Docitive Networks

A Step Beyond Cognition

Mischa Dohler

CTTC, Barcelona, Spain

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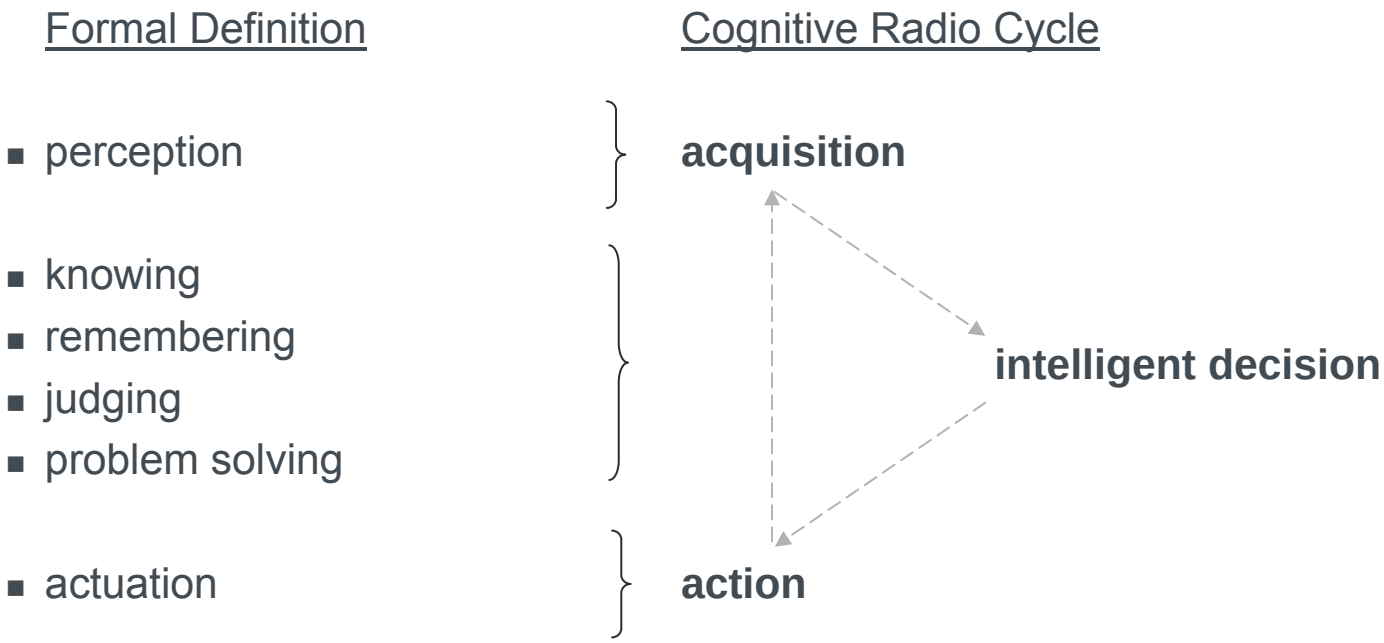
Baseline Cognition

Formal Definition of Cognition

- A cognitive system “involves perception; knowing, remembering; thinking, judging, problem solving; and intelligent actuation” [1]:

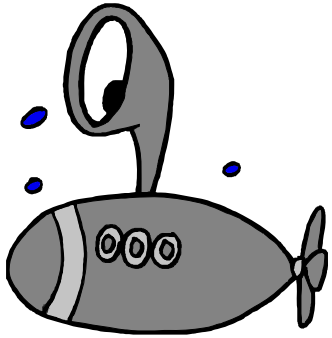


[1] http://psychology.about.com/od/cindex/g/def_cognition.htm

Alternative Definition of Cognition

- A cognitive system “a system which is working properly under conditions it was initially not designed for” [2]:
  - humans fly:

  - humans dive:



  - humans think:

[2] Apostolos Kontouris, Orange Labs, France, 2007.

Misleading Connotation of Cognition

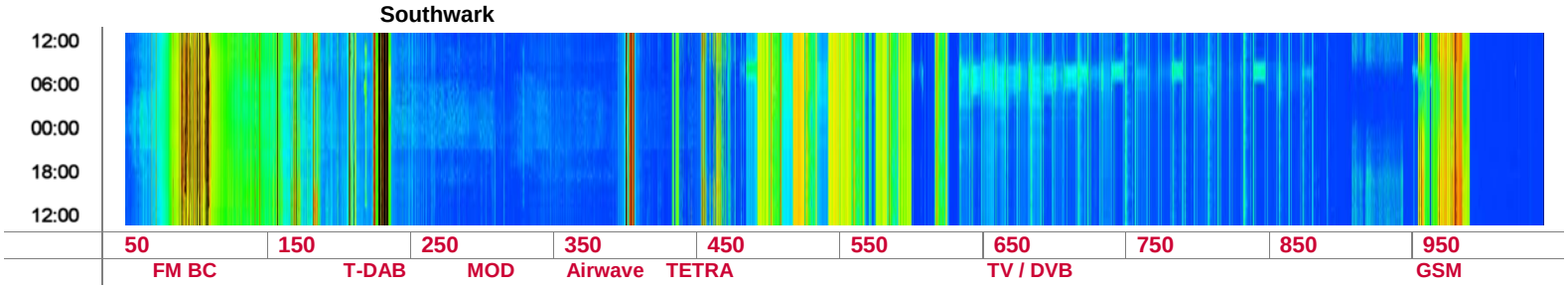
- An estimated 95-97% of publications containing the term “cognitive” are actually opportunistic at best.

- The main thrust of all these publications has been along …
  - spectrum is scarce in general - is it? -
  - thus let’s use spectrum holes - many? -
  - for this we need spectral sensing - useful? -
  - then act by comparing thresholds - new ? -

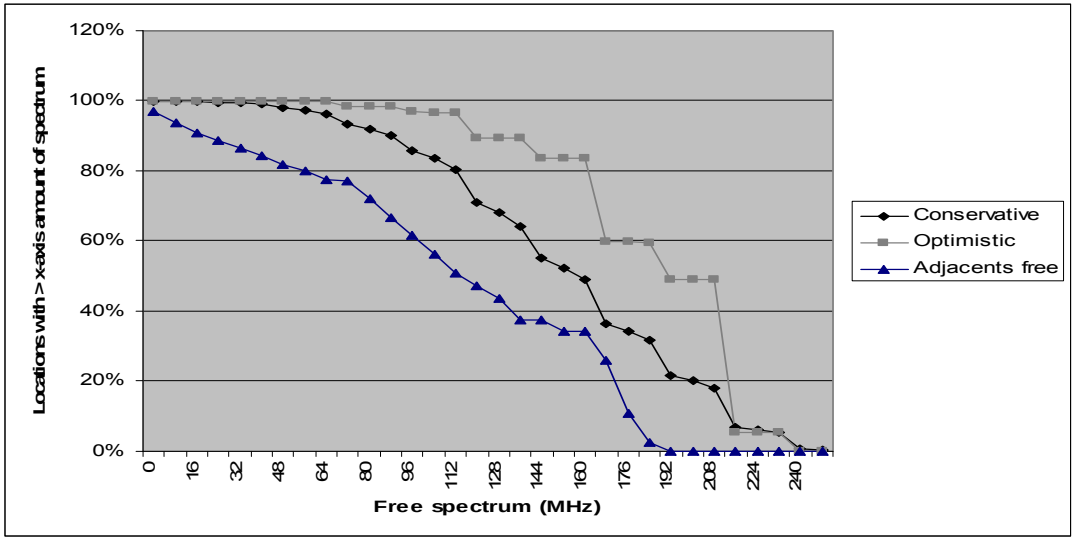
- Clearly not intentional, but “cognitive” is often misleading:
  - once a fashionable buzzword for getting a proposal funded
  - impressive transition to hype and then overripe well before actually used
  - waning reputation of cognitive makes it difficult to support subsequent research

Example: Interleaved Spectrum

- Apparently large amount of spectrum unused [3]:



- However [3]:



[3] @ Prof William Webb, Head of Ofom R&D, UK, from presentation at CTTC, 15 April 2009

Example: Interleaved Spectrum

- Study conducted by Ofcom concludes [3]:
  - benefits estimated to have value of £200m-£300m
  - DTT e.g. has an equivalent value in the region of £50bn
  - thus maximum of 0.5% probability of interference
- Methods potentially guaranteeing this interference probability:
  - spectral sensing
  - global beacon channels
  - geolocation → preferred solution
- Problems with sensing [3]:
  - hidden node sensing margin is up to 35dB
  - this is beyond any non-cooperative sensing techniques
  - cooperative sensing not answer either (unreliability/costly planning)

[3] @ Prof William Webb, Head of Ofom R&D, UK, from presentation at CTTC, 15 April 2009

Overview

1. Baseline Cognition
2. From Cognition to Docition
3. Wireless Multi-Agent Systems
4. Vision & Challenges
5. Conclusions

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From Cognition to Docition

A Case For Docitive Systems

- State of human cognition heavily depends on teachers encountered during one's life, who generally impact:
  - learning space
  - learning speed
  - teaching abilities

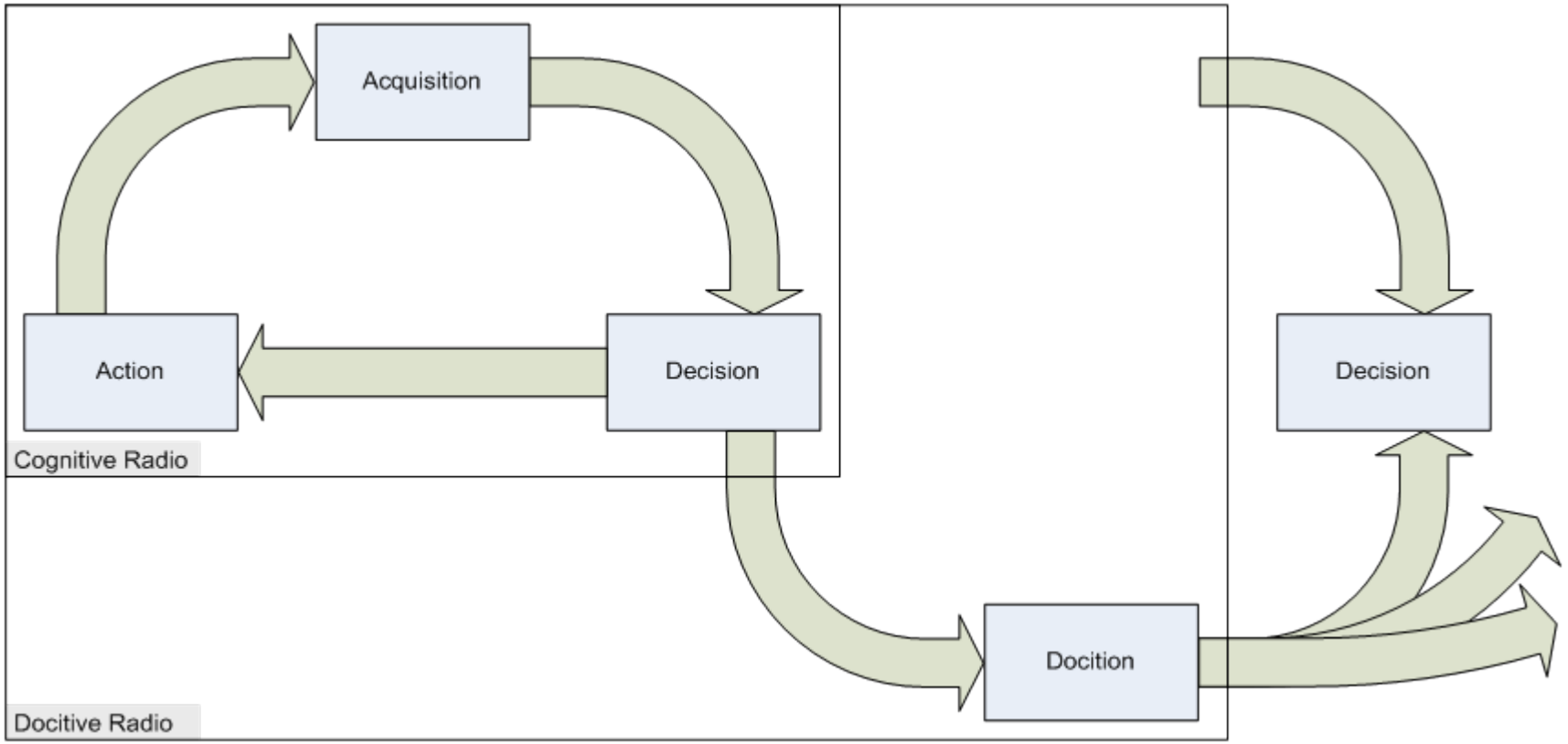
- Concept of Docitive Systems is inspired by so-far-successful Problem Based Learning (PBL) concept:
  - mimics the well-functioning society-driven teacher-pupil paradigm
  - introduce rigorous framework for above observations, where

radios are encouraged to teach other radios

  - with the aim to significantly improve performance of current (cognitive) systems
  - origin is from "docere" = "to teach" ("cognoscere" = "to know/learn")

Docitive System Cycle

- Extension of Cognitive Cycle by Docition:



Cognitive Part of the Cycle

- Acquisition:
  - individual and/or collaborative sensing;
  - docitive information from neighboring nodes;
  - environmental/docitive information from databases; etc.
- (Intelligent) Decision:
  - core of a cognitive radio which learns and draws decisions;
  - majority today are simple opportunistic decision-making algorithms;
  - more sophisticated unsupervised, supervised or reinforcement learning available.
- Action:
  - ensures that the intelligent decisions are actually carried out;
  - typically handled by a suitably reconfigurable software defined radio (SDR);
  - also through policy enforcement protocols, among others.

Docitive Part of the Cycle

- Concepts borrowed from Problem Based Learning (PBL):
  - proponents: Lev Vygotsky, John Dewey, Jean Piaget, Michael Gardener, etc.
  - teachers are encouraged to be coaches – not information givers;
  - pupils work as a team using critical thinking to synthesize and apply knowledge; they apprehend through dialogue, questioning, reciprocal teaching, and mentoring
- Docition:
  - realized by means of entity facilitating knowledge dissemination and propagation;
  - paradigm comprising dissemination of information which facilitates learning.
- State-of-the-art:
  - sharing of end results (e.g. cooperative sensing or central database);
  - multi-agent systems (machine learning community);
  - distributed artificial intelligence (AI community).

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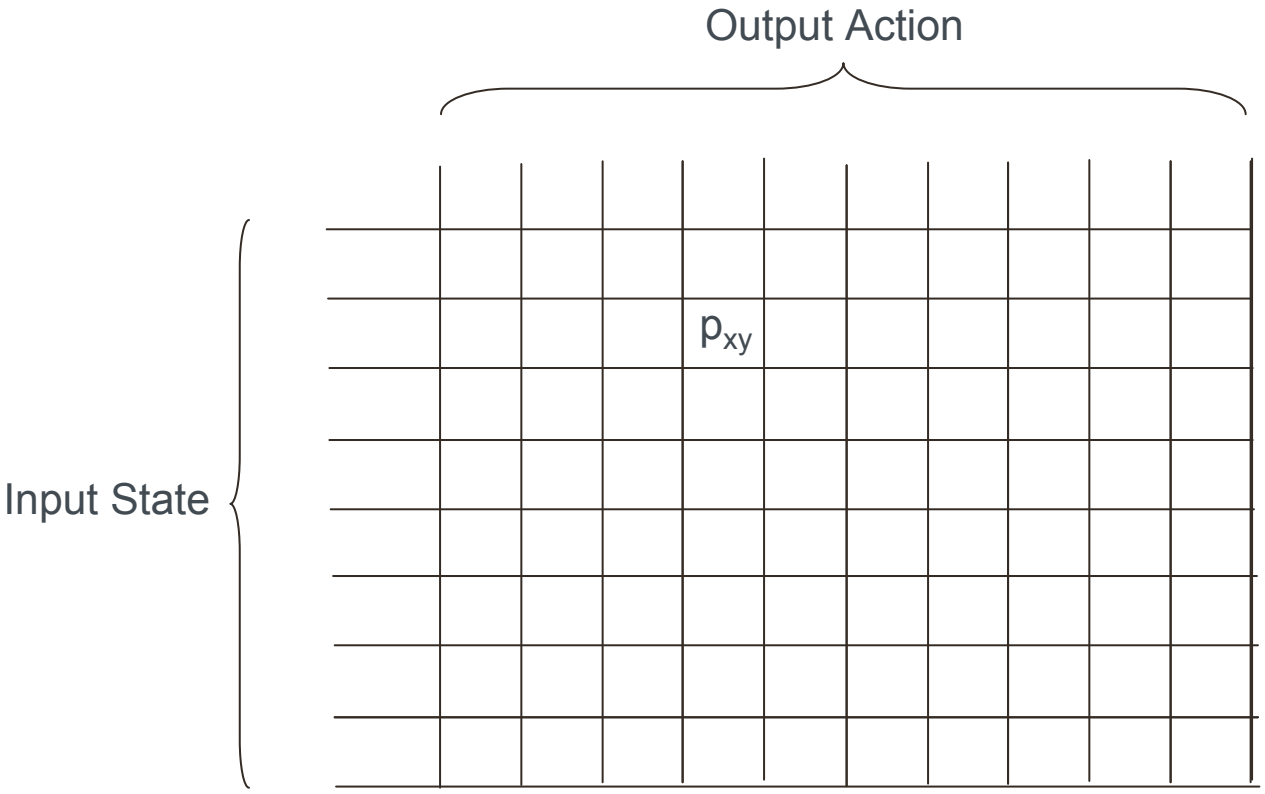
Wireless Multi-Agent Systems

Single-Agent Baseline System

- For given environmental state-action space find transition probabilities such that reward is maximized:



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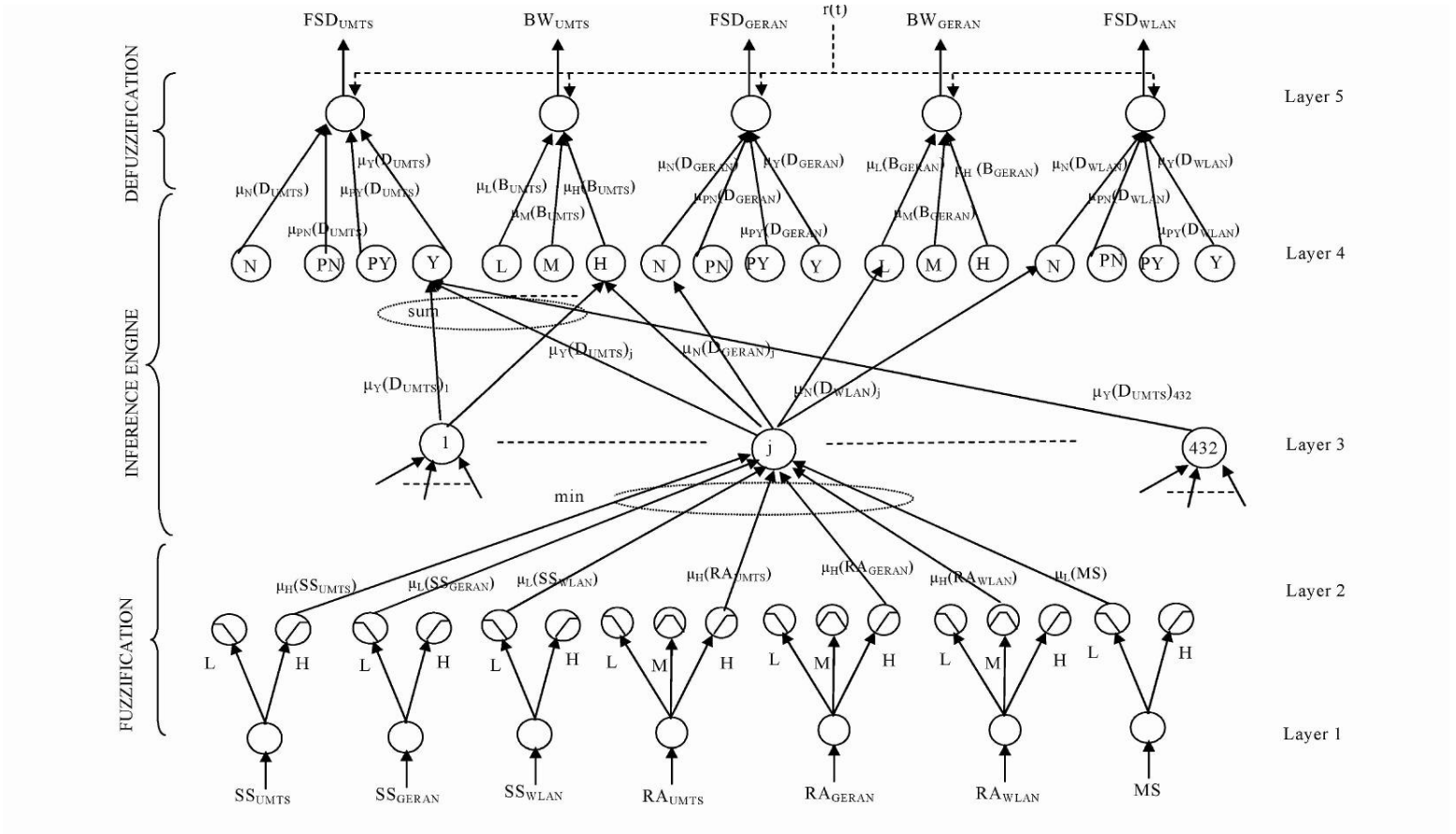

Multi-Agent Systems

- Q-Learning, being a typical learning mechanism for single agent systems, can be adapted to distributed settings:
  - implementation of decentralized Q-learning;
  - training process is extremely complex for increasing state-action space;
  - nodes thus could learn some disjoint or random parts of the state-action space;
  - this facilitates learning but does not yield the end-result *per sé*.
- We propose investigation into different degrees of cooperation, essentially trading cognition versus docition:
  - independent learners
  - cooperative learners
  - team learners

Degree of Cooperation

- Independent Learners:
  - nodes do not cooperate since they ignore actions and rewards of other nodes;
  - they learn their strategies independently.
- Cooperative Learners (different degrees):
  - independent learning but sharing of instantaneous information about states;
  - share sequences of state, action/reward/learned state-specific decision policies;
  - perform joint tasks yielding longer learning but less oscillations.
- Team Learners:
  - multi-agent system is regarded as a single agent in which each joint action is represented as a single action;
  - optimal Q-values for the joint actions are learned using single-agent Q-learning;
  - no communication is needed between the nodes but they all have to observe the joint action and all individual rewards.

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Vision & Challenges

Quantifying Cognition & Docition

- Quest for viable measure for “intelligence”:
  - attempted across numerous domains over past centuries
  - no generic answer as most are application tailored (e.g. IQ test)
- There is a common trait, however:
  - intelligence is related to ability to bring order from seeming disorder
  - example of quasi-uniformly distributed random numbers:

16	3	2	13
5	10	11	8
9	6	7	12
4	15	14	1

- Universal quantifying measure for order & disorder: **entropy**

Entropy as Guiding Metric

- We draw the following qualitative observations:
  - “stupid” radio: increases disorder at output w.r.t. input
  - “clever” radio: decreases disorder at output w.r.t. input
- Straightforward rough quantitative formulation:

> intelligence = input entropy – output entropy

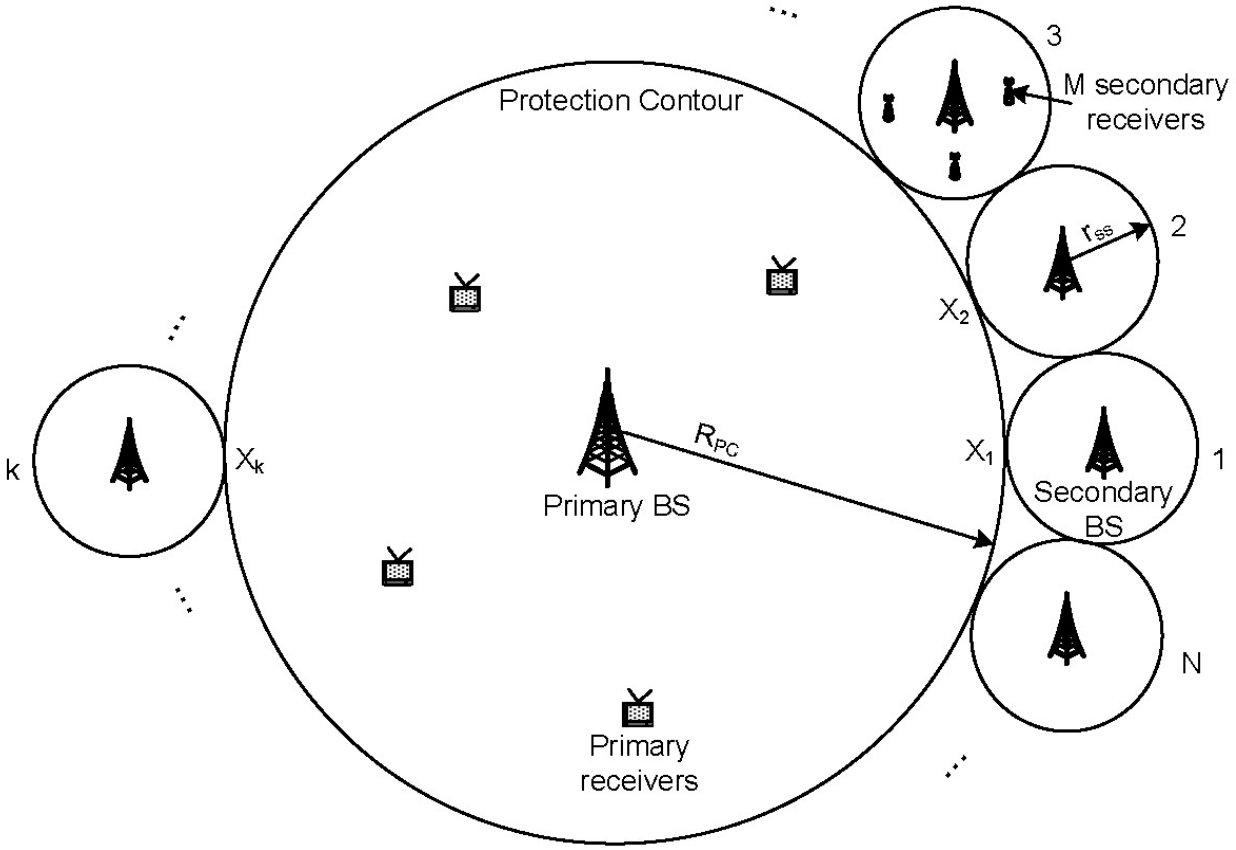
- Direct implications onto docitive systems:
  - input and output entropies are easy to measure and observe in a real system
  - facilitates the establishments of intelligence gradients in a system
  - allows establishing teaching costs along these gradients
  - docition should follow the steepest gradient

Entropy as Guiding Metric

- The following example metrics pertain to a single radio:
  - **current intelligence** = actual input entropy – achieved output entropy
  - **maximal intelligence** = max. input entropy – minimal output entropy
  - **learning ability** = (maximal – current) intelligence
- The following example metrics pertain to the network:
  - **intelligence gradient** = Δ of current intelligence between nodes
  - **degree of docition** = sum over intelligence gradient / number of nodes
- Example configurations:
  - selfish power control: Gaussian distribution → I_1
  - cognitive radio with SINR region: uniform distribution → $I_2 > I_1$
  - cognitive radio with SINR target: Dirac-delta distribution → $I_3 > I_2 > I_1$

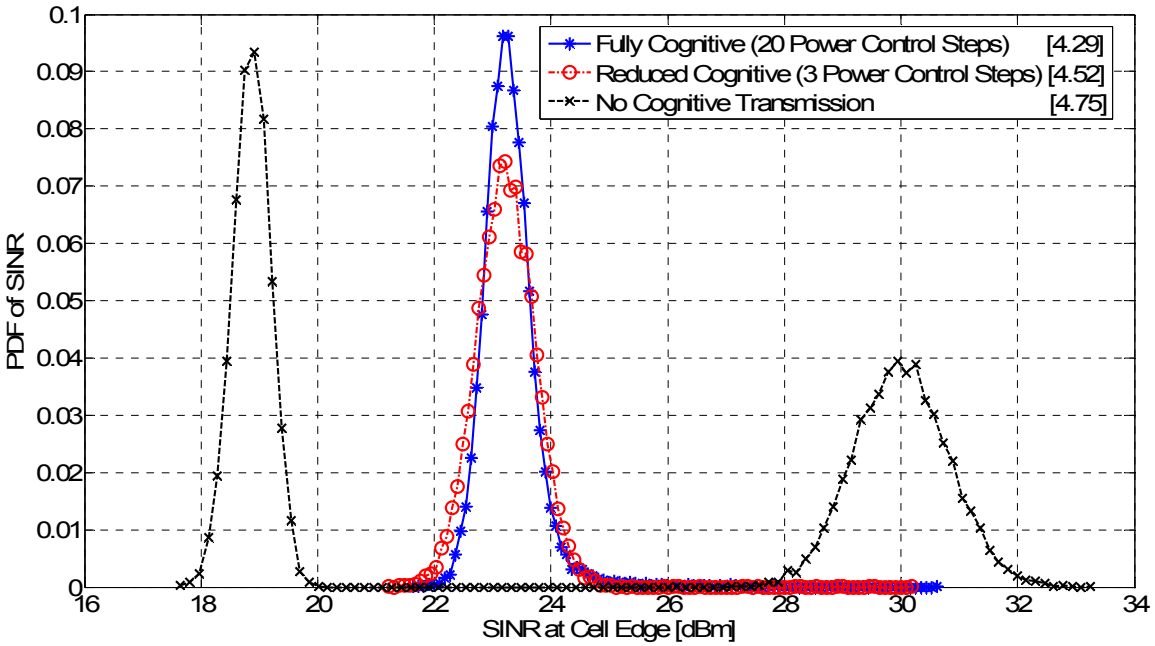
Example Cognitive Wireless System

- Primary DTV receivers in protection zone, surrounded by secondary cognitive users with constraints on SINR levels:



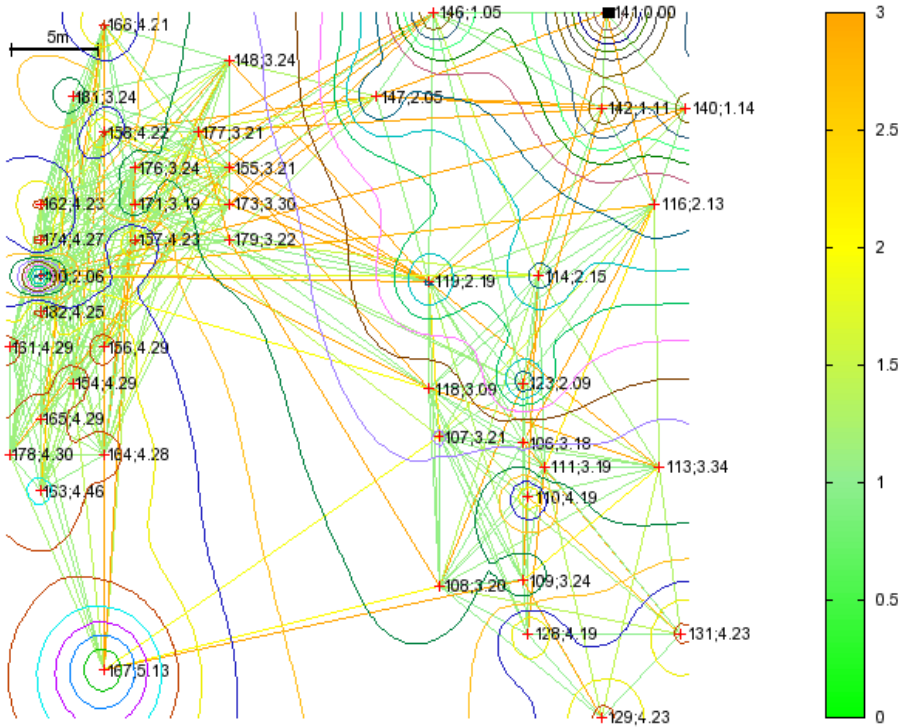
Example Cognitive Wireless System

- Different degrees of cognition yield different intelligence levels:
  - full cognitive scenario with 20 power control steps (entropy = 4.29)
  - reduced cognition with 3 power control steps only (entropy = 4.52)
  - no cognition but only selfish power control (entropy = 4.75)



Example Cognitive Wireless System

- Building docitive gradients by incorporating:
  - gradient of intelligence
  - mapping it to potential gains
  - weigh it against cost of cooperation



Challenging Open Problems

- Numerous interesting and pertinent research areas open up, such as:
  - Information Theory: How much side information needs to be taught to pupils?
    Impact of feedback, renewal rate, etc.?
  - Wireless Channel: What are the coherence times of the channel?
    Do they allow sufficient time for learning/teaching?
  - PHY Layer: How much rate/energy should go into teaching?
    Which PHY states should be taught?
  - MAC Layer: Can we re-use known broadcast approaches?
    Which MAC states should be taught?
  - System: What is the optimal ratio teachers versus pupil?
    What is the optimal teaching schedule?
    Should every pupil also be teacher?
    What exactly is best taught?
    Facilitator of emergent behavior?

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Conclusions

Conclusions

- Cognitive Systems:
  - very well but fairly generically defined
  - little truly cognitive systems available today
- Docitive Systems:
  - yet another generic concept with room for (mis)interpretation
  - framework with no claim for total novelty and open for discussions
  - “bad teacher teaches end-result – good teacher facilitates learning”
  - CD + DR = more efficient radio
- Acknowledgements:
  - Petri Mähönen, RWTH Aachen in Germany, for pointer to multi-agent systems
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  - Ana Galindo-Serrano, CTTC, for provision of large set of simulation results