Cognitive radio – new players, a different game

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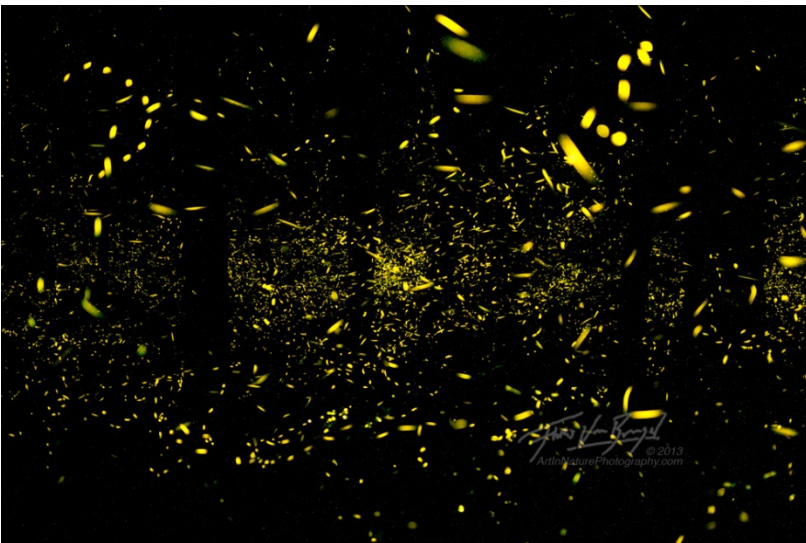University of Technology

Where innovation starts

Story line

- **Inspiration from nature**

- **Self-organisation and cognitive capabilities**

- **Agile decision taking: some examples**
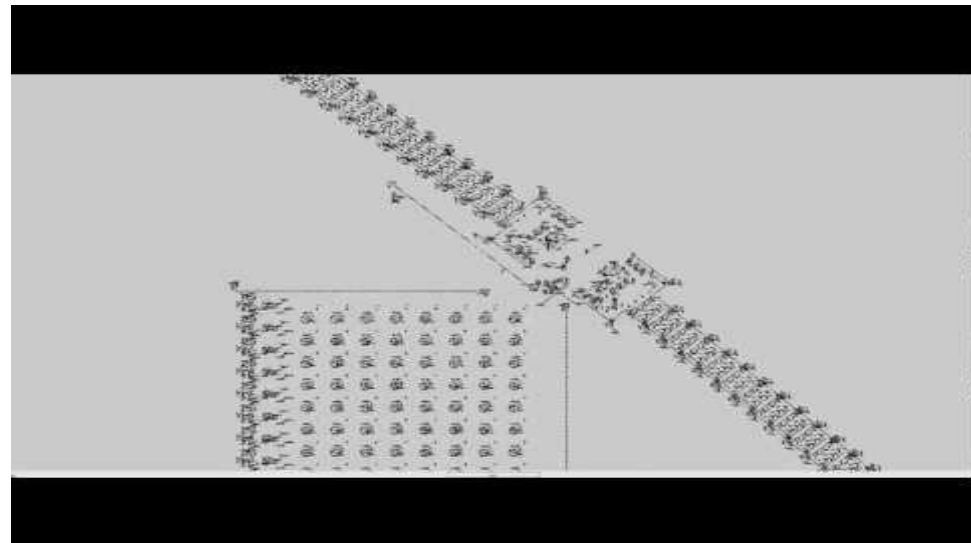
- **New perspective: game theory**

Starlings – nature and self-organization
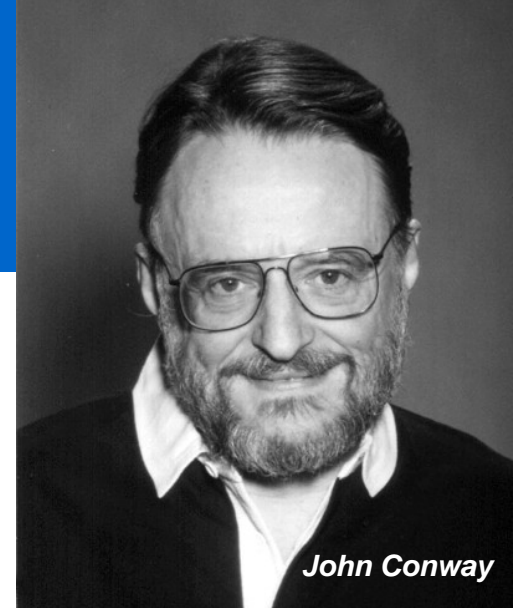
And more: fire-flies, game of life

(c) Floris van Breugel, Art in Nature

Global structure ⇔ local action

John Conway

Charlotte Hemelrijk

- **Game of life explained on local level:**
  - **Each cell has eight immediate neighbors, and can be in one of two states: on or off, occupied or empty, alive or dead. Two simple rules govern the outcome of any initial state:**
    - A live cell will remain alive in the next generation if it has either two or three live neighbors.
    - An empty or dead cell will be occupied or come to life in the next generation if it has exactly three live neighbors. In all other situations living cells die and dead cells remain dead.
- **Starlings – how do they do it?!**
  - 'telepathic skills of starlings' (Selous, 1931)
  - Charlotte Hemelrijk: a model, explained based on 7 neighbours and 3 rules of action (Hildenbrandt, Carere & Hemelrijk, 2009)
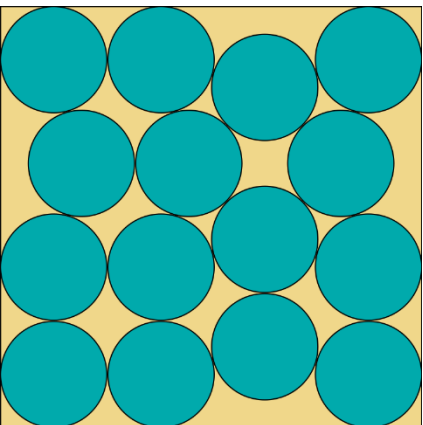   - **Separation**
    - **Alignment**
    - **Cohesion**

Intermezzo: the 'why' and 'how' of structure

- **Why is structure needed, and how do we go about it?**
  - **Why: structure ➔ optimal use (packing space), optimal because of scarcity, guarantees (quality, economical, ...) – on what level do we want to have guarantees ("hard" ➔ regulated, statistical ➔ design)**
  - **How: partitioning, protocols, design / system architecture**

(c) Agricultural Research Service

Source: "Circles packed in square 15" by Toby Hudson.

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Self-organisation and cognitive capabilities

- **SON architectural types: distributed, centralized and hybrid**
  - **Self configuration (plug-and-play) – needed because of shortage of personnel, new business model (sharing cost), cutting cost of installation (e.g. sensor networks; smart paint / wallpaper, pre-installed)**
  - **Self optimization – follow (continuous) change of environment, when is a change significant in order to prevent 'ping-pong', role of heuristics**
  - **Self healing – reduce impacts of failure (e.g. national roaming, load sharing, downgrading, ...), self starting ➔ self configuration**

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# Self-organisation and cognitive capabilities

Lorin Maazel

- **Most SON features in 4G / LTE+ are of C-SON nature: an element of 'direction' seems to be required to optimize**
  - **Natural question in case of D-SON features: study the impact on performance of neighbours**
- **C-SON requires signalling, is less agile, includes delay –**
  - **D-SON requires {local information, storage and computing}-capabilities;**
  - **Starling example: distributed (localised) decisions based on neighbour-information [flight model]**

Agile decision-taking – some examples

- **Cognitive cockpit:**
  - **Dealing with (new) unforeseen events**
  - **Using 'stored knowledge' or resort to basic principles**
- **'Use': ABC, lowest cost, …**
  - **911 sms, 802.11p (➔ G5)**
- **Re-use': permission or forgiveness?**
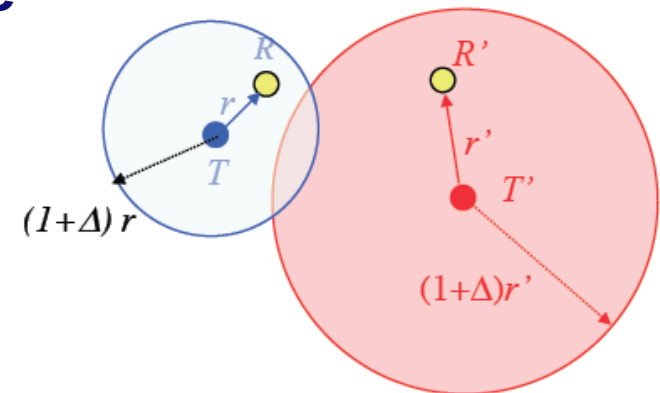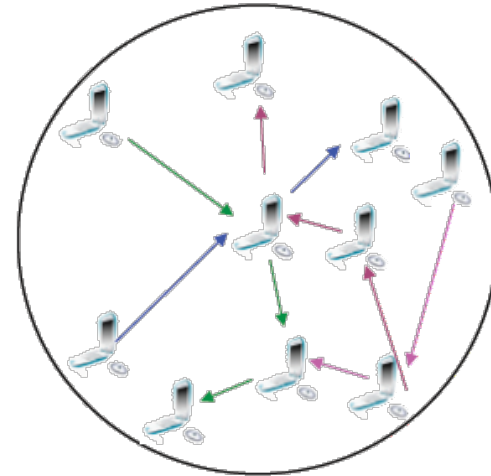- **'Multi-use': downloading your local cognitive app**
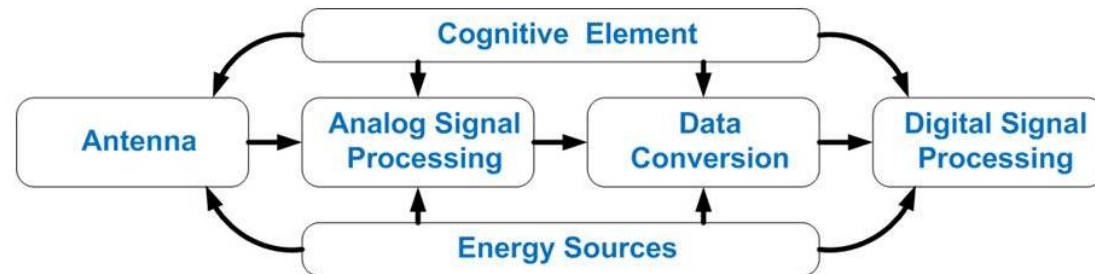
Wi-Fi Assist

Automatically use cellular data when Wi-Fi connectivity is poor.

Wireless multi-hop networks

- **Basic idea:**
  - **n nodes, each able to transmit with W bits/s**
  - **packets succesfully received when local interference is absent or sufficiently low**

P. Gupta

- **Basic protocol: receiver R should be**
  - **within range *r* of its corresponding transmitter T**
  - **outside footprint $(1+\delta)r'$ of any other transmitter T' using range *r'*.**

June 26, 2009 , P. R. Kumar

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From idea to concept

- **Kumar (2003) showed that elegantly that**
  - **transmissions consume area**
  - **this area has radius $\delta \times r_i / 2$ around the receiver, for every pair {T_i, R_i} with $|T_i\text{-}R_i| = r_i$.**

- **Using straightforward arguments we can show that:**
  - **from an output-power perspective it's better to use multiple hops**
- **With Kumar's argument, it's better to use <u>short (many)</u> multiple hops**
  - **take care of 'connectedness'!**
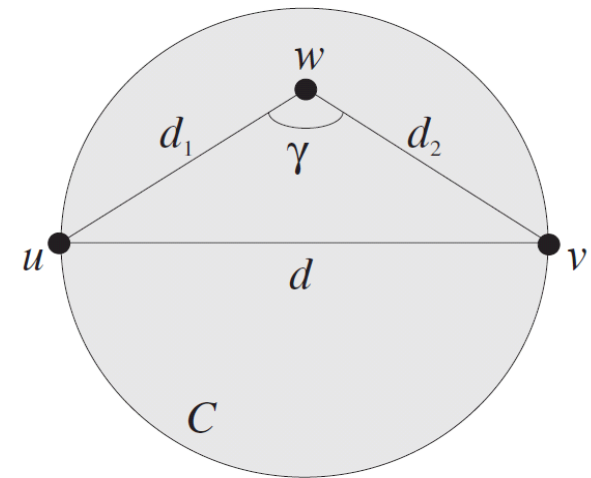
Locally managing global connectedness in a mesh / ad-hoc network

- **Topology control decides which hops / logical links to keep, and which to cut**
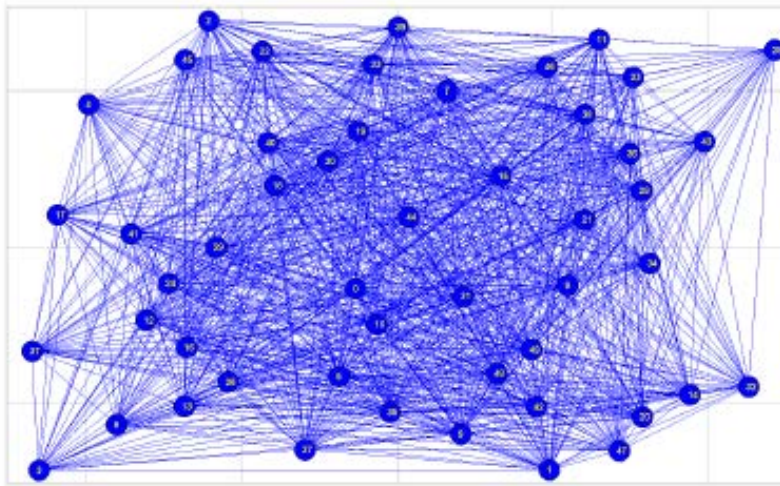 - **Challenge: varying path loss, mobility!**

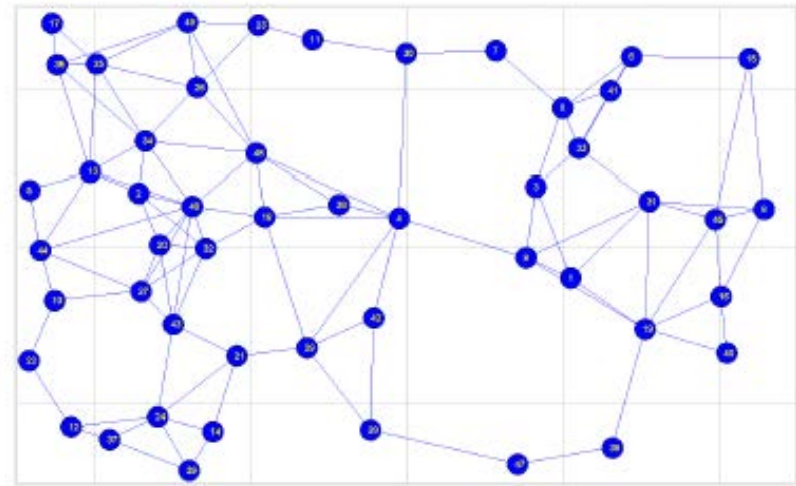FIGURE 5.1: Network topology at maximum power.

FIGURE 5.4: Network topology after application of proposed algorithm.

Source: Daniel Tadesse / Jan Stoter / Erik Fledderus

Mimicking nature: local synchronisation (fire flies)

- **Time synchronization is a crucial component of infrastructure for Wireless Sensor Networks (WSNs).**
  - **Most applications of WSNs make extensive use of time synchronization mechanisms like Time Division Multiple Access (TDMA) scheduling, accurate timestamping of events, coordinate activities of the network or data fusion.**

- **The unique requirements of wireless sensor networks, compared to traditional networks, in terms of precision, lifetime, energy and scope of the synchronization achieved, make the traditional synchronization methods unsuitable for WSNs.**
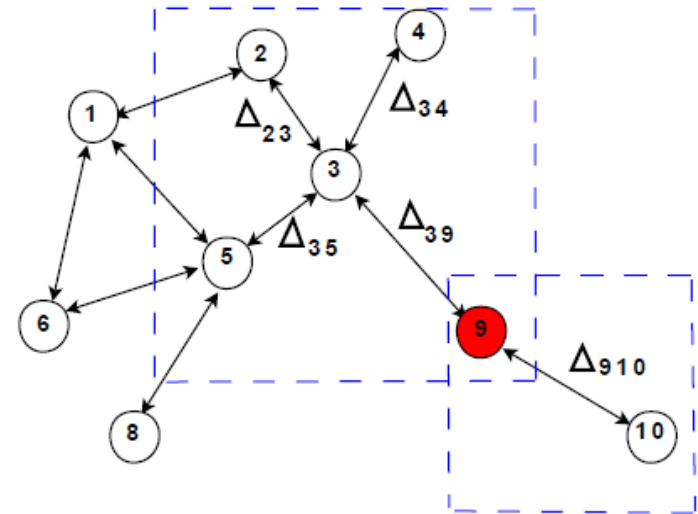
© Fasika Assegei / Frits van der Wateren / Erik Fledderus
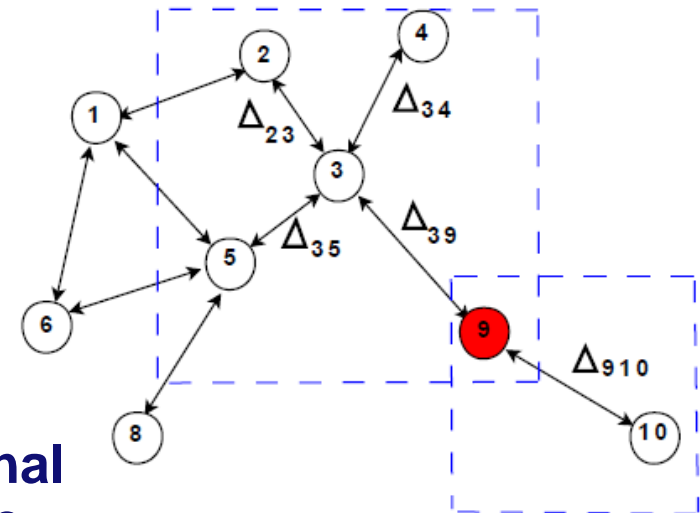
Mimicking nature: local synchronisation (fire flies)

- **gMAC – protocol: 'gossip'-like**
  - **Received messages from other nodes are collected and 'broadcasted'**
  - **Part of the message, the nodes are transmitting the slot number which it is transmitting. This information is used in the determination of the time that the message is sent.**

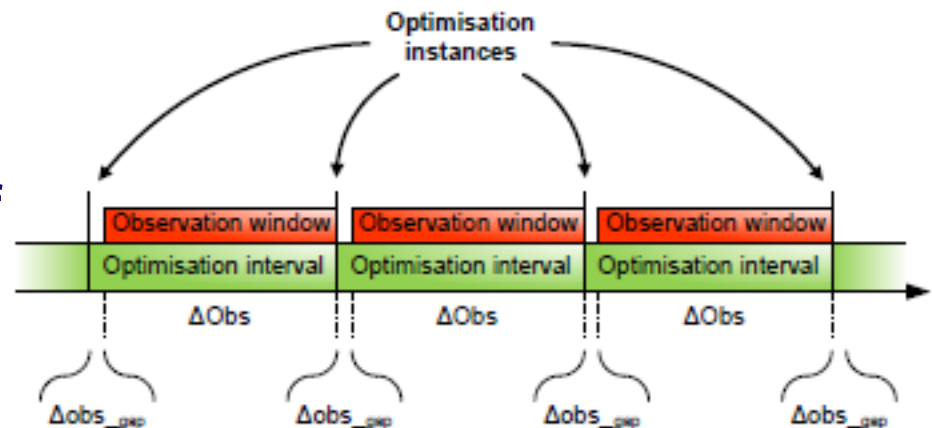$$\Delta t_{ij}^{(n)} = t_i^{(n)} - t_j^{(n)}$$

$$t_i^{(n+1)} = t_i^{(n)} + T_i^{(n)} - \xi_i^{(n)}$$

$$\xi_i^{(n)} = f\left(\Delta t_{ij}^{(n)}\right)$$

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Heterogeneous networks: load sharing

- **Classic example: hand-over**
  - **Key 'play'-variables: hysteresis, time-to-trigger (observation window)**
  - **Context: availability of alternatives, load, other KPIs of alternatives**
  - **KPIs of the result: qualit of experience**
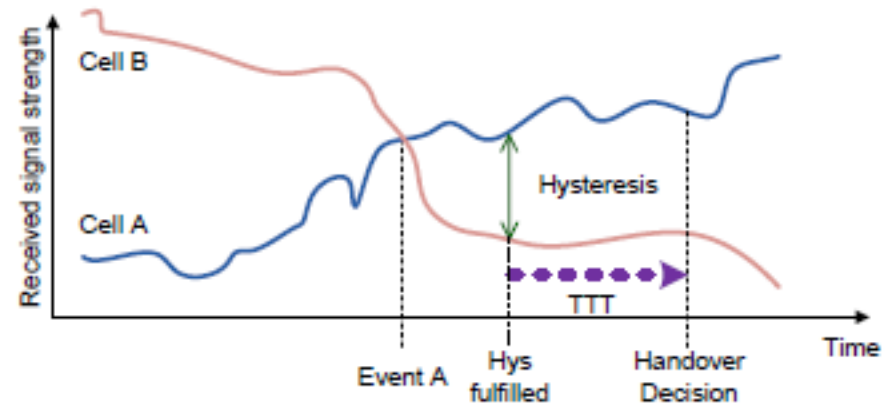
Source: Thomas Jansen, PhD Thesis – TU Braunschweig, 2015.

Spectrum harvesting

- **Regulation: technology neutral (or 'agnostic')**

- **New domains where wireless plays a key enabling role (automotive, smart grids, precision agri-culture): 'buy' or 'make' – and in case of 'make': claim on spectrum**
  - **Internet of things important driver**

- **Dual-use of spectrum (shared access)**

# Reflection on examples

- **Use of heuristics to simplify near-optimal decision-making**

- **Optimal decisions without taking into account the price of information is useless**

- **'Ping-pong' effect is relative to speed of change, so not always a bad thing – example of stock market shows that extremely rapid following changes is a way of gaining ('gaining from change') – but this has a price**

Cognitive cycle

Joseph Mitola III
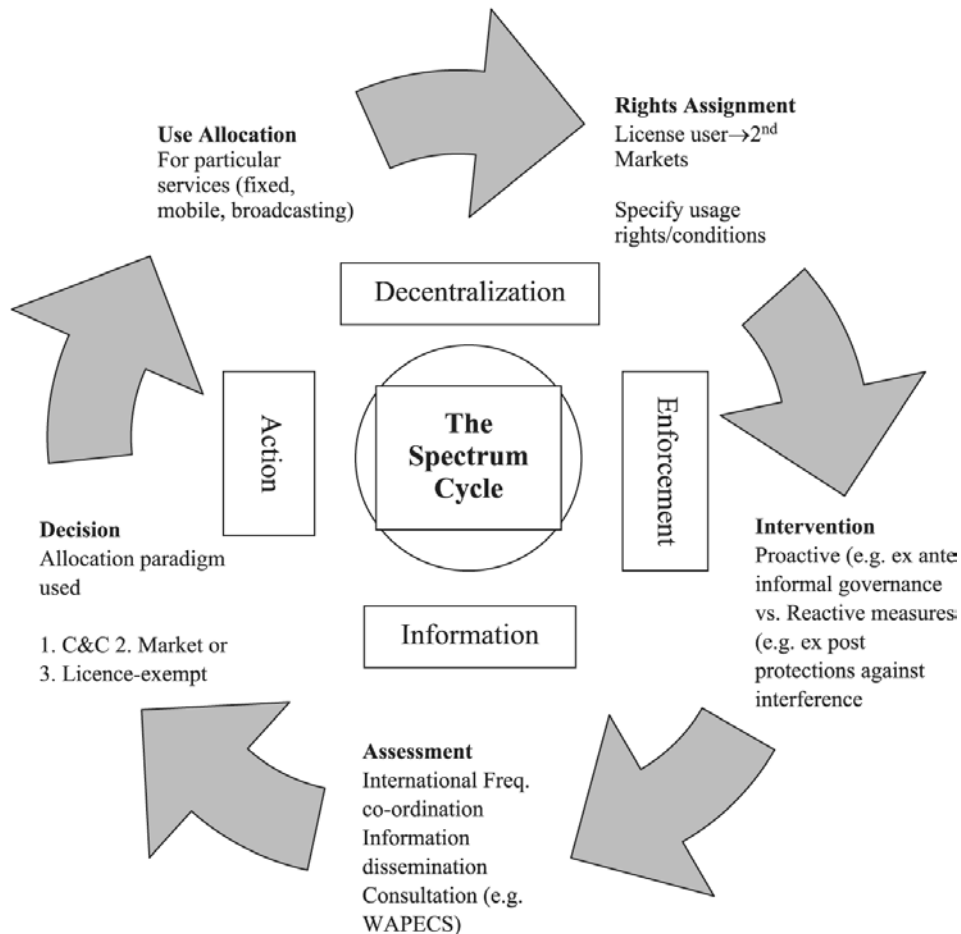
- **Challenging Questions:**
 - Under what conditions will recursions settle to a steady state?
  - What is that steady state?
  - Will the resources be shared equally?
  - Is the steady state stable?
  - How much signalling overhead is required?

Heuristics & choice patterns

- **Nodes / users / terminals / players that do not or hardly communicate with each other and still want to make the best of it, together ... This is the field of game-theory**

Game theory

John Nash

- **A set of mathematical tools used to model and analyse interactive decision processes**
- **Important elements for a normal form game:**
  - **A finite set of players (decision makers)**
  - **An action space**
  - **A set of utility functions, quantifying the players' preferences over the game's possible outcomes**

- **Assumption: players act in their own self-interest**
- **Important steady-states are Nash equilibria:**
 - **no player can improve its payoff by unilaterally changing its action**

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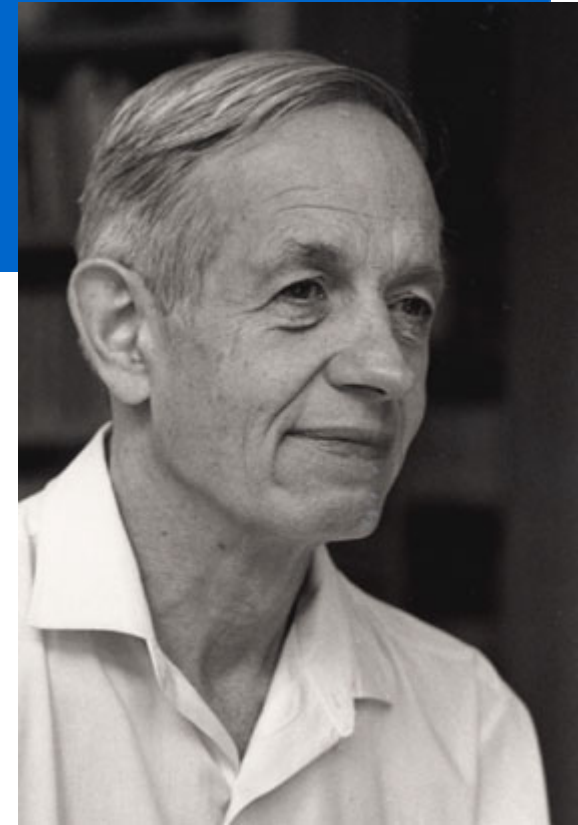
Some notions from game theory

- **Besides normal form games: repeated game model**
  - **sequence of stages, in each stage a normal form game**
  - **fully characterised by a player function (who is allowed to adapt play in a certain stage) and a set of decision rules (how to update your previous decisions)**
  - **important: convergence and stability**
  - **Lyapunov stability: a* is LS iff**

Alexander M. Lyapunov

$$(\forall \varepsilon > 0)(\exists \delta > 0)(\forall k \geq 0)\left(\left\|a^0, a^*\right\| < \delta \Rightarrow \left\|a^k, a^*\right\| < \varepsilon\right)$$
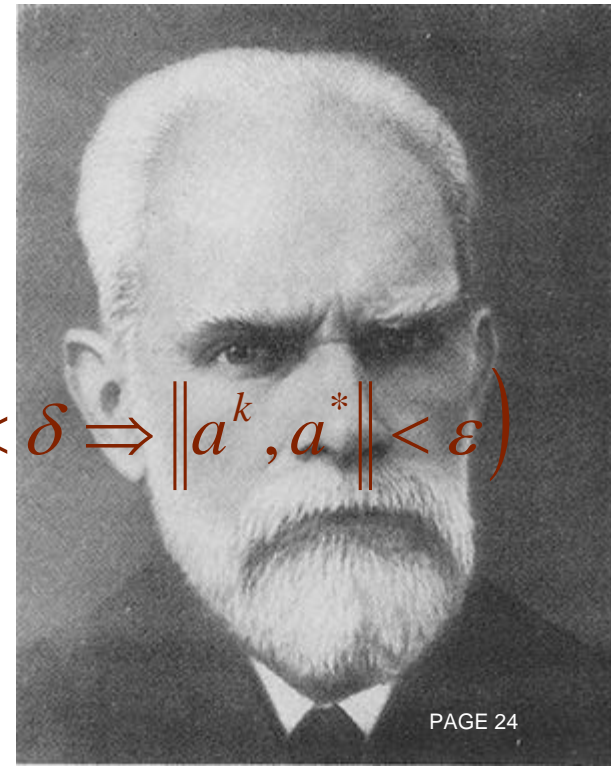
Applying game theory to cognitive radio

- **Each node in the network is a player**
- **The various alternative available to a node forms the node's action set**
- **Observation provides arguments to evaluate ('absolute') the utility function, and orientation determines the valuation ('relative') of the utility function**

1. Does the algorithm have a steady state?
2. What are those steady states?
3. Is the steady state(s) desirable?
4. What restrictions need to be placed on the decision update algorithm to ensure convergence?
5. Is the steady state(s) stable?

- **Questions 1-3 are addressed by standard Game Theory**
- **Questions 4-5 can be solved by introducing certain game models (Potential Game Model and Supermodular Game Model)**

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Applications

- **Frequency Selection Adaptive Interference Avoidance**

- **OFDM Channel Filling**

- **Distributed Power Control**

- **Smart routing of data**

REFERENCE:
- **James Neel et al., "Using Game Theory to Analyse Physical Layer Cognitive Radio Algorithms", Virginia Tech, 2006.**

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Conclusion / outlook

- **Nature-inspired models (starlings, fish, fire flies) show that locally processed information about a relative small neighbourhood produces 'agile behaviour'**

- **Number of domains where agile behaviour is required increase**

- **Game theory is a powerful new perspective on bringing 'master design' to 'local decision making'**

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