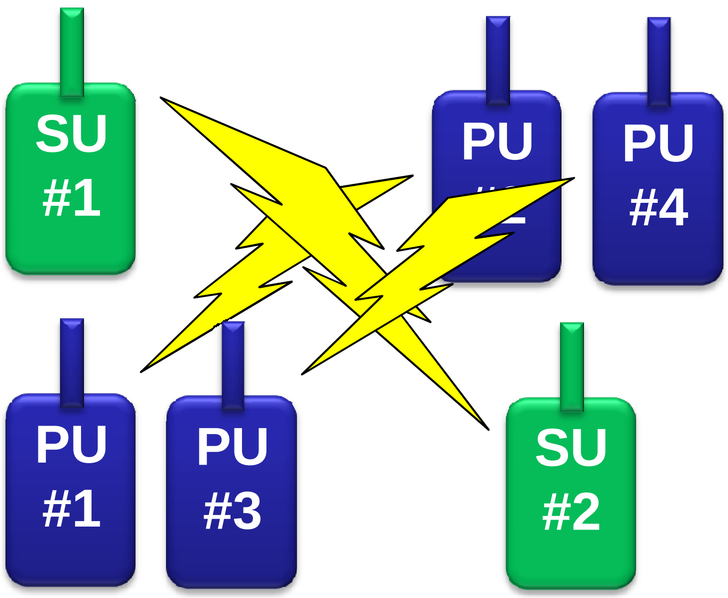
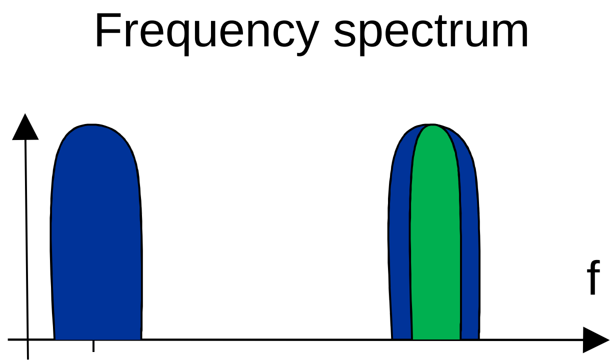
Opportunistic Spectrum Access - OSA

- In a radio network of primary users (PU)
- Secondary users (SU) are allowed to use vacant channels
- At the condition that SUs leave the occupied frequency as soon as a PU wants to use it





Secondary user requirement

- **Secondary users need to incorporate cognitive radio (CR) features in the equipments**
  - – sensors
  - – reconfigurable radio capabilities

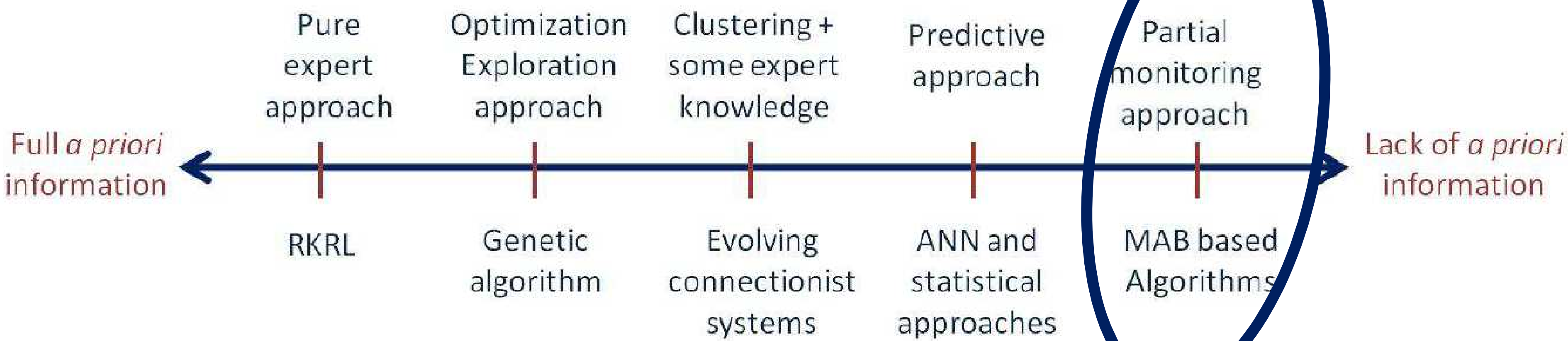
➔ in addition to usual radio processing

- **Sensor**
  - – detection of primary user at the same frequency
- **Reconfigurable operators**
  - – carrier frequency, etc.
- **Learning means to predict the channels availability**

No a priori knowledge

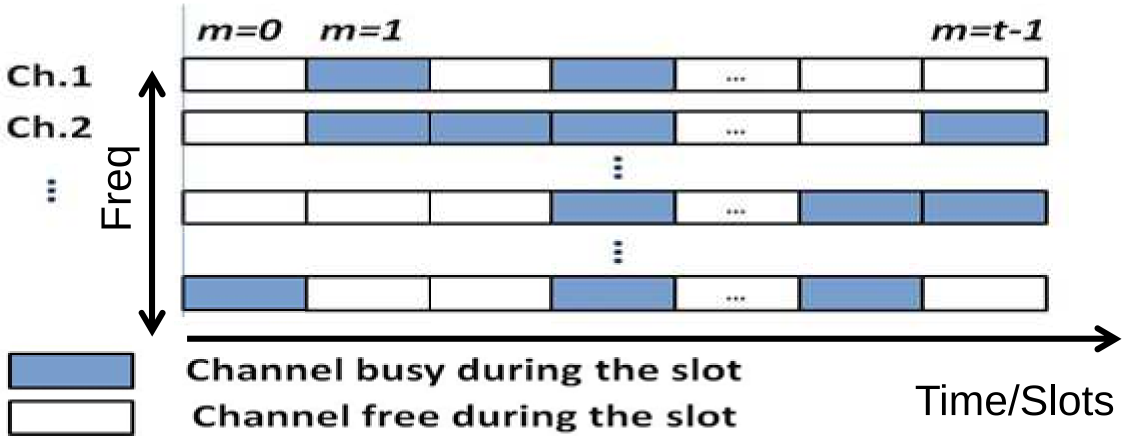
- **Multi-Armed Bandit model**
  - reinforcement learning from machine learning

K Machines = K frequency bands



Primary network hypothesis

- **Primary network: bands occupation**
  - time is slotted



- **Secondary network**
  - minimum interference with PUs
  - sense PUs activity with imperfect sensing

Learning based on partial knowledge

- **We do not sense all bands in parallel because it would require**
  - a wide band RF
  - then just make the vacancy average rate of each band to know the best
- **Keep the same bandwidth as a legacy radio**
  - one channel RF bandwidth
- **Learn the entire band vacancy**
  - having just the knowledge of one channel at each iteration

Secondary network hypothesis

- **At each iteration, a SU**
  - selects only one channel based on the knowledge it has acquired through sensing
  - senses if the channel is occupied
  - transmits (exploit) only if this channel is detected vacant
  - updates (explore) his knowledge for next iteration, based on a reward for RL

TTcs	TTs	Transmission?	Reward
Selects a channel	Senses the channel	Communicate if possible	Performance Evaluation

➔ sense (choose) most vacant channel = more transmission opportunities

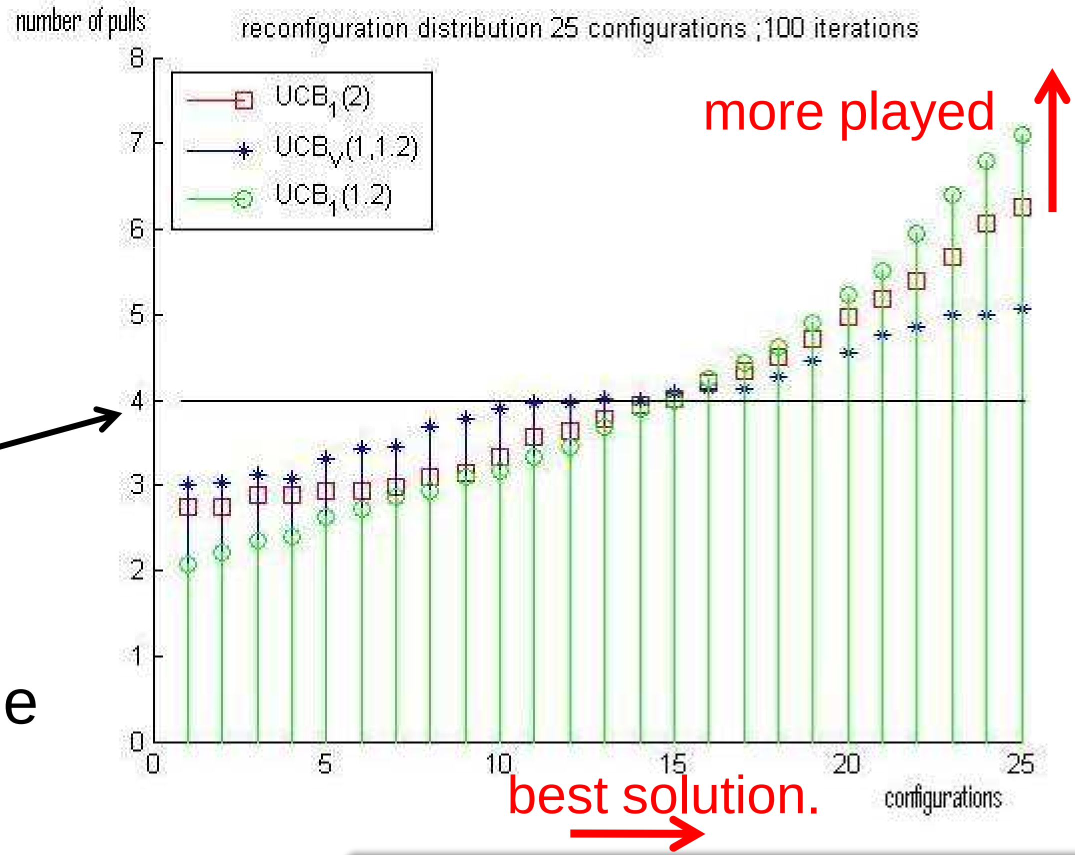
- **Hypothesis**
  - Each arm is a frequency band
  - All bands have the same bandwidth (same reward per band in terms of data rate)
  - Empirical mean $\bar{X}_{k,T_k(t)}$ is updated by (reward)
    - 0 if the channel is already occupied by PU
    - 1 if the channel is free
  - UCB_1 chooses the highest index B:

$$B_{k,t,T_k(t)} = \bar{X}_{k,T_k(t)} + A_{k,t,T_k(t)} \rightarrow A_{k,t,T_k(t)} = \sqrt{\frac{\alpha.\ln(t)}{T_k(t)}}$$

[2] Wassim JOUINI, Damien ERNST, Christophe MOY, Jacques PALICOT, "Upper confidence bound based decision making strategies and dynamic spectrum access," International Communication Conference, ICC'10, Cape Town, South Africa, 26-29 May 2010

Example with 25 alternatives

- **UCB gains in convergence to the best solution over uniform choice**
- 100 iterations

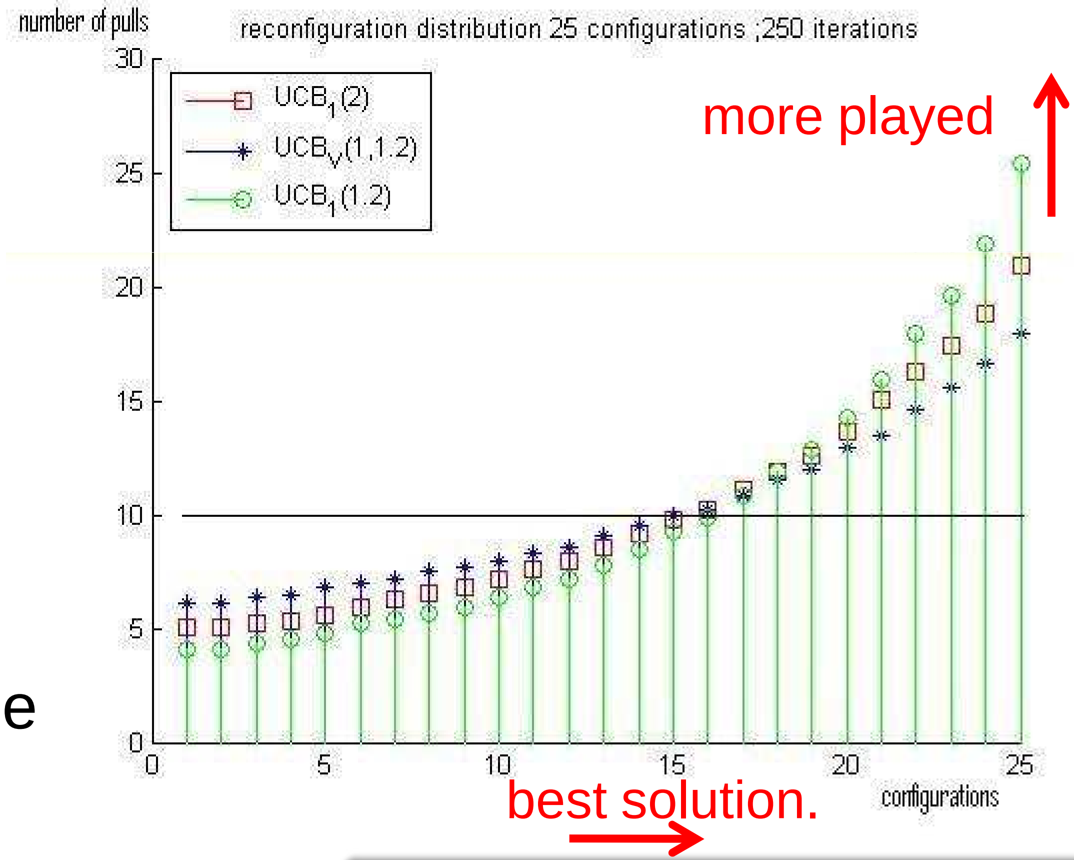


NB: Solutions are ordered with no loss of generality (the higher the index, the better)
➔ best solution is #25

Example with 25 alternatives

- **UCB gains in convergence to the best solution over uniform choice**

- 250 iterations

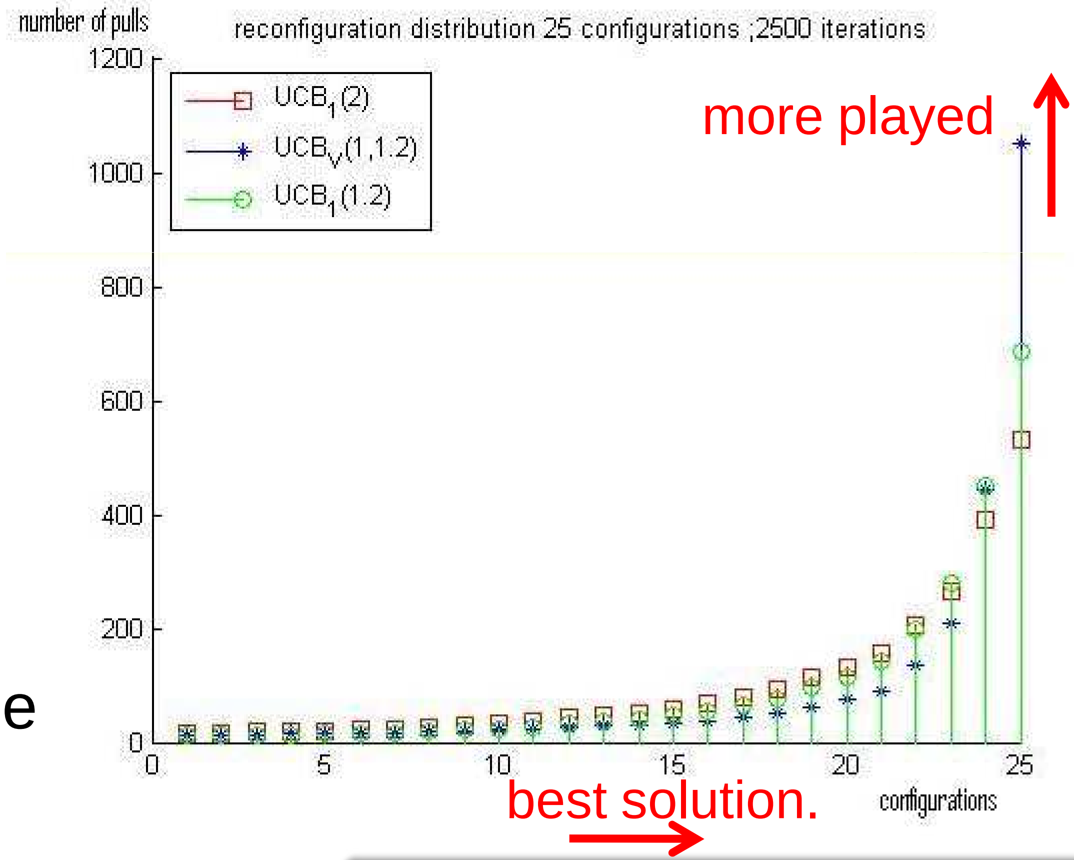


NB: Solutions are ordered with no loss of generality (the higher the index, the better)
➔ best solution is #25

Example with 25 alternatives

- **UCB gains in convergence to the best solution over uniform choice**

- 2500 iterations



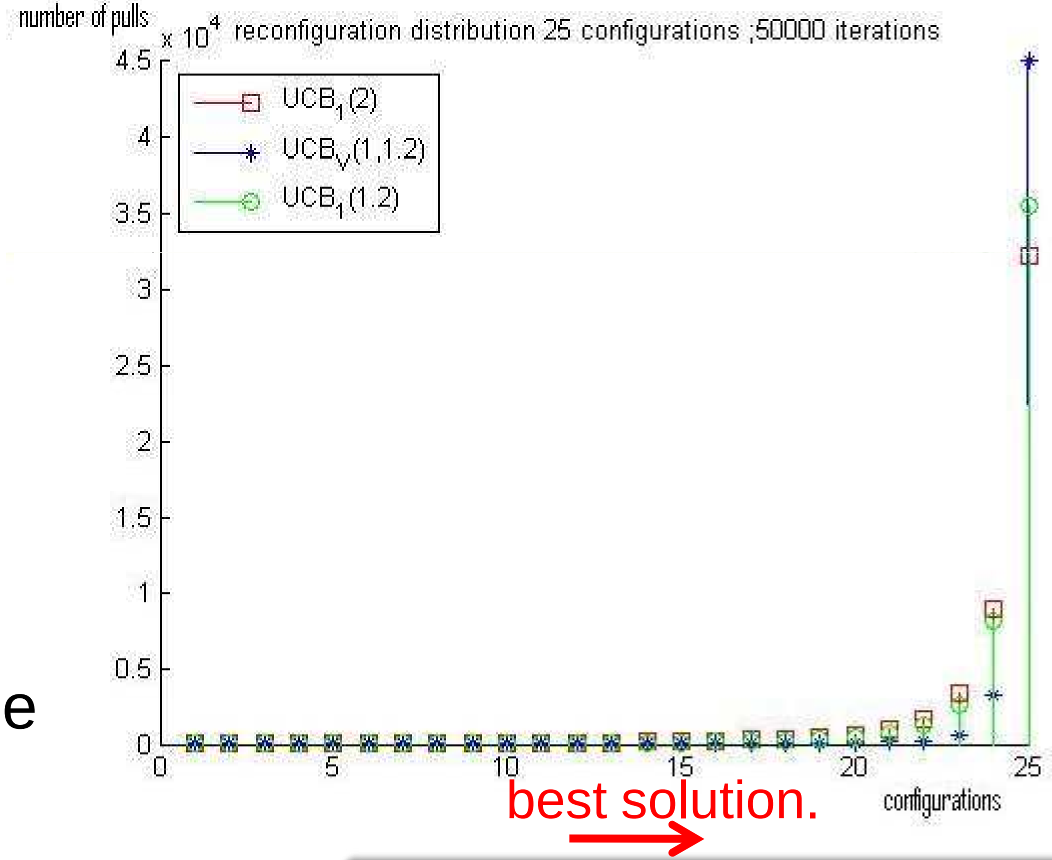
NB: Solutions are ordered with no loss of generality (the higher the index, the better)
➔ best solution is #25

Example with 25 alternatives

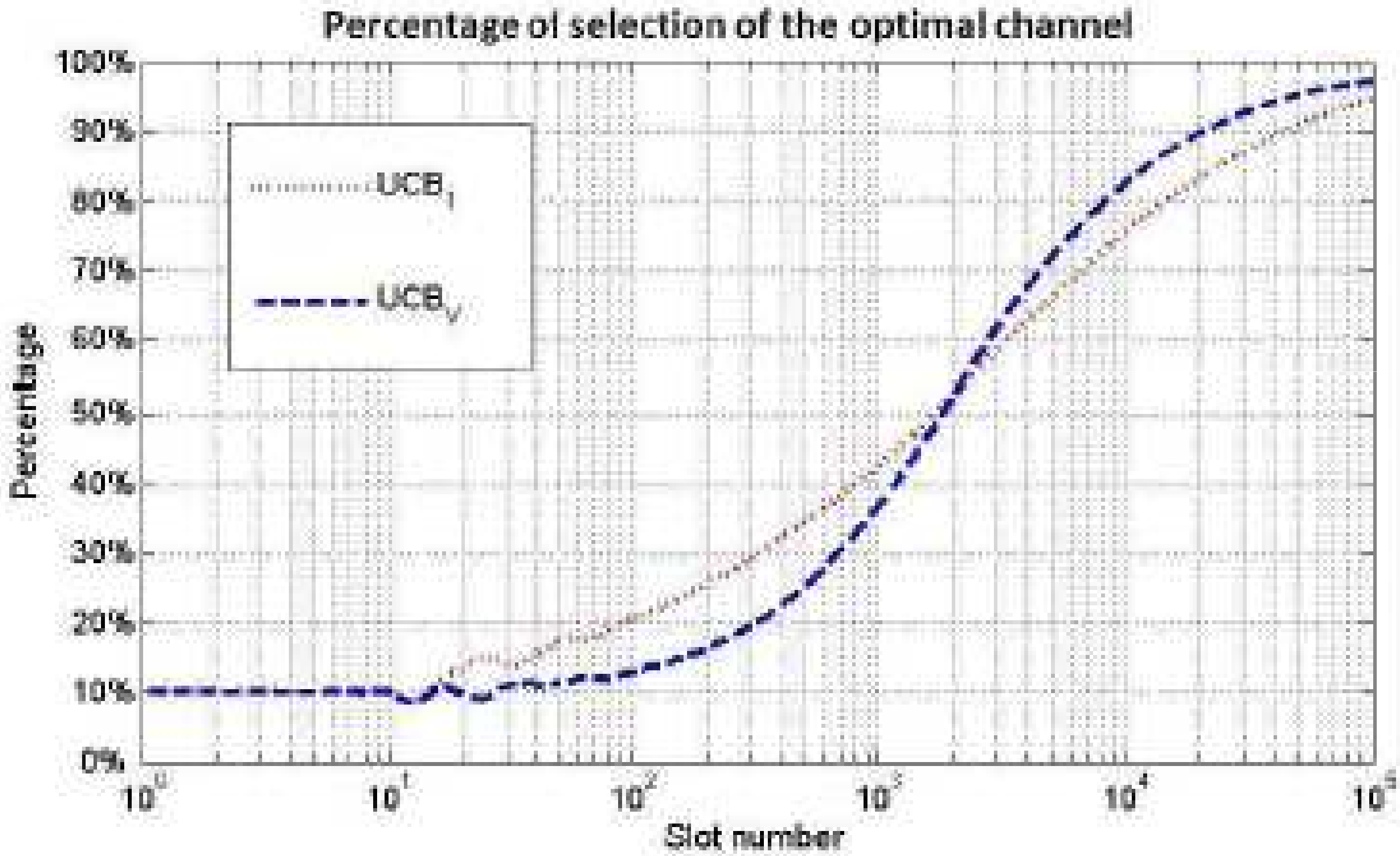
- **UCB gains in convergence to the best solution over uniform choice**

- 50000 iterations

NB: Solutions are ordered with no loss of generality (the higher the index, the better)
➔ best solution is #25

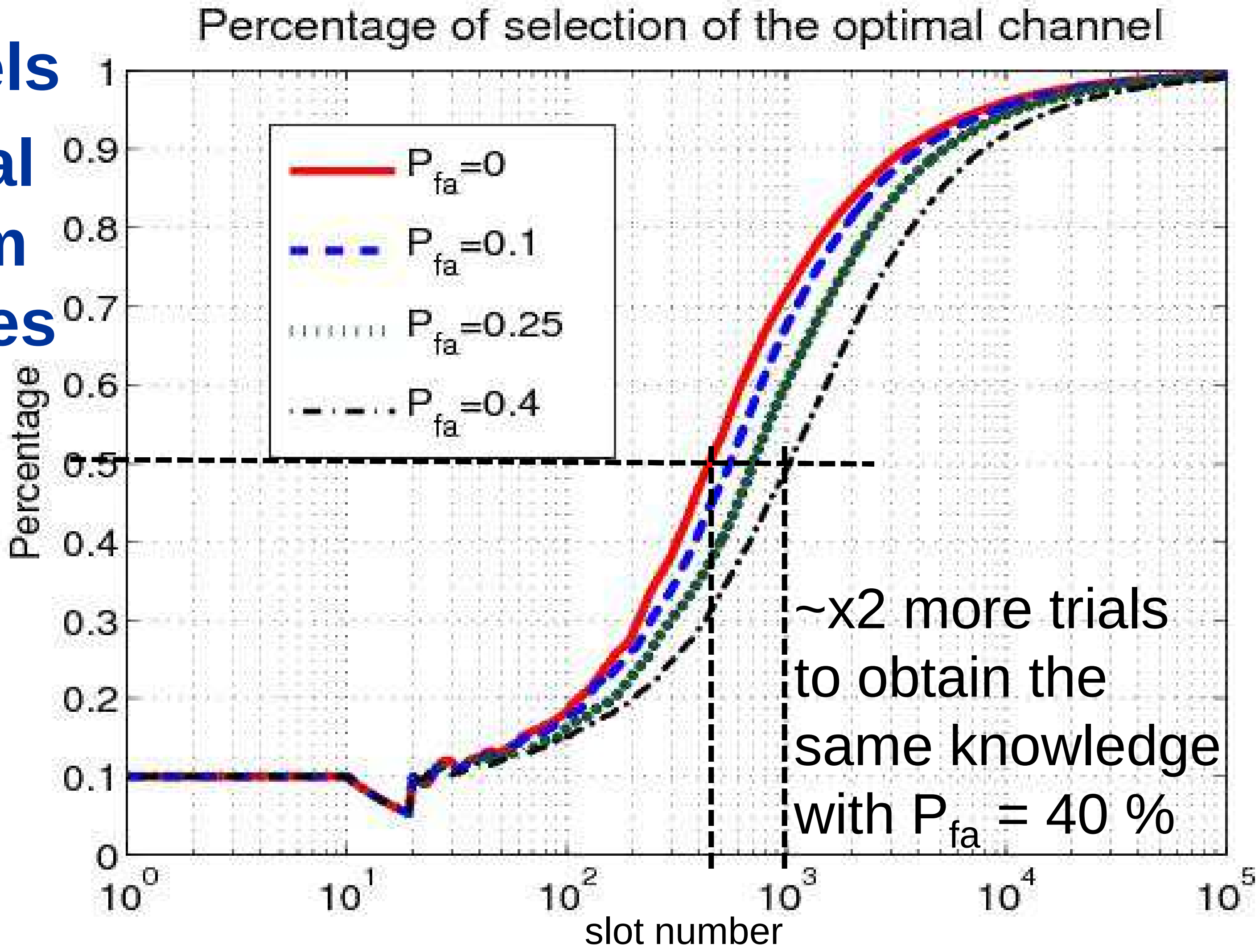


% of optimum channel selection



Effect of sensing errors I

- **10 channels**
- **for several false alarm probabilites**



[3] Wassim JOUINI, Christophe MOY, Jacques PALICOT "Upper Confidence Bound Algorithm for Opportunistic Spectrum Access with Sensing Errors" CrownCom'11, 1-3 June 2011, Osaka, Japan

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Experimental platform

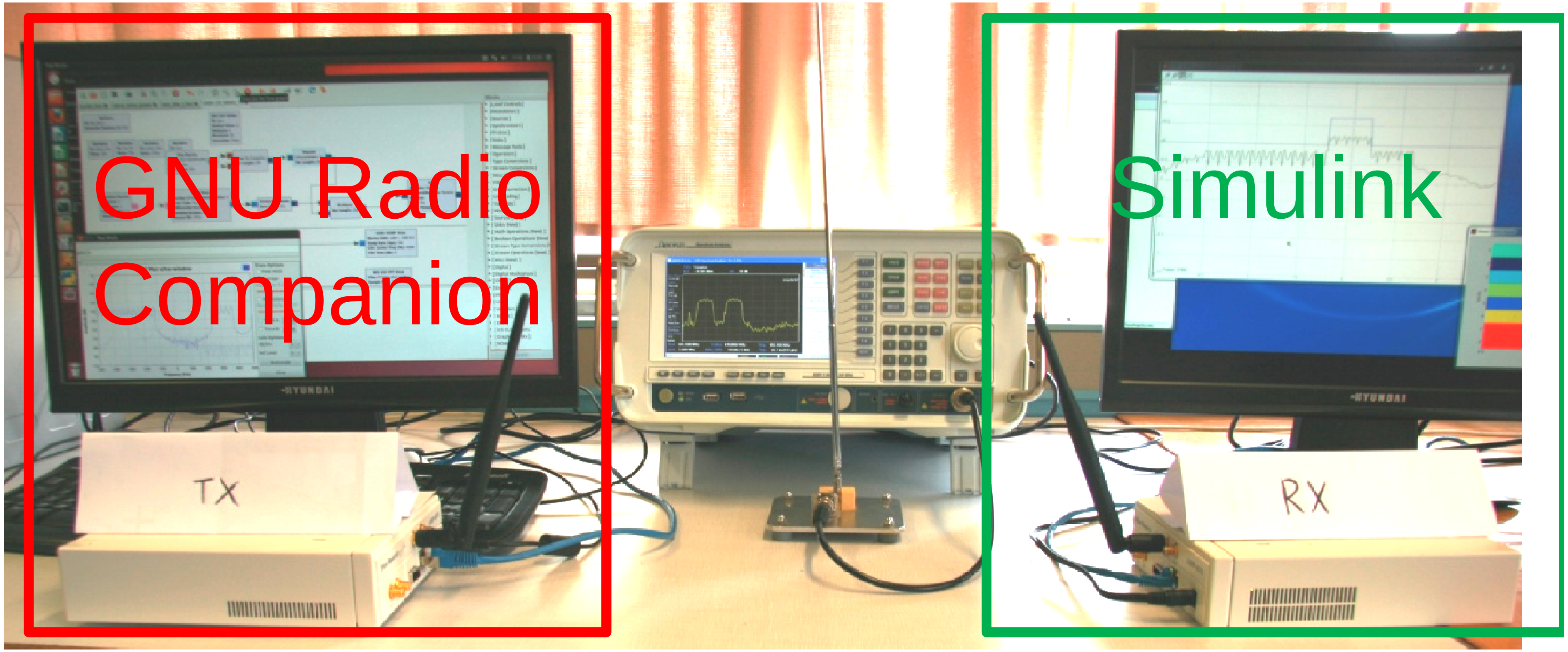


Figure 3 – Experimental testbed for learning in an OSA context.

- LEFT: primary network transmission (TX)
- RIGHT: one secondary user learning algorithm, implementing an energy detector as a sensor (RX).

Results

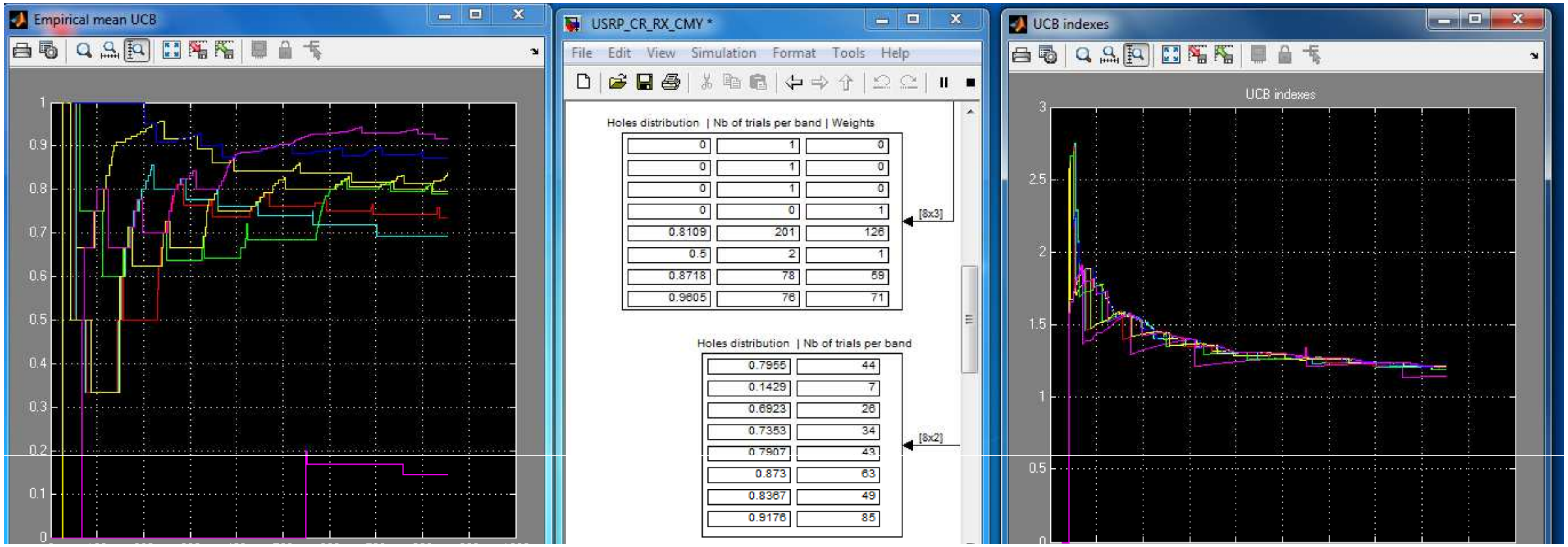


Figure 4 - Evolution during first 350 iterations of an experiment

- Left hand side: empirical average vacancy rate $\overline{X}_{k,T_k(t)}$ of the 8 channels derived from UCB.
- Right hand side: UCB indexes $B_{k,T_k(t)}$ evolution.
- Bottom middle table: UCB results
- Top middle table: WD results.

UCB evolution

- **After 73 iterations**
  – uniform search would have tried 10 times each
  – UCB really favors best channel (not at infinity)

	emp.prob	nb trials	target prob
channel#1	0.70	10	0.5
channel#2	0	3	0.3
channel#3	0	3	0.4
channel#4	0.6	10	0.5
channel#5	0.70	10	0.6
channel#6	0.60	10	0.7
channel#7	0	3	0.8
channel#8	**0.96**	**24**	**0.9**

Holes distribution	Nb of trials per band
0.7	10
0	3
0	3
0.6	10
0.7	10
0.6	10
0	3
0.9583	24

UCB evolution

- **After 1500 iterations**
  - best 3 channels selected 80 % of time

Holes distribution	Nb of trials per band
0.7273	110
0.3158	19
0.4483	29
0.5581	43
0.7956	181
0.8444	315
0.8442	308
0.8949	628

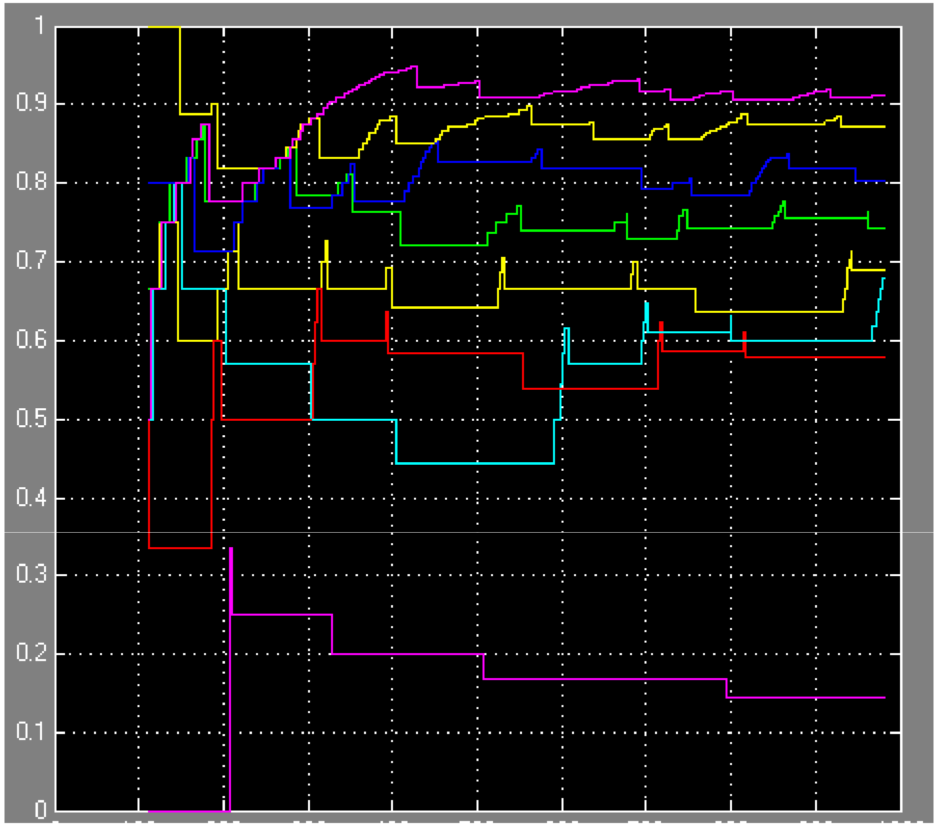
UCB evolution

- **After 7000 iterations**
  - best channel selected more than 50%
  - as 90% probability of vacancy for this chanr
  - in the worst case where all the other channe would be always occupied, SU has found transmission opportunities 50% of the time
  - for the two best channels: up to 75%

Holes distribution	Nb of trials per band
0.7032	219
0.2692	26
0.5352	71
0.573	89
0.7864	557
0.8022	718
0.8414	1532
0.8718	3783

Empirical probability of vacancy

- **Derived by UCB algorithm during 350 iterations:**
  - #8 violet 0.91 0.9
  - #7 yellow 0.87 0.8
  - #6 blue 0.80 0.7
  - #5 green 0.74 0.6
  - #4 red 0.58 0.5
  - #3 lht bl. 0.68 0.4
  - #2 purple 0.14 0.3
  - #1 light yell. 0.80 0.5



- **Very fast good estimation**
- **Proven at infinity**
- **Can be obtained in ms**

Impact of sensing errors

- **Not all for WD**
- **experimental results are a little bit too much optimistic in general**
  - certain probability of misdetection.
  - we can not definitely state

➔ **Future work will do**

channel	EPV UCB	EPV WD	PVSE
#8	0.87		0.90
#7	0.84	0.82	0.80
#6	0.80	0.77	0.70
#5	0.79	0.72	0.60
#4	0.57		0.50
#3	0.53		0.40
#2	0.27		0.30
#1	0.70		0.50

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Conclusion

- **Learning for decision making in cognitive radio equipments (e.g. decentralized)**
  - no a priori knowledge on the environment
  - MAB approach
  - UCB algorithm
- **Analytical results and proofs**
- **First ever real experiments results**
  - can really be used: good results before infinity!
  - resistant to sensing errors: convergence is OK
  - comparison of 2 algorithms (can do for others)

Thanks for your attention

- **If you want to read more**
  - SCEE research team web site: http://www.rennes.supelec.fr/ren/rd/scee/
  - SCEE vision on Cognitive Radio: http://www.rennes.supelec.fr/ren/perso/cmoy/SCEE-CR/
  - mail to: christophe.moy@supelec.fr
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