Self-Organization in Autonomous Sensor/Actuator Networks [SelfOrg]

Dr.-Ing. Falko Dressler

Computer Networks and Communication Systems
Department of Computer Sciences
University of Erlangen-Nürnberg

http://www7.informatik.uni-erlangen.de/~dressler/
dressler@informatik.uni-erlangen.de

Overview

- **Self-Organization**
  Introduction; system management and control; principles and characteristics; natural self-organization; methods and techniques
- **Networking Aspects: Ad Hoc and Sensor Networks**
  Ad hoc and sensor networks; self-organization in sensor networks; evaluation criteria; medium access control; ad hoc routing; data-centric networking; clustering
- **Coordination and Control: Sensor and Actor Networks**
  Sensor and actor networks; communication and coordination; collaboration and task allocation
- **Self-Organization in Sensor and Actor Networks**
  Basic methods of self-organization – revisited; evaluation criteria
- **Bio-inspired Networking**
  Swarm intelligence; artificial immune system; cellular signaling pathways

Collaboration and Task Allocation

- Multi-robot task allocation
- Intentional cooperation
- Emergent cooperation

Collaboration and Task Allocation

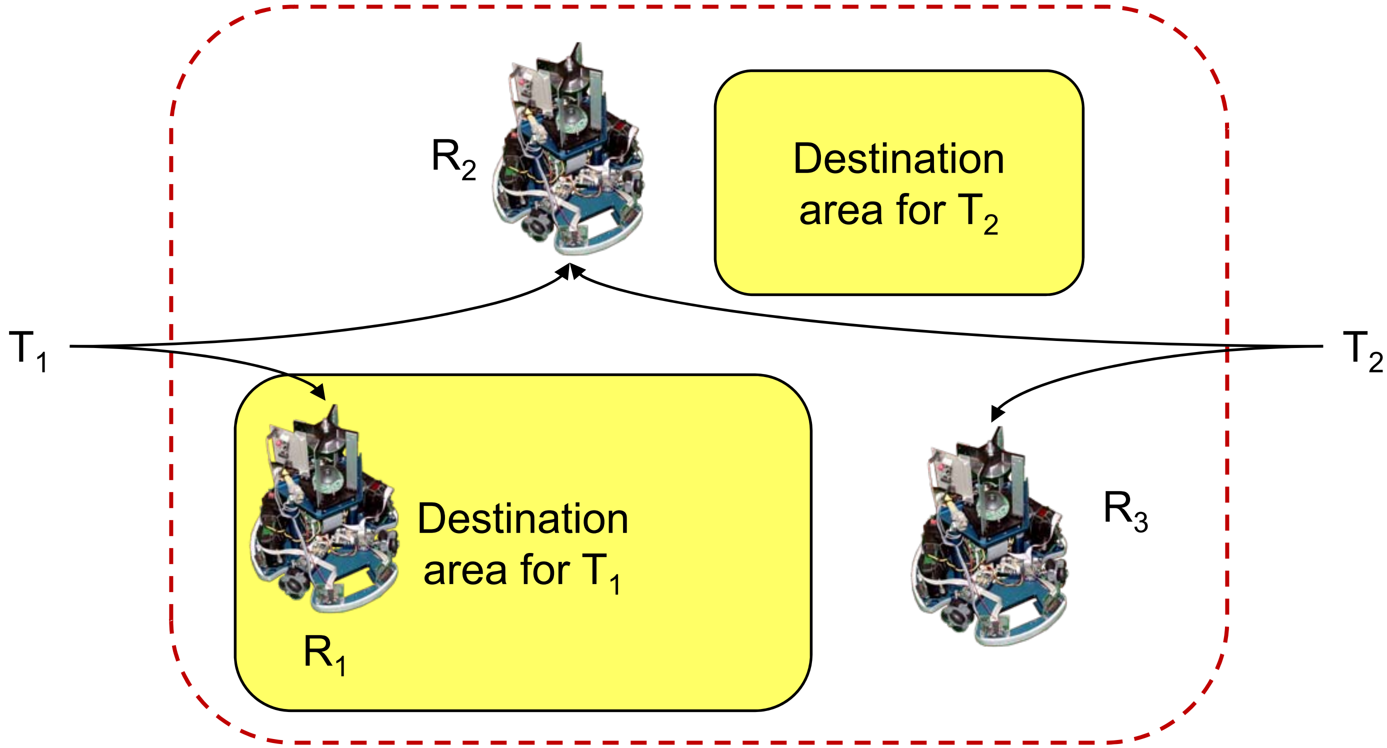
- Task and resource allocation
  - Without loss of generality → multi-robot task allocation (MRTA)

- Constraints in SANETs
  - Communication – necessary information exchange
  - Energy – still, we consider battery-powered systems
  - Time – execution time, real-time considerations

- Categories
  - Intentional cooperation – with purpose, exploitation of heterogeneity, often through task-related communication
  - Emergent cooperation – without explicit coordination

Multi-robot task allocation – Problem formulation

- Identify an appropriate (autonomous) system that
  - Has the required resources
  - These resources are available
  - The system is available to perform the requested task



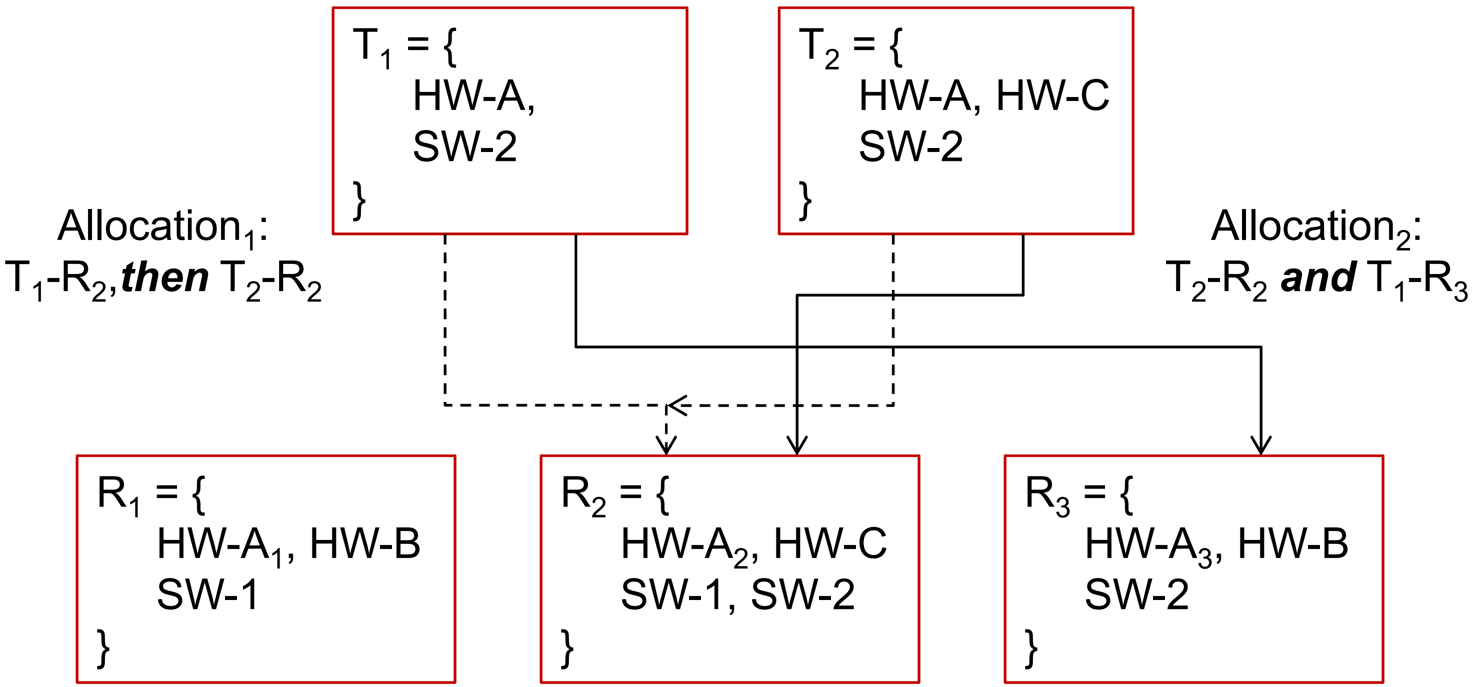
MRTA

- Types of resources
  - CPU capacity
  - Memory / storage
  - Energy
  - Time
  - Optimal position

# hardware capabilities	
processor {PowerPC, 8MHz}	// processor of type PowerPC with 8MHz
memory {128MB}	// memory size 128MB
chassis {indoor, 1m/s}	// indoor movement with a speed of 1m/s
camera {color, 1Mpixel}	// color camera with 1Mpixel resolution
# software capabilities	
mapping software	// algorithms for dynamic map generation
JPEG encoder	// JPEG picture encoder
face recognition	// face recognition software
object tracking	// computational and memory expensive tracking

MRTA

- Parallel vs. sequential execution



MRTA

- Allocation process
  - ***(Self-)election*** – identification of available nodes that show the required properties
  - ***Allocation proposal*** – first shoot matching the requirements
  - ***Optimization*** – allocation improvement

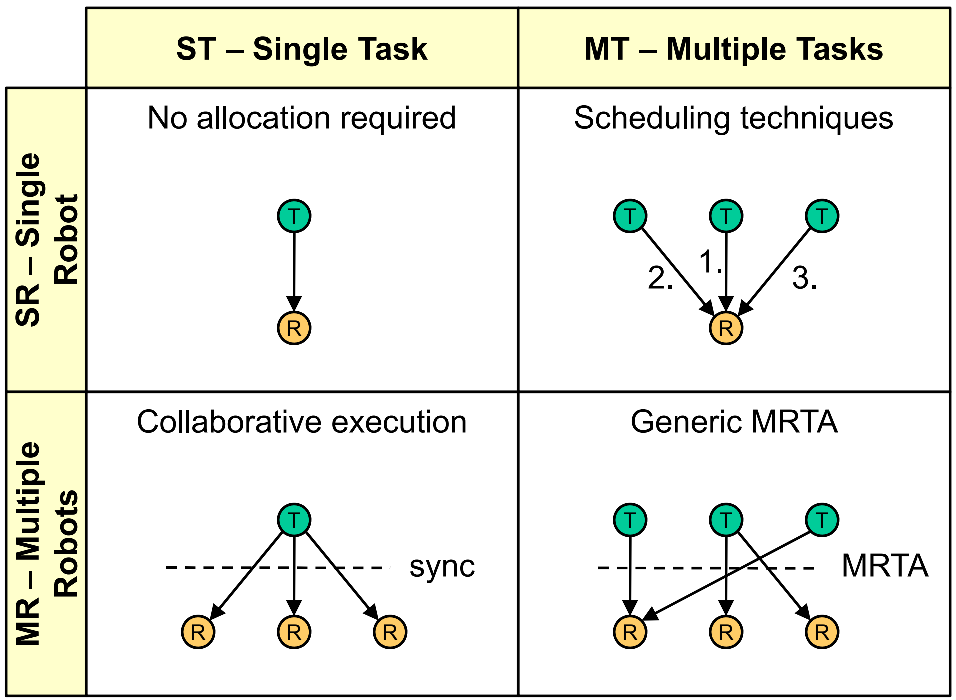
- Optimization
  - Motivation-based – The exploitation of the needs of single systems to motivate them to participate on a given task.
  - Mutual inhibition – The inhibition of specific actions according to the quality or task execution or as a strategic action.
  - Team consensus – The exploitation of decisions in a group of autonomous systems for team-level allocation improvements.

MRTA

- Formally, MRTA is a mapping of tasks T_n to robots R_m according to a utility function U

$$T_n \xrightarrow{U(T_i^*, R_j^*)} R_m$$

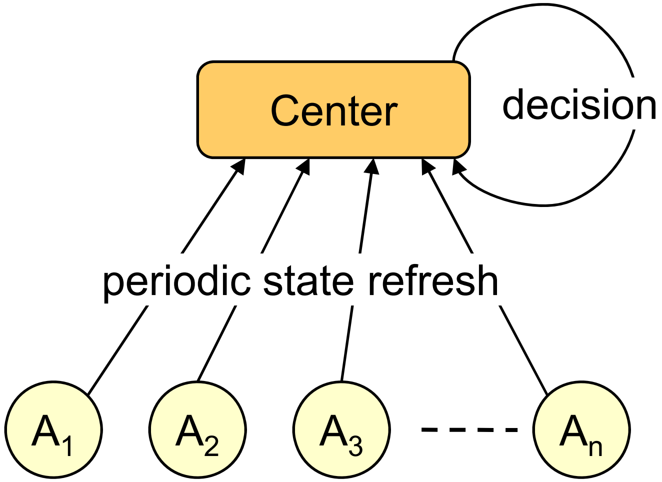
- Taxonomy



Intentional cooperation

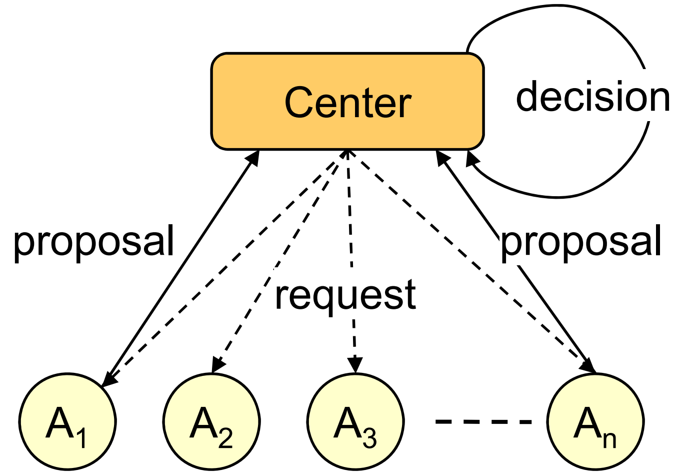
- Also known as ***auction-based*** task allocation

- **Open agent architecture (OAA)**
  - Centralized task allocation
    1. Facilitation – central facilitator performs allocation algorithms
    2. Delegation – the facilitator delegates tasks to appropriate systems
  - Pros: optimized decision taking
  - Cons: state maintenance can be expensive



Intentional cooperation

- **MURDOCH** – center-based task allocation



- Auction protocol
  - *Task announcement* – The auctioneer publishes an announcement
  - *Metric evaluation* – A metric-based evaluation is performed at each agent to the best fitting agent
  - *Bid submission* – Each candidate agent publishes its resulting task-specific fitness in form of a bid message
  - *Close of auction* – The auction is closed after sufficient time has passed. The auctioneer processes the bids and determines the best candidate. The winner is awarded a time-limited contract to execute the task
  - *Progress monitoring / contract renewal* – The auctioneer continuously monitors the task progress

Dynamic Negotiation

- Negotiation protocols
  - Tasks can interact arbitrarily
  - Agents must negotiate the assignment of resources to tasks in dynamically changing environments

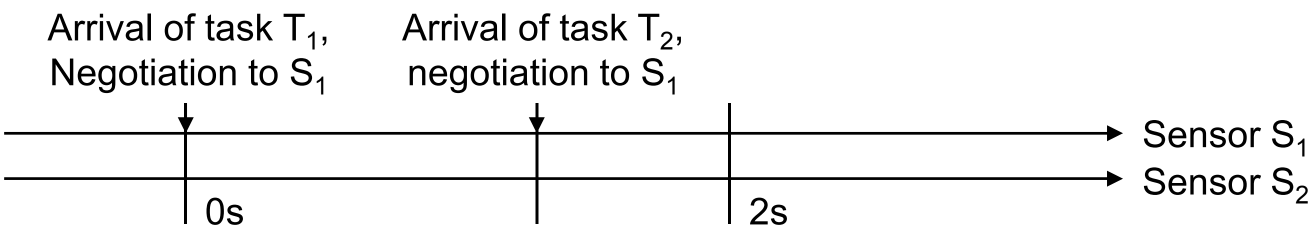
    → term ***negotiation*** to refer to any distributed process through which agents can agree on an efficient apportionment of tasks among themselves

  - Center-based task assignment (see MURDOCH)

Sensor challenge problem

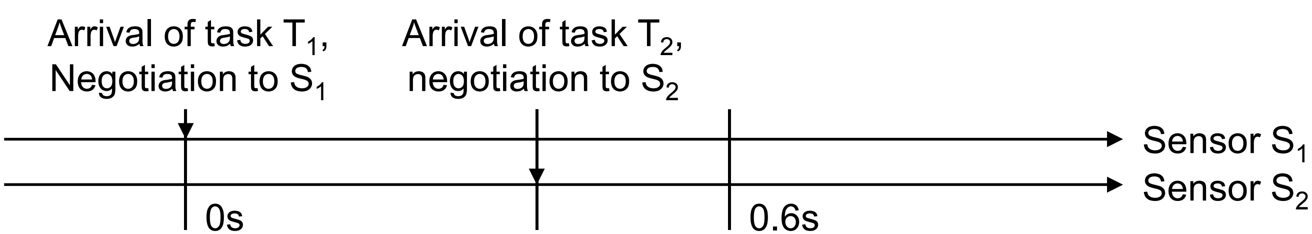
- If a deactivated emitter is activated, the beam is unstable and will not give reliable measurements for 2 seconds

  → if one task is immediately followed by another in the same sector, the beam will not require the 2 second warmup → this corresponds to ***positive task interaction***



- Consider that only one of three detectors on a sensor can be scanned at a given time and each scan takes between 0.6-1.8 seconds

  → two sequential tasks that are less than 0.6 seconds apart and occur in separate sectors will ***interact negatively***



Center-based assignment

- Formal definition
  - Task allocation system: $M = \langle A, T, u, \mathbf{P} \rangle$
  - $A = \{a_1, \ldots, a_n\}$ is a set of n agents with some agent designated as the mediator
  - $T = \{t_1, \ldots, t_m\}$ is a set of m tasks
  - $u: A \times 2^T \rightarrow \mathbb{R} \cup \{\infty\}$ is a value function that returns the value which an agent associates with a particular subset of tasks
  - $\mathbf{P}$ is an assignment (or partition) of size n on the sets of tasks T such that $\mathbf{P} = \langle P_1, \ldots, P_n \rangle$, where P_j contains the set of items assigned to agent a_j
  - We refer to $\mathbf{P}$ as a *proposal*; for example $P_5 = \langle a_1, a_5, a_3 \rangle$ corresponds to the allocation in which task t_1 is assigned to agent a_1, t_2 to a_5, and t_3 to a_3
  - The *objective function* f determines the desirability of an assignment based on the values that each agent ascribes to the items it is assigned

$$f(p, A) = \sum_{a \in A} u(a, p) \quad p \in \mathbf{P}$$

Center-based assignment

- Formal definition (cont'd.)
  - The *negotiation problem* is that of choosing an element p^* of ***P*** that maximizes the objective function

$$p^* = \arg\max_{p \in \mathbf{P}} f(p, A)$$

  - The proposal chosen is called the ***outcome*** of the negotiation

- Both, mediation and combinatorial auctions are examples of algorithms that can be used to solve the assignment problem
  → class of center-based assignments (CBA)

Auctions

- Sequential auctions? (serialized item allocation)
  - Simple bidding rules
  - Provide no context (list of other tasks to which an agent will be assigned in later auctions)
  - Assumptions must be made about the outcomes of other, related auctions

- Combinatorial auctions? (for exploring allocations of items that interact → agents have the freedom to choose particular bunches of items)
  - Allow an agent to pick certain bundles of tasks which might interact in a favorable way
  - Introduce a bid generation problem

→ ***re-allocation*** might help to solve these issues

Mediation Algorithm

- Basic idea
  - An agent is selected to act as mediator
  - It implements a ***hill-climbing search*** in the proposal space
  - Use of a communication channel

    (costly in terms of time, etc. but assumed to be lossless)

- Mediation algorithm
  - Inputs: P, A, update procedure such as AIM (allocation improvement mediation)
  - Supports group decisions

  - The algorithm is anytime: it can be halted at any time and will return the best proposal found so far
  - Therefore, the mediation is applicable even if the agents do not know in advance how much time they will have to negotiate

Mediation Algorithm

```
function MEDIATION returns an outcome
    inputs: P, G, UpdateProcedure
let b ← 0, b_val ← VALUE(0)
loop
    c ← next value generated by
          UpdateProcedure
    broadcast c to G
    for each G_i in G
        receive msg_i from G_i
    c_val ← VALUE(msg_1, msg_2, …, msg_n)
    if (c_val > b_val) then
        b ← c, b_val ← c_val
until (stop signal)
return b
```

1. Mediator initializes b (representing the best proposal found so far) along with an initial value
2. An update procedure generates another proposal c (current proposal)
3. This proposal is broadcast to the group G
4. Each agent responds with a message msg_i based on the proposal c
5. Messages are combined to form a value
6. If the value is preferred to the current b_{val}, b is updated with the current proposal

Allocation Improvement

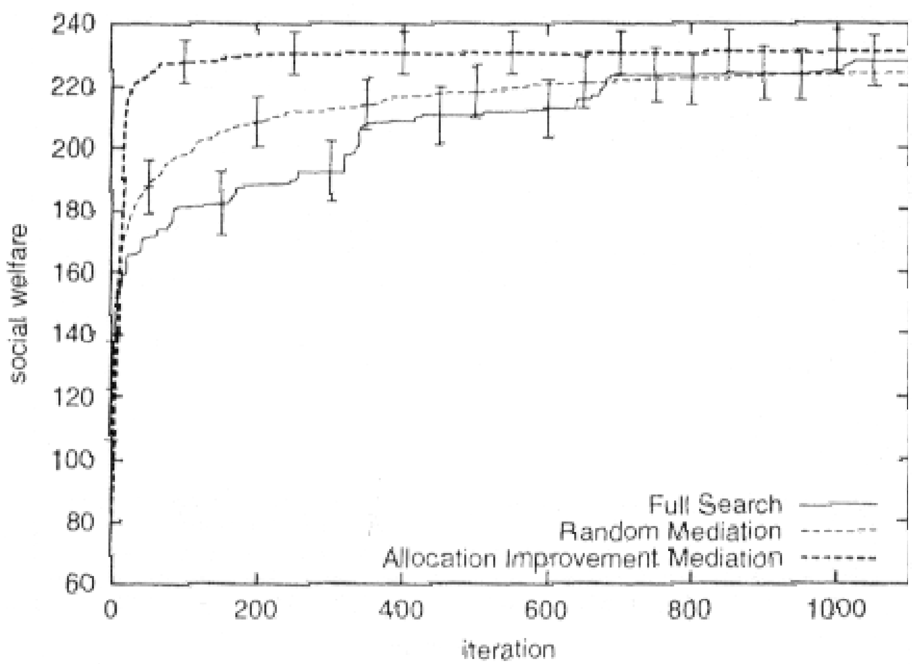
- Update procedure for mediation that supports task allocation domains

```
let p ← a random element of P - {0}; return p
for i = 1 … |T|
    for t ← every set of tasks of size I
        for a ← every possible assignment of agents in A to tasks in t
            q ← substitute a in p; return q
            if qval > pval in mediation then p ← q
```

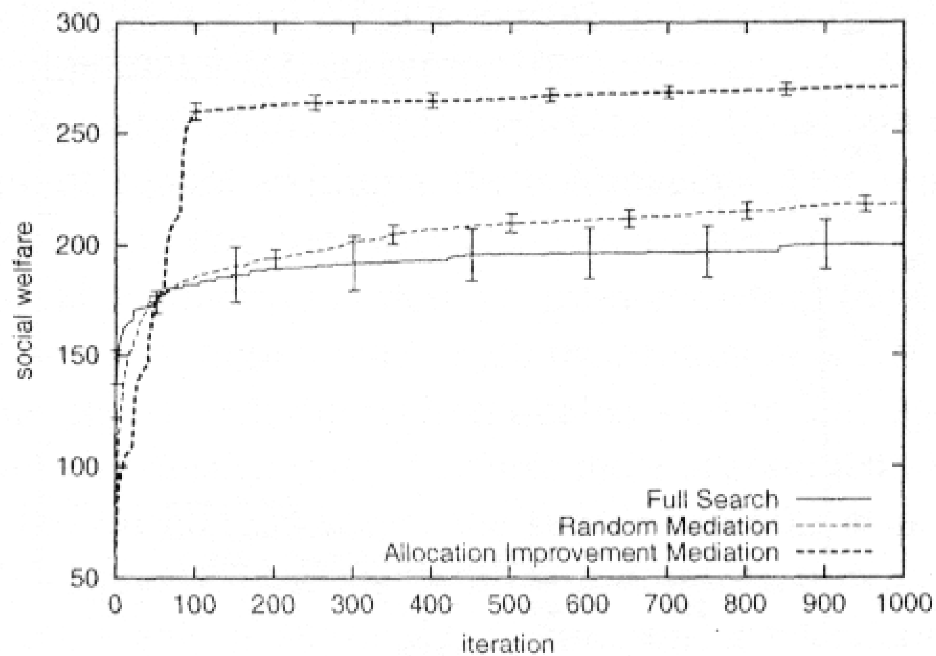
- The first proposal p is chosen randomly from **P**
  - The proposal provides a context, from which subsequent proposals are generated, e.g. it might return <{t2},{t0,t1}>, i.e. agent 0 is assigned task 2 and agent 1 to tasks 0 and 1
  - This context is common to all agents and ensures that each task is assigned to an agent
- Subsequent iterations
  - the procedure returns proposals that result from making substitutions in p for i-tuples of tasks where i goes from 1 to |T|
  - p is always maintained to correspond to the best proposal in mediation

Experimental Analysis

- Allocation Improvement Mediation
- Random Mediation (returns a random element of **P** at each iteration)
- Full Search (simply returns successive elements of **P**)



4-agent sensor domain



20-agent sensor domain

Intentional cooperation: Where to go?

- So far, only sets with static resources have been investigated into, what about the possibility to let tasks and resources dynamically appear and disappear?

- First solution (usually found in the literature): the ongoing negotiation is interrupted / a re-allocation is initiated.

- More practicable (and more sophisticated): dynamic mediation
  - a mixture of central coordination and mediation
  - The bids are enriched to include all relevant local state information

    → a *negotiation space* is available at the mediator (set of resources and tasks)
  - This negotiation space might change because of
    - A *negotiation event* (the mediator considers a new resource)
    - A *domain event* (a new task appears)

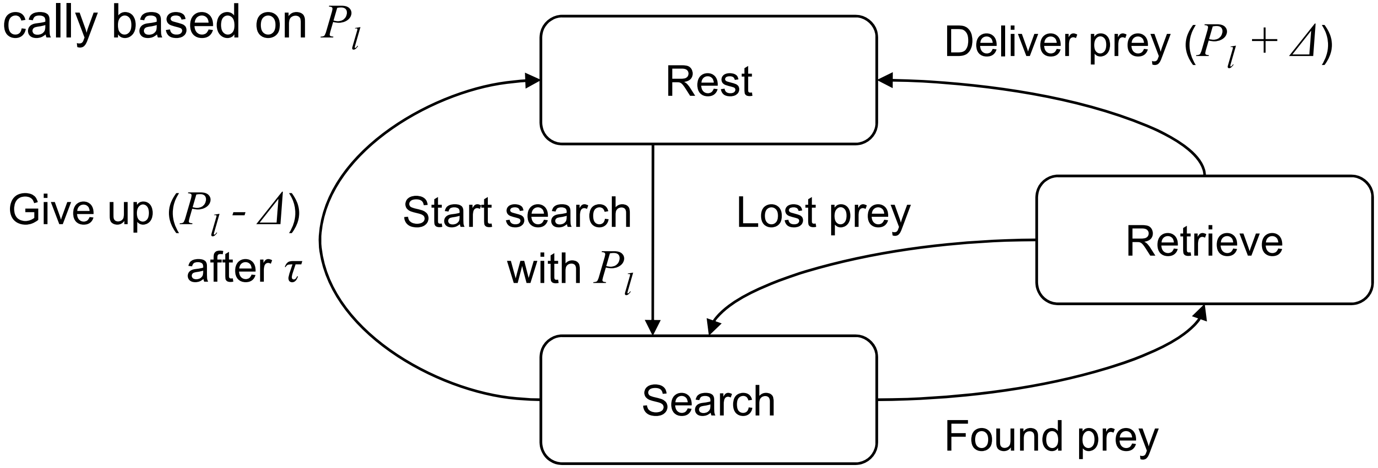
Emergent cooperation

- Motivated by biological analogies such as swarm intelligence → ant-like cooperation

- Based on stimulation techniques
  - Stimulation by work
  - Stimulation by state

Stimulation by work

- Based on observed system efficiency $\eta = income / costs$
  - Inspired by prey retrieval
- Efficiency increase
  - If too many robots search for prey, the probability to be successful will decrease → can be used for maintaining a probability P_l to leave the nest (and to forage)
  - If a huge bunch of prey is available, all robots will be successful → P_l can further be updated
- Task allocation
  - Probabilistically based on P_l



Stimulation by state

- Encounter pattern based on waiting time
  - #encounters between robots → waiting time $w(k)$ for the kth encounter
    - Robot density
  - #encounters with targets → waiting time $w'(k)$ for the kth encounter
    - Target density
  - Task demand $S(k) = w(k) / w'(k)$ is the ratio between robot density and target density

- Social dominance
  - Dominating (i.e., successful) robots will continue to perform a particular task
    - Probabilistic decision according to the task demand of two encountering robots
    - If successful: $\theta(t) = \theta(t - 1) + \delta$
    - If not successful: $\theta(t) = \theta(t - 1) - \delta$

Summary (what do I need to know)

- ***Task and resource allocation***
  - Multi-robot task allocation (MRTA)
  - Objectives and principles

- ***Intentional cooperation***
  - On purpose, optimized allocation procedures
  - Centralized task allocation, e.g. OAA
  - Center-based task allocation, e.g. MURDOCH, Mediation

- ***Emergent cooperation***
  - Without purpose, group-level behavior emerges out of single-node behaviors
  - Stimulation by work
  - Stimulation by state

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