Bio-Inspired Networking

– The Road to Efficient and Sustainable Mobile Computing –

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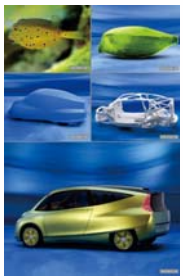
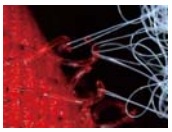
Bio-Inspired: A Very Old Story …


Icarus & Daedalus


Da Vinci


Vaucanson's Duck


Mercedes Bionic Car


Velcro


Wright Brothers

Why Seek Inspiration from Biology?

- Living organisms are *complex adaptive systems*
  - Artificial systems are going in that direction too
- Look for *new solutions* to difficult problems
- Life has many *self-** features which are also desirable in artificial systems:
  - Self-organization
  - Self-adaptation
  - Self-healing ability
  - Self-optimization
  - Self-robustness

The Term "Bio-Inspired"

- ***Bio-inspired*** demonstrates the strong relation between
  - A particular system or algorithm
    - which has been proposed to solve a specific problem
  - And a biological system
    - which follows a similar procedure or has similar capabilities
- Bio-inspired computing represents a class of algorithms focusing on efficient computing
  - e.g. in optimization processes and pattern recognition
- Bio-inspired systems rely on system architectures for massively distributed and collaborative systems
  - e.g. in distributed sensing and exploration
- Bio-inspired networking is a class of strategies for efficient and scalable networking under uncertain conditions
  - e.g. in delay tolerant networking

Biologically Inspired Problem Solving

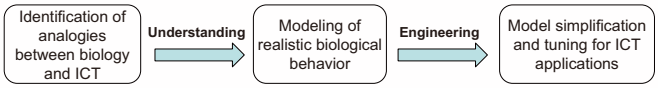
- Typical problems that can be tackled with bio-inspired solutions are characterized by the:
  - Absence of a complete mathematical model
  - Large number of (inter-dependent) variables
  - Non-linearity
  - Combinatorial or extremely vast solution space

Why Bio-Inspired Networking?

- Structural view: communication is an intrinsic part of an organization
- Example organizations:
  - Brain (organization of neurons)
  - Animal "super organisms" (ant/bee colonies)
  - Human society
- Those natural and living organizations seem better organized than the current Internet!

Design of Bio-Inspired Solutions

- Identification of analogies
  - In swarm or molecular biology and ICT systems
- Understanding
  - Computer modeling of realistic biological behavior
- Engineering
  - Model simplification and tuning for ICT applications

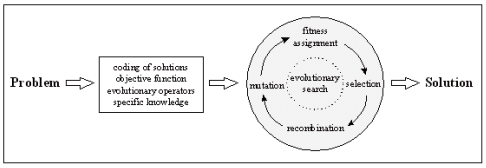


Example of Bio-Inspired Research Fields

- Evolutionary Algorithms (EAs)
- Artificial Neural Networks (ANNs)
- Swarm Intelligence (SI)
- Artificial Immune System (AIS)
- Cellular Signaling Pathways

Evolutionary Algorithms (EAs)

- Mainly rooted on the Darwinian theory of evolution
- An EA uses some mechanisms inspired by biological evolution
  - Reproduction, Mutation, Recombination, Selection
- EAs represent a set of search techniques used in computing to find the solutions to optimization problems



Evolutionary Algorithms (EAs)

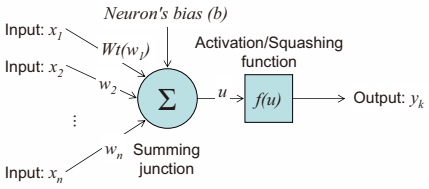
- EAs can be categorized into the following Classes
  - Genetic Algorithms (GAs)
  - Evolution strategies
  - Evolutionary programming
  - Genetic programming
  - Classifier systems
- Examples
  - Simulated annealing
    - Generic probabilistic meta-algorithm for the global optimization problem
  - Simulated hill-climbing
    - A mathematical optimization technique which belongs to the family of local search

Artificial Neural Networks (ANNs)

- A Neural Network is a network of biological neurons
- ANNs are non-linear statistical data modelling tools
- Used to acquire knowledge from the environment (known as self-learning property)
- The weights of the neurons are determined in a learning process
- They can be used to model complex relationships between inputs and outputs or to find patterns in data

Artificial Neural Networks (ANNs)

- A neuron *k* that connects *n* inputs can be described as:



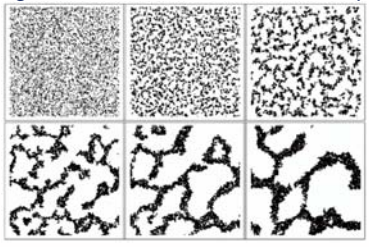
$$y_k = f(u_k) = f\left(\sum_{j=1}^{n} w_{kj} x_j + b_k\right)$$

Swarm Intelligence (SI)

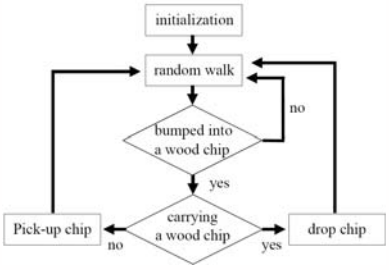
- An Artificial Intelligence (AI) technique based on the observations of the collective behavior in decentralized and self-organized systems
- Typically made up of a population of simple agents interacting locally with one another and with their environment (no centralized control)
- Local interactions between autonomously acting agents often lead to the emergence of global behavior
  - *Examples*: Ant/bee/termite colonies, bird flocking, animal herding, bacteria growth, and fish schooling

SI – Example of Ant Colonies

- Ants solve complex tasks by simple local means
- Ant productivity is better than the sum of their single activities
- Ants are "grand masters" in search and exploration



SI – Example of Ant Colonies



"The emergent collective intelligence of groups of simple agents." (Bonabeau)

SI Properties

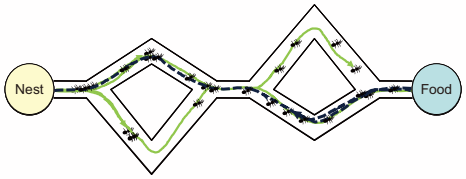
- Properties of Swarm Intelligence
  - Agents are assumed to be simple
  - Indirect agent communication
  - Global behavior may be emergent
    - Specific local programming not necessary
  - Behaviors are robust
    - Required in unpredictable environments
  - Individuals are not important

What is Stigmergy?

- Stigmergy is a mechanism of spontaneous, indirect coordination between agents or actions, where the trace left in the environment by an action stimulates the performance of a subsequent action, by the same or a different agent
  - Produces complex, apparently intelligent structures, without need for any planning, control, or even communication between the agents
  - supports efficient collaboration between extremely simple agents, who lack any memory, intelligence or even awareness of each other
- Stigmergy is a form of self-organization first observed in social insects

SI Example: Collective Foraging by Ants

- Starting from the nest, a random search for the food is performed by foraging ants
- Pheromone trails are used to identify the path for returning to the nest
- The significant pheromone concentration produced by returning ants marks the shorted path



Principles of Swarm Intelligence

- What makes a Swarm Intelligent system work?
  - Positive Feedback
  - Negative Feedback
  - Randomness
  - Multiple Interactions
- Positive Feedback reinforces good solutions
  - Ants are able to attract more help when a food source is found
  - More ants on a trail increases pheromone and attracts even more ants
- Negative Feedback removes bad or old solutions from the collective memory
  - Pheromone decay
  - Distant food sources are exploited last
    - Pheromone has less time to decay on closer solutions

Principles of Swarm Intelligence

- Randomness allows new solutions to arise and directs current ones
  - Ant decisions are random
    - Exploration probability
  - Food sources are found randomly
- Multiple Interactions: No individual can solve a given problem. Only through the interaction of many can a solution be found
  - One ant cannot forage for food; pheromone would decay too fast
  - Many ants are needed to sustain the pheromone trail
  - More food can be found faster

SI Routing Overview

- Ant-Based Control
  - Ant Based Control (ABC) is introduced to route calls on a circuit-switched telephone network. ABC is the first SI routing algorithm for telecommunications networks
- AntNet
  - AntNet is introduced to route information in a packet switched network
  - AntNet is related to the Ant Colony Optimization (ACO) algorithm for solving Traveling Salesman type problems
- AntHocNet
  - A MANET routing algorithm based on AntNet which follows a reactive routing approach
- Termite
  - Also a MANET routing algorithm

SI Application in MANET Routing

- Routing in MANETs is an extension of Ant Foraging!
  - Ants looking for food…
  - Packets looking for destinations…
- Can routing be solved with SI?
- Can routing be an emergent behavior from the interaction of packets?

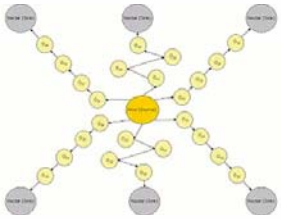
Ant-based Task Allocation

- Combined task allocation according to ACO paradigm has been investigated for MANETs
- The proposed architecture for MANETs is completely dependant on probabilistic decisions
- During the lifetime of the MANETs, nodes adapt the probability to execute one task out of a given set

Bee Colony Optimization (BCO)

- The BCO algorithm is inspired by the behavior of a honey bee colony in nectar collection
  - This biologically inspired approach is currently being employed to solve continuous optimization problems
    - training neural networks, job shop scheduling, server optimization

BCO provides a population-based search procedure in which individuals called foods positions are modified by the artificial bees with time and the bee's aim is to discover the places of food sources with high nectar amount and finally the one with the highest nectar



Bee Colony Optimization (BCO)

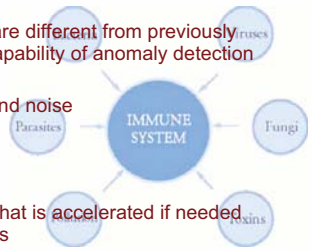
- Artificial bees fly around in a multidimensional search space and some (employed and onlooker bees) choose food sources depending on their experience of and their nest mates, and adjust their positions
- Some (scouts) fly and choose the food sources randomly without using experience
- If the nectar amount of a new source is higher than that of the previous one in their memory, they memorize the new position and forget the previous one
- Thus, ABC system combines local search methods, carried out by employed and onlooker bees, with global search methods, managed by onlookers and scouts, attempting to balance exploration and exploitation process

Artificial Immune System (AIS)

- Artificial immune systems are computational systems inspired by theoretical immunology and observed immune functions, principles and models, which are applied to complex problem domains
- The primary goal of an AIS is to efficiently detect changes in the environment from the normal system behavior in complex problem domains

Why the Immune System?

- Recognition
  - Ability to recognize pattern that are different from previously known or trained samples, i.e. capability of anomaly detection
- Robustness
  - Tolerance against interference and noise
- Diversity
  - Applicability in various domains
- Reinforcement learning
  - Inherent self-learning capability that is accelerated if needed through reinforcement techniques
- Memory
  - System-inherent memorization of trained pattern
- Distributed
  - Autonomous and distributed processing



AIS – Application Examples

- Fault and anomaly detection
- Data mining (machine learning, pattern recognition)
- Agent based systems
- Autonomous control and robotics
- Scheduling and other optimization problems
- Security of information systems
- Misbehavior detection for MANETs based on the DSR protocol (Boudec and Sarafijanovic, 2004)

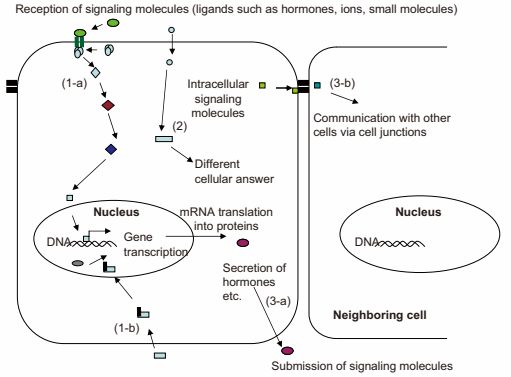
Molecular and Cell Biology

- Properties
  - Basis of all biological systems
  - Specificity of information transfer
  - Similar structures in biology and in technology
    - → Especially in computer networking
- Lessons to learn from biology
  - Efficient response to a request
  - Shortening of information pathways
  - Directing of messages to an applicable destination

Info Exchange in Cellular Environments

- Signaling in biological systems occurs at multiple levels and in many shapes
  - Signaling describes interactions between individual molecules
- Main cellular signaling techniques
  - Intracellular signaling
    - The information processing capabilities of a single cell
    - Received information particles initiate complex signaling cascades that finally lead to the cellular response
  - Intercellular signaling
    - Communication among multiple cells is performed by intercellular signaling pathways
    - Objective is to reach appropriate destinations and to induce a specific effect at this place

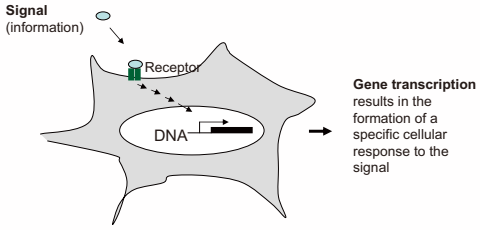
Intracellular Signaling Pathways



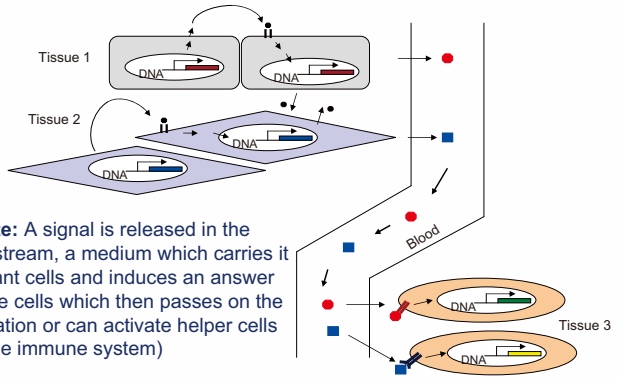
- Transfer via receptors on cell surface
- Reorganization of intracellular structure
- After processing the information, a specific cellular answer is initiated
- The effect could be the submission of a molecule

Intracellular Information Exchange

- **Local:** A signal reaches only cells in the neighborhood. The signal induces a signaling cascade in each target cell resulting in a very specific answer which vice versa affects neighboring cells



Intercellular Information Exchange



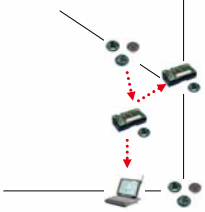
Remote: A signal is released in the blood stream, a medium which carries it to distant cells and induces an answer in these cells which then passes on the information or can activate helper cells (e.g. the immune system)

Lessons to be Learnt

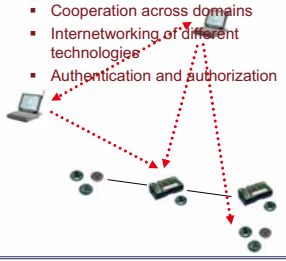
- The adaptation of mechanisms known from molecular and cell biology promises to enable more efficient information exchange
- New concepts for behavior patterns of network nodes
  - Improved efficiency and reliability of the entire communication system
  - Flexible self-organizing infrastructures
- Main concepts to be exploited in the context of communication networks
  - Signaling pathways based on specific signal cascades with stimulating and inhibitory functionality used for intracellular communication
  - Diffuse (probabilistic) communication with specific encoding of the destination receptors for intercellular communication

Adaptation to Networking

- Local mechanisms
  - Adaptive group formation
  - Optimized task allocation
  - Efficient group communication
  - Data aggregation and filtering
  - Reliability and redundancy



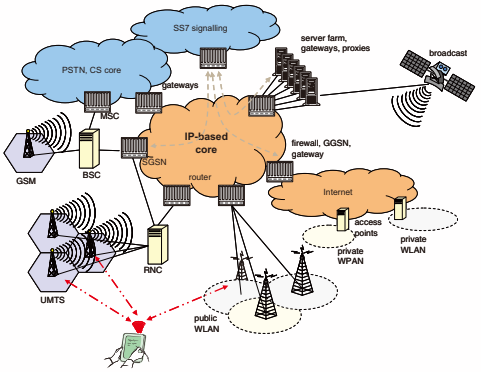
- Remote mechanisms
  - Localization of significant relays, helpers, or cooperation partners
  - Semantics of transmitted messages
  - Cooperation across domains
  - Internetworking of different technologies
  - Authentication and authorization



Heterogeneous Mobile Networks

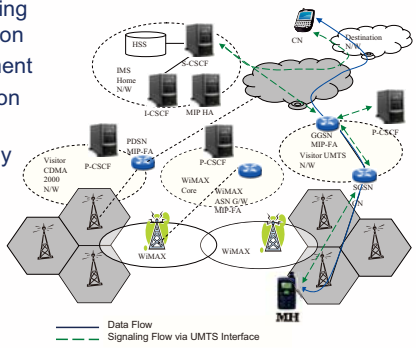
NGMN will be an integrated platform interconnecting multiple networks for seamless user connectivity for multimedia applications anytime and anywhere

It is the ultimate solution to the problem of ubiquitous mobile communications!

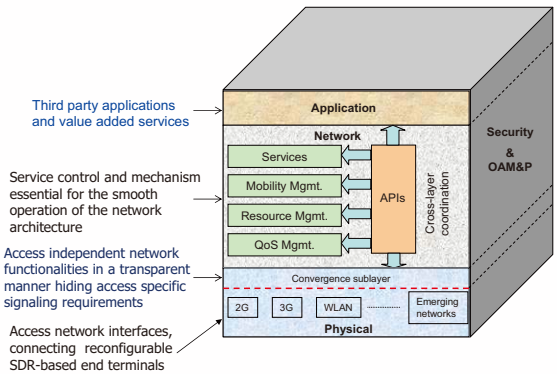


Networking Issues in NGMN

- Internetworking routing and address allocation
- Resource management
- Traffic and congestion control
- Mobility among many networks
- Network address translation
- Network protocol translation



Complex NGMN Design

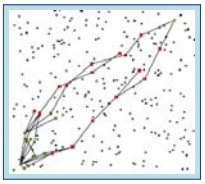


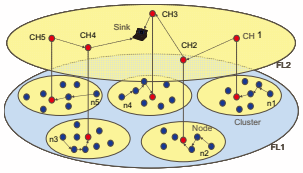
NGMN Requirements

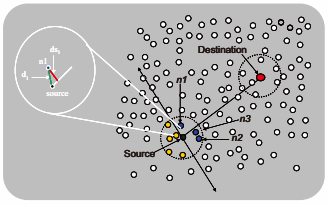
- Heterogeneous networking technologies, devices, and services keep changing in NGMN over the time
  - A centralized control/management tends to be an infeasible approach for NGMN
- The dynamic NGMN architecture and protocols need to have
  - scalability, self-organization, self-adaptation, and sustainability
- By appropriately mapping key biological principles to NGMN architectures it is possible to create a scalable, self-organizable, self-adaptable, and sustainable network
  - Such network is motivated by the inspirations from various biological systems' abilities to naturally adapt to the changing environment

Hierarchical Wireless Sensor Networks

- Sensor clustering for efficient routing
- Layered topology design for better data aggregation
- Secure sensor networking

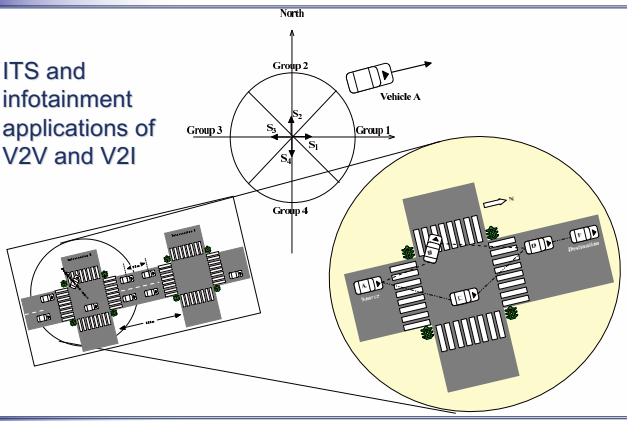






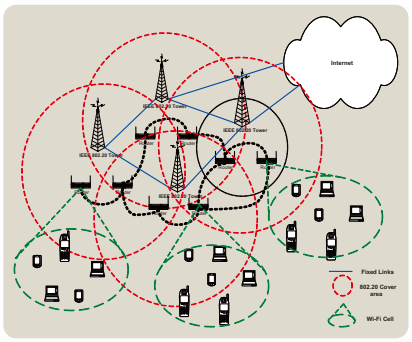
Vehicular Ad Hoc Networks

ITS and infotainment applications of V2V and V2I



Multi-layered Wireless Mesh Networks

- Developing a new backbone network for the Internet
- Applications:
  - Emergency
  - Fault tolerance
  - Increased throughput
  - Reliability



Closing Remarks

- Very little number of studies on biologically inspired network models exist in the literature
  - Available models mainly imitate some biological coordination aspects
- As for the nature, however, they could have great potential to assist with better and more efficient network management in telecomm networks, particularly for the future dynamic non-centralized heterogeneous environment
  - for scalability, self-organization, self adaptation, and sustainability

Thank You

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