SEVENTH FRAMEWORK PROGRAMME
THEME 3
Information and Communication Technologies

Grant agreement for:
Collaborative project, Small and medium-scale focused research project (STREP)

Deliverable D1.1:

Definition of Research Targets and Results for Models, Fundamental Laws and New Complexity Measures on Dynamicity, Restricted Locally Computation and Co-operation

Project acronym: FRONTS
Project full title: Foundations of Adaptive Networked Societies of Tiny Artefacts
Grant agreement no.: 215270

Responsible Partner: UPC
Report Preparation Date: Tuesday, 14 April, 2009

Contents

1 Introduction

The use of networks of tiny artifacts are becoming a key ingredient in the technological development of XXI century societies. An example of those networks are the networks with sensors, where some of the artifacts have the ability of sensing the environment and communicate among themselves. There is myriad of know applications for those networks, from the study of the roaming herds of endangered species to perform highway traffic control. Another example would be an heterogeneous embedded swarm of mobile robots and static rely stations.

Depending on the purpose for which the networks where designed, they could have certain characteristics: pervasiveness, ubiquity, massive scale, device hetereogenity, subnetwork autonomy, decentralization, human interaction and emergent behavior.

Therefore, the study of such systems involve several and very different areas of computing: hybrid and distributed systems, communication systems and protocols, circuit design, multi-agent systems, ad-hoc networks, algorithmic design, complexity theory or pervasive and ubiquous computing. Consequently, one can assume that this kind of systems are intrinsically complex. In fact, there is no easy way to design a universal sensor network that acts properly in all possible situations.

In recent years, there has been plenty of experimental results regarding these kinds of networks. It is important to understand the computational process and behavior of the different types of artifact's networks, which will help in taking the maximum profit of the networks and in designing more efficient next generation networks. For instance in the particular case of networks with sensors several proposals (taxonomies and surveys) that elucidate the distinguishing features of sensor networks have been published ([ASSC02, ECPS02, Nag05, TAGH03, VRAC08]). These proposals state clearly the need of formal models that capture the clue characteristics of sensor networks and that enable their study through the possibility of predict their behavior, efficiency and optimality in any kind of applications.

2 Task 1.1: Dynamicity models and algorithmic consequences

2.1 Motivation and problem description

Mobile communication in embedded networks, as for example networks with mobile sensor, present a paradigm shift from backbone networks, such as cellular telephony, in that the data is transferred from node to node via peer-to-peer interactions and not over an underlying backbone of routers. Naturally, this engenders new problems regarding optimal routing of data under various conditions over these dynamic networks. In this setting, the generalized case of mobile network routing using shortest paths or least cost methods are complicated by the arbitrary movement of the mobile agents thereby leading to variations in link costs and connectivity [Sch02]. Temporal dependencies in networks topologies are hard to be effectively captured in the previous existing *static* graph models (Random Geometric Graphs, Near Neighbor Proximity Graphs, Random Intersection Graphs). This fact, naturally motivated the study on modelling network dynamics, creating new graph models which capture the dynamic nature of the connectivity, and help in the design of efficient routing and communication algorithms, where an important ingredient to measure the efficiency of the algorithms is the ability to adapt on the flight to changing network topologies [CBD02].

We propose to continue the development of new graph theoretical models and algorithms that capture the evolution of connections for embedded dynamic networks. There is plenty of work done on the design of Data Structures for keeping connectivity in dynamic evolving graphs, where at each step either a vertex is added or a very small constant number of edges are added or removed (see for ex. [GHSZ01, DEGI08, CPR08]). However, in many applications of the dynamic networks, at each step there could be drastic changes in the topology of the net, as all artifacts may be displaced at the same time, for instance a swarm of micro-robots doing random search in the streets of a city. Therefore, new models of dynamic graphs are needed, which take into consideration possible high dynamic setting at each step. Some of the teams in the consortium have experience in two models: the *Evolving Graph model* and the *Dynamic Random Geometric Graphs*. Both models have capture some of the desired properties of the networks we want to study. Using both model, we propose to do a comparative study of the complexity of cost-effective routing schemes in mobile networks, and find computationally tractable and distributed algorithms for them.

2.2 State of the art and previous work

The first significant results on networks taking time into account were given by Ford and Fulkerson in 1958 [FF58]. The authors studied maximum flow problems with a discretized time, and developed a technique that is still used today: *time-expanded graphs*. Since then, numerous problems were addressed (see for ex [PJO95]). Other works related to time dependent networks can be found in [KS02, KLS02], where flow algorithms are studied in static networks with edge traversal times that may depend on the number of flow units traversing it at a given moment. Therefore, different techniques were developed in the literature in order to cope with the dynamics of networks as well as with their time dependency. For instance, in [Dre69, Hal77] shortest time paths were first addressed.

The *evolving graph* model is a formal abstraction for dynamic networks. We consider an indexed sequence of subgraphs of a given graph, where the subgraph at a given index point corresponds to the network connectivity at the time interval indicated by the index number. The time domain is further incorporated into the model by restricting *journeys* (the equivalent of paths in usual graphs) to *never* move into edges which existed only in past subgraphs. Centralized algorithms were proposed for finding *foremost*, *shortest*, and *fastest* journeys in dynamic mobile networks modeled by evolving graphs [BXFJ03]. Other results in evolving graphs show that old questions treated on usual graph models for static networks may be unsettled in a dynamic setting (scheduled transmissions, sleeping modes, mobility, etc.), requiring new insights.

The *Random Geometric Graph* has been one of the choices to model static wireless networks, were the nodes represent the agents or artifacts and two nodes share an edge if there is a direct connection between them, i.e. if the distance between both agents is less or equal to a parameter r specifying the maximal broadcasting distance of the agents. The underlying graph could be directed or undirected, depending on the ways that the agents have to communicate ([Hek06, DPS03]). In recent years, several researchers have proposed variations of the random geometric graph model to perform experiments on connectivity, power needed to keep the network operative a nd information distribution on mobile networks [JBRAS03, SB02, BB04]. Formal analytical results were given in [DPSW08], where the authors provide asymptotic estimations on the length of full connectivity for the ad-hoc communication net of agents moving randomly on an underlying grid graph. These values were given as a function of communication power of the agents, number of agents and size of the underlying grid. A study of the connectivity of *Dynamic Random Geometric Graph* was done in[DMP08]. The Dynamic Random Geometric Graph model was introduced in [Gue87]: Starting from a static random geometric graph, at each time step, all the nodes move in random directions in the unit torus, and the connectivity among nodes depends on the broadcasting distance r.

2.3 Research targets

A first goal is to see which of the models fits better the requirements of the different examples of networks and how the models could be modified to capture more characteristics of a given embedded network. In particular, we aim to study the complexity of routing problems such as distributed routing problems, energy aware routing problems, routing with finite prediction problems and error recovery routing problems. Network design issues arise also naturally even in networks that seem at first sight unorganized or randomly deployed. Such issues include local network optimization by moving, adding, altering the course or otherwise modifying one or several nodes in the network; global network optimization by assigning sleep phases in radio networks, organizing the nodes into hierarchical groups in mesh networks, and generally structuring communications into predefined patterns. The main network aspects we want to develop in combination with dynamicity include the imperative of distributed computing where nodes have only a local knowledge of their neighbors. In fixed schedule dynamic networks where we only know network evolution for a certain period of time the messages must be sent towards the target. This class of networks contains mobile radio networks, where the speed of radios is known at any given date, so the state of the network can be predicted for a given period of time. It contains more generally any dynamic network where connections are induced by known physical properties which can be reasonably predicted in the near future. When the prediction window is not large enough to contain the entire journey of a message from its source to its destination, it is necessary to have a metric that measures how close a message is from its destination, so that the routing aims at reducing this distance. It is thus necessary to investigate DiDRG08 possible metrics and study their impact on the routing. Errors made in predicting the future state of the network, or even errors made on the present state of the network must be addressed. For instance, this kind of errors are commonly made when overlooking interference problems in radio networks. Other errors may happen at the physical level, with unexpected link or node failures. When developing routing protocols, it is necessary to know how this errors affect message delivery.

Inside of the consortium and as described with more detail in D2.1, some partners are gathering data from field cases considering scenarios involving vehicles in traffic and groups of robots [FSW+09]. The theoretical models and communication algorithms designed for mobile network communication have to be contrasted with the experimental data obtained from the described scenarios.

3 Task 1.2: Computation models and algorithmic consequences

3.1 Data gathering models

One of the main issues concerning sensor and wireless networks is data gathering, i.e. collecting data from multiple nodes in a central sink node, which may process the data or act as gateway to other networks.

State of the art and previous work

The problem of gathering data in a radio network was considered by Bar-Yehuda et al. [BYII93] who proposed a distributed approximation algorithm for minimizing the completion time of transmissions. Bermond et al. [BGK+06] considered the same gathering problem in the context of wireless access to the Internet in villages. The authors proved that the problem of minimizing the completion time is NP-hard and presented a greedy algorithm with asymptotic approximation ratio at most 4. Bermond et al. did not consider the case where data packets can be dynamically released in the network. In previous work [BKMSS08a] we considered the same problem with arbitrary release times and proposed a simple on-line greedy algorithm with the same approximation ratio. In previous work [BKMSS08b] we also studied on-line distributed algorithms for the problem when the objective is to minimize the maximum flow time of a data packet.

First Results

In [BKMSS08c], we study data gathering in a wireless network through multi-hop communication, with the objective of minimizing the average flow time of a data packet. The flow time of a data packet is the time elapsed between its release at the release node and its arrival at the sink. Flow time minimization is a largely used criterion in scheduling theory that more suitably allows to assess the quality of service provided when multiple requests occur over time. The problem we consider is NP-hard; we prove that it is also hard to approximate. Moreover, we show that a rather simple algorithm (inspired by the Shortest Remaining Processing Time of scheduling theory) gives a 5-pseudoapproximation on all networks, meaning that augmenting the processing speed of the algorithm by a factor of 5 is enough to offset the hardness and compare favorably to the optimal solution for the original instance. This type of analysis, called resource augmentation, has already been used successfully in the context of several other machine scheduling problems Our algorithm schedules different packets using dynamic priorities, which seems to be required when optimizing this type of objective function (in contrast with the case of minimizing maximum flow time).

In [CEL$^+$09] we study online nonclairvoyant speed scaling to minimize total flow time plus energy. Energy consumption has become a key issue in the design of microprocessors, as major chip manufacturers produce chips with dynamically scalable speeds, and associated software that enables an operating system to manage power by scaling processor speed. In this paper, we consider the objective of minimizing a linear combination of total flow and total energy used. We study nonclairvoyant speed scaling assuming an off-line adversary that dynamically chooses the speed of its own machine. We first consider the traditional model where the power function is $P(s) = s^\alpha$. We give a nonclairvoyant algorithm that is shown to be $O(\alpha^3)$-competitive. We then show an $\Omega(\alpha^{1/3-\epsilon})$ lower bound on the competitive ratio of any nonclairvoyant algorithm. We also show that there are power functions for which no nonclairvoyant algorithm can be $O(1)$-competitive.

Research Targets

In the next future we aim to study issues connected to real-time constraints in decentralized networks. Real-time constraints combine with the decentralized nature of the networks and with energy constraints to make the achievement of even the simplest tasks difficult. Our aim is to analyze algorithms for problems of this type that can be implemented in realistic models without relying on sophisticated computations.

3.2 Random intersection graphs

Motivation and problem description

In random intersection graphs (RIGs) the vertices choose randomly labels from a universal set; two vertices that have chosen at least one label in common are joined by an edge. RIGs can be used to model local interactions quite accurately, at least compared to the classical $G_{n,p}$ model where edges appear independently with probability p. In particular, the $G_{n,p}$ model seems inappropriate for describing sensor networks because it lacks certain important features of such networks (such as a scale free degree distribution and the emergence of local clusters). One of the underlying reasons for this mismatch is its independence of the edges, in other words the missing transitivity that characterizes sensor networks: if vertices x and y exhibit a relationship of some kind in the network and so do vertices y and z, then this suggests an interaction between vertices x and z, too.

For example, we consider the following scenario concerning efficient and secure communication in sensor networks: the vertices in the RIG model correspond to sensor devices that blindly choose a limited number of resources among a globally available set of shared resources (such as communication channels, encryption keys etc). Whenever two sensors select at least one resource in common (e.g. a common communication channel, a common encryption key), a communication link is implicitly established (represented by a graph edge); this gives rise to communication graphs that look like random intersection graphs. Particularly for security purposes, the random selection of elements in RIGs can be seen as a way to establish local common keys on-line, without any global scheme for predistribution of keys. In such a case, the set of labels can be a global set of large primes (known to all) but each node selects uniformly at random only a few. Two nodes that have selected a common prime can communicate securely. Notice that no other node can know what numbers a different node has selected. Thus, the local communication is guaranteed to be secure. In the case when the shared resource is the wireless spectrum, then two nodes choosing the same label (frequency) may interfere, and the corresponding link in the intersection graph abstracts a conflict, while an independent set (vertices with no edges between them) abstracts a set of sensors that can simultaneously access the wireless medium.

State of the art and previous work

RIGs were introduced by M. Karonski, E.R. Sheinerman and K.B. Singer-Cohen [MKSC99]. The relation of the Erdos/Renyi and RIGs spaces were investigated in [FSSC00]. The uniform RIGs model, in which to each vertex a random subset of λ labels of the universal set of labels is independently assigned, was proposed in [GJ02] . Connectivity and communication security aspects of uniform RIGs are studied in [BG08, PMM$^+$04].

Previous work by FRONTS partners [NRS07, NRS04, ES05, RS05], prior to the beginning of the project, investigate expansion properties and give tight bounds on the mixing and the cover time of random walks on instances of the RIG model, proposes algorithms for finding large independent sets in RIGs (however, no attempt was made to see how close the independent sets given by those algorithms are to optimal size), finds thresholds for the appearance of hamilton cycles and efficiently constructs hamilton cycles.

First results

In [NRS09] we investigate important combinatorial properties (independence and hamiltonicity) of RIGs. These properties provide useful insight to algorithmic design for important problems (like secure communication and frequency assignment) in distributed networks of tiny artifacts characterized by locality of interactions and resource limitations, such as sensor networks.

Research targets

We plan to investigate additional important combinatorial properties of RIGs (with a first candidate being the chromatic number, which strongly relates to resource management problems). Also, to come up with efficient algorithms for important relevant problems (like coloring). Finally, we aim at devising new related models and interesting RIG variations that better model networks of tiny artefacts.

3.3 Population Protocols

Motivation

The notion of a computation by a population protocol was introduced in [AAD$^+$04], [AAD$^+$06] to model distributed systems in which individual agents are so limited computational devices that can be represented as finite state machines. Each agent has $O(1)$ total memory capacity, which means that the description of any protocol designed for such a system should be independent of the population size (there is no room for unique identifiers). In the basic model the agents are passively mobile and interact whenever two of them meet each other. The agents are passively mobile in the sense that mobility is determined by an adversary scheduler.

Under these assumptions, which are in fact realistic restrictions, we would like the agents to be able to carry out computational tasks that cannot be carried out by individual agents. Each agent receives a piece of input (e.g. by sensing its environment) and the goal is to ensure that every agent can eventually output the value that is to be computed.

Previous work and State of Art

The state of the art can be found in [AR07], an excellent survey by J. Aspnes and E. Ruppert. According to [AAD$^+$04] a **population protocol** $\mathcal{A}$ consists of finite **input and output alphabets** X and Y, a finite set of **states** Q, an input function $\iota : X \to Q$ mapping inputs to states, an **output function** $\omega : Q \to Y$ mapping states to outputs, and a **transition function** $\delta : Q \times Q \to Q \times Q$ on pairs of states. Due to the fact that such systems cannot realise when computation is over, they also defined the notion of stable computation.

In the case of a complete (all-pairs) interaction graph there is an exact characterization of the stable computable predicates: they are precisely the **semilinear predicates**, i.e. those predicates described by first-order logical formulas in **Presburger arithmetic**. Many extensions of the basic model have been reported in the literature. The scheduler has been assumed to pick the next interacting pair uniformly at random (**probabilistic population protocols**), the communication to be **one-way** instead of two-way in the basic model, the graph to permit only some but not all the interactions to occur (**restricted interaction graph**) and also there have been some first results about **fault-tolerant population protocols**.

In fact, this new field remains widely unexplored. There are still many open problems already stated and we strongly believe that many questions that need to be answered have not even been stated yet.

First Results

In [CS08] we have studied the **dynamics** (and stability) of probabilistic population protocols, via the differential equations approach. We provided a quite **general model** and showed that it includes the model of [AAD$^+$04], in case of very large populations. For the general model we also gave a **sufficient condition for stability** that can be **checked in polynomial time**. Finally, we studied two interesting subcases: (a) protocols whose specifications are **configuration independent**. We showed that they are always stable and that their eventual subpopulation percentages are actually a Markov Chain stationary distribution, and (b) protocols that have **dynamics resembling virus spread**. In this case we showed that their dynamics are actually similar to the well-known Replicator Dynamics of Evolutionary Games. We also provided a sufficient condition for stability in this case.

Research Targets

Random transitions model. We intend to examine the exact characterization of the class of predicates that can be stably computed by a realistic generalization of the basic model in which the transition function permits **random transitions**. We strongly believe that such a model is more general in the sense that it can stably compute predicates that are not semilinear.
Optimizing population protocols. We have already started to extend the basic model by certain necessary assumptions that do not trivialize the model and will give it the ability to **stably solve** various optimization problems on the communication graph. Extensions and protocols for such problems have not been proposed yet in the literature and we strongly believe that such extensions give rise to a new totally unexplored case in the field of population protocols. This is a natural extension since the basic model is not capable of solving optimization problems concerning the links of the communication graph.
Verification. We intend to examine the verification of protocols deviced for the basic model of population protocols and its various extensions. That is, given the model and the specification of a protocol we would like a deterministic Turing machine to inform us (predict) in polynomial time if the protocol will be able to meet its design objectives.

3.4 A formal computation model

Motivation and problem description

Existing models coming from distributed systems [Pel00], hybrid systems, ad-hoc networks [Hen96, LSV01] and circuit design [TIM08, tB03] capture some of the features of embedded networks, but either they do not seem to capture specific characteristics of the systems in an appropriate way or they capture features that are not representative. Therefore, it seems necessary to develop formal models that are specific for different classes of embedded networks. In this Section, we present a proposal of a formal model for the particular case of the networks with sensors, which is sufficiently flexible to capture some of the distinguishing features of this kind of networks.

The setting is described by the following two elements:

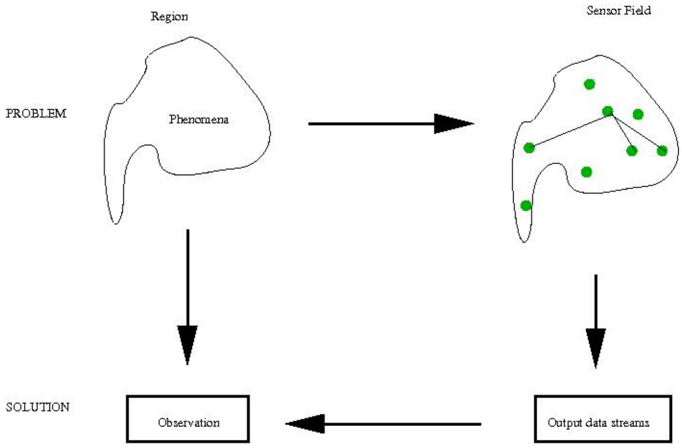

Figure 1: Solving a problem with networked sensors.

the observers, which are the end users and **the phenomenon**, which is the entity of interest to the observers, that is monitored and analyzed by network. Multiple phenomena are allowed in the same network.

Depending on the information required by the observers from the environment, we can formulate different kind of problems of interest:
Monitoring: The observer is interested in receiving data periodically from a geographical region or from a class of individuals. *Alarm*: The observer wants to be informed after the occurrence of a specific event in a geographical region or in a class of individuals. *Tracking*: The request of the observer consists on tracking or recovering the path followed by a mobile phenomenon in a region. *Driving*: The observer wants to drive remotely a mobile element depending on the phenomenon observed in a region. *Pebbling*: The observer wants to add marks to the environment to guide a mobile artifact.

Those problems have to be **solved** on a decentralized network composed of sensing units and other elements. It is necessary to re-examine the meaning of successful computation and define different performance metrics to measure the efficiency. Figure 1 presents our vision of *problem solving* using a network with sensors. In this schema, the information is discretized in two ways: First the environment is sampled on a discrete set of locations, and second the measures taken by the sensors are digitalized to the corresponding precision. To analyze the correctness and performance of the system we are faced with a double task; on one side there is a computational problem to be solved by a particular network; on the other side, it is necessary to assess whether the observation of the phenomenon is valid. Both tasks will require different analysis tools.

The distinctive peculiarities of the computational system define new parameters to be evaluated in order to measure the performance of the system. Metrics are needed to allow us to estimate the suitability of an specific or generic network topology or the possibility of emergent behavior with pre-specified requirements.

State of the art and previous work

Many different models capturing some of the features of artifact networks have been studied. In the setting of distributed systems a number of common standard models appear in the literature (cf [LL90, Lyn96]). The basic framework of a point-to-point communication network follows numerous references, as are for instance l [Dij74, Gal76, GMS77, LeL77, Gal82, Pel00] .

Models for hybrid systems have also been studied. For instance in [Hen96] it is introduced the model of Hybrid Automaton which formalizes a combination of discrete–continuous systems. Afterwards in [LSV01] it is considered a model of Hybrid Automaton with a separation of possible actions into input and output actions. The *Team Automata* is presented in [Ell97] and formalized in [tB03]. Under this model each component is an automaton with distinguished input, output, and internal actions. Input actions are not under the automaton's control but instead are triggered by the environment including other component automata. Output and internal actions are under its control, but only the output actions are observable by other automata.

A model inspired from swarm networks is proposed in [TIM08]. It is shown how boolean circuit computation can be obtained by means of particular configurations of swarm of agents. A proposal for modelling a wireless connected swarm of mobile robots is presented in [WLNM08].

The study of problems arising from processing large data streams resulting from *networking on* massive data is an emerging theory [Mut05]. A similar approach has been used in wireless sensor networks [dAFN+08]. A basic problem in wireless communication protocols is the scaling coordination [EGHK99]. An approach to the solution of that problem is given by the *directed diffusion* developed in [HSE03].

A first model: Static Synchronous Sensor Field

This first proposal combines the notion of graph automata together with data streams. This combination is inspired in a similar idea developed in the context of concurrent programming [Hoa81].

We assume a clear cut between *sensing* and *acting*, where sensors artifacts *sense* the environment and *act* on the environment. Depending on the particular application they use or not those capabilities.

The *connection graph* of a sensor network is a pair $\mathcal{N} = (N, E)$, where N is the set of nodes (corresponding to artifacts) and E is the set of directed connections between them, and (i, j) denotes a directed connection from device i to device j. If node i corresponds to a sensor, then it can:

- receive information from the environment and through any of the *incoming* links
- send information to the environment and through the *outgoing* links.

To simplify the formal description, we suppose that each node can do these actions. If device i is not a sensor, then the information sent or received from the environment is empty.

To give a description of a system one must define for each device k a set of states Q_k and a transition function δ_k. A state is defined to be an assignment of values to some set of variables (ordinary program variables, message buffers, program counters ...) or all what is needed to describe completely the instantaneous state of the local computation. Moreover it must indicate whether the device wants to receive data from some of its neighbors or from the environment as well as to send data to some of its neighbors or to the environment.

The computational behavior of k is defined by a transition function δ_k that depends on its local state, the measurements of the environment and on the data received from other sensors. Let us define $I(k) = \{i \mid (i,k) \in E\}$ and $O(k) = \{j \mid (k,j) \in E\}$. An *instantaneous device configuration* is a tuple $(q, (x_{ik})_{i \in I(k)}, u)$ that indicates the actual state $q \in Q_k$, the data x_{ik} that k receives from i, $\forall i \in I(k)$, and the data u that k receives from the environment.

Given $(q, (x_{ik})_{i \in I(k)}, u)$, a computation step of device k is well defined by δ_k. Formally, $\delta_k(q, (x_{ik})_{i \in I(k)}, u) = (q', (y_{kj})_{j \in O(k)}, v)$, which means that device k: (1.-) changes its state q to $q' \in Q_k$; (2.-) sends y_{kj} to j, $\forall j \in O(k)$; (3.-) sends v to the environment. The case that k either does not send or receives a value is denoted by λ.

Sensor Field's Computation. Define a *network instantaneous configuration* as a tuple $\mathbf{c} = (c_k)_{k \in N}$, where c_k is an instantaneous configuration of k. Say that $\mathbf{c} = (c_k)_{k \in N}$ produces $\mathbf{c}' = (c'_k)_{k \in N}$ in one step of $\mathcal{N}$ if for each $k \in N$, $c_k = (q_k, (x_{ik})_{i \in I(k)}, u_k)$ and $\delta_k(q_k, (x_{ik})_{i \in I(k)}, u_k) = (q'_k, (y_{kj})_{j \in O(k)}, v_k)$ then $c'_k = (q'_k, (x'_{ik})_{i \in I(k)}, u'_k)$, where $x'_{ik} = y_{ik}$ and u'_k is the new environment measurement.

A *computation* of $\mathcal{N}$ is a sequence of configurations $\mathbf{c^0}, \mathbf{c^1}, \ldots, \mathbf{c^t}, \mathbf{c^{t+1}}, \ldots$, eventually infinite, where $\mathbf{c^0}$ is the initial configuration and for each $t \geq 0$, $\mathbf{c^{t+1}}$ is obtained in one step from $\mathbf{c^t}$.

Define the *stream behavior* of a sensor field $\mathcal{N}$ as $((\mathbf{u}_k)_{k \in N}, (\mathbf{v}_k)_{k \in N})$, where $\mathbf{u}_k = u_k^0 u_k^1 u_k^2 \ldots$ is the input data stream of device k and $\mathbf{v}_k = v_k^0 v_k^1 v_k^2 \ldots$ is the output stream of device k to the environment. Notice that this information can be extracted from its computation, u_k^t denotes the measured data by device k in configuration $\mathbf{c^t}$ and v_k^t denotes the data output by device k to the environment in configuration $\mathbf{c^t}$.

Assume that a sensor field $\mathcal{N} = (N, E)$ is deployed in a geographic region. **A problem can be defined** by expressing a *goal*, that is, some temporal property expressed in terms of the sensor field behavior. For example,

> Average Temperature Monitoring: From any sensor $k \in N$, $\mathcal{N}$ outputs a data stream $\mathbf{v}_k = v_k^0 v_k^1 v_k^2 \ldots$ such that after some time step t, v_k^{t+i} is the

average temperature among all the measurements taken at time i.

Alerting: Given two values k and t, and a particular node i, the user wants to get an alerting message at node i if at time t' at least one of the measured data is above the threshold k.

Research targets

Different types of units might have different restrictions on the quantity of information that they handle. In complexity theory, there is a clear cut difference on computing capabilities between unrestricted data storage (Turing machines) and finite data storage (finite automata). The target of this research is to analyze whether similar quantifications have an impact on computation on embedded networks. In particular, it seems plausible that one fundamental difference will appear on the scalability of the required data. Storing only a constant amount of data versus storing a logarithmic or a polynomial (in the size of the network) amount of data.

The present research first will consider the particular case of static networks, as a way to obtain a basis for identifying fundamental parameters and performance metrics, to analyze the difficulty of solving a problem. Moreover, the static network could be considered as the objective of the emergent behavior of the real network which is created and kept by self-organization. This approach have been addressed already by two different teams within FRONTS for the particular network topology of mesh of stars and a particular real network (random sector graph) [ÀDP+08, DPS03]. On a second step the model should incorporate further sources of dynamicity to the network: mobility, faults, collisions.

It is conceivable that the nature and topology of the network will play a relevant role in the "tractability" of some problems. The final goal of the research is finding fundamental parameters that could be used to identify threshold values that guarantee that a given problem can be "efficiently" solved on a network or on a family of networks.

3.5 Evolutionary Game Theory

Motivation

Classical evolutionary game theory models organisms in a population interacting and competing for resources. The classical model assumes that the population is infinite. Interaction is modelled by choosing two organisms uniformly at random , who then play a 2 persons symmetric game.

One of the fundamental aspects of evolutionary theory is to characterize which strategies are resilient to small mutant invations. Specifically , it is assumed that a large fraction of the population (the incumbents) adopt the same strategy , while the rest (the mutants or invaders) adopt some other strategy. The incumbent strategy is stable if the incumbents retain a higher fitness than the mutants.

Such a model can capture a system of a huge number of tiny artifacts which interact in pairs. Locality can be captured if we allow only certain interactions to take place. Adaptiveness (to a mutant strategy) is then somehow the inverse of stability i.e. one can examine under what conditions (on fitness and ineractions rates) the system will adapt to a new strategy that the mutants bring.

Previous work and State of Art

While classical evolutionary theory is a huge and mature field, see e.g. [Wei95] , however evolutionary dynamics on networks has not been studied in depth yet. Even the recent algorithmic work focuses on studying evolutionary dynamics that achieve some kind of equilibria at the end (see e.g [FKS08]). The only work that we know on evolutionary dynamics on finite networks is that of [KS06] .

Research Targets

Evolutionary Dynamics on Networks. We intend to examine stability and adaptiveness in the case where random interactions take place only between pairs of neighbouring agents. A graph defines agents proximity. For the examination of adaptiveness, one can divide the mutants into those with normal fitness and those with abnormal fitness. The system should be able to adapt to interactions with invaders of normal fitness (seen as a particular kind of deviation from the current fitness of the system) , while the system should resist mutants with abnormal fitness. Rates of adaptiveness and thresholds for the fraction of mutants to have any effect can be studied.

Various dynamics and limited rationality. When two neighbouring agents interact, the way they interact is important. A well studied interaction is the so-called Replicator Dynamics, where an agent copies the state of a neighbour if the neighbour has more fitness. Such simple laws of interaction can capture the fact that tiny artefacts work with simple programs and are severely limited wrt computation and intelligence. We intend to study a variety of such dynamics , each obeying to a simple law of local intercation. We see connections to the model of Population Protocols for nets of tiny artefacts here.

4 Task 1.3: Cooperation models and algorithmic consequences

4.1 Congestion Games

Motivation and problem description

In this task we have to cope with the selfish aspect of artefacts in the “competition” for resources. We study the problem of congestion during data propagation in wireless sensor networks as a result of selfishness and the lack of a central authority. We study the performance of approximate Nash equilibria for congestion games with linear latency functions. In many situations, approximate Nash equilibria provide a more reasonable equilibrium concept than Nash equilibria: It makes sense to assume that an agent is willing to accept a situation that is almost optimal to him, especially considering that Nash equilibria cannot be computed effectively [DGP06, CD06]. A natural question then is how the performance of a system is affected when its users are approximately selfish: What is the *approximate price of anarchy* and the *approximate price of stability*? Clearly, by allowing the players to be almost rational (within an ϵ factor), we expand the equilibrium concept and we expect the price of anarchy to get worse. On the other hand, the price of stability should improve. The question is how they change as functions of the parameter ϵ. This is exactly the question that we address in this work.

State of the art and previous work

We study two fundamental classes of games: the class of atomic congestion games [Ros73, MS96] and the class of non-atomic congestion (or selfish routing) games [BMW56, DS69, Mil96]. Both classes of games played central role in the development of the area of the price of anarchy [KP99, RT02b, RT02a]. Although the price of anarchy and stability of these games for exact equilibria was established long ago [RT02b, CK05b, CK05a, AAE05]—and actually some work [Rou02, Rou05] addressed partially the question for the price of anarchy of approximate equilibria—our results add an unexpected understanding of the issues involved.

First results

In [CKS08] we give almost tight upper and lower bounds for both the price of anarchy and the price of stability for atomic and non-atomic congestion games. Our results not only encompass and generalize the existing results of exact equilibria to ϵ-Nash equilibria, but they also provide a unified approach which reveals the common threads of the atomic and non-atomic price of anarchy results. By expanding the spectrum, we also cast the existing results in a new light. For example, the Pigou network of two parallel links, which gives tight results for exact Nash equilibria of selfish routing, remains tight for the price of stability of ϵ-Nash equilibria but not for the price of anarchy.

Research targets

Possible future directions include the extensions of the study of approximate equilibria to other latency functions and to interesting special cases of congestion games, for example, games with malicious players.

4.2 Random Markov Fields

Motivation and problem description

A central problem in a any foundational approach to networks of small artifacts is to model the process of how local changes are to be propagated until a new steady state is accomplished. A comprehensive project like FRONTS will have to investigate more than one such models, not all of which will prove equally successful in shedding light to what actually takes place in “real situations".

One approach that seems to be very promising is to model networks of artifacts as a Random Markov Field. Roughly, a Markov Field, or more generally a Probabilistic Graph Model is a graph with probability distributions on values assigned to the vertices in a way that the joint probability of an assignment $\bar{x}$ on all vertices is the product of the marginal probabilities of the assignment on each vertex v, conditional on the the values of the assignment on v's neighbors (for a nice introduction, see [Jor04]). The teams of RACTI and UPC work in tandem for the study of this approach. The main objective will be the study of message exchanges in an artifact network as a statistical inference process.

State of the art and previous work

It is not necessary, and space does not permit, to repeat here the importance and the recent advances of Probabilistic Graphical Models (see [WJ03]). With respect to related existant research results where members of UPC and RACTI have contributed, we should mention [ART06, MMW07, MS08], where the main contribution is the formalization of a recent propagation algorithm motivated by Physics (Survey Propagation) and having found applications in Constraint Satisfaction problems.

First results

A first result in this direction was an improvement of the upper bound of threshold point where a random Boolean formula becomes almost surely unsatisfiable [DKMPG08]. Although this result is not directly related to statistical inference, it was reported within FRONTS as its main contribution was the formal study of a highly, and in the long range, interdependent network (the Boolean formula) of elementary “particles" (the literals). The main technical tool used in this work was the computation of the expected number of various kinds of steady (non-contradicting) states of the formula.

Research targets

The first target is to discover cases where Survey Propagation or other message propagation algorithms on probabilistic graphical models become exact. There is very little known in this direction. Essentially, the exactness is only proved when the underlying network is a tree.

A second step is to investigate whether cases where exactness is already known or will be proved might have any impact on the design of tiny artifact networks.

5 Task 1.4: Unification of Results

The unification of the results is described analytically in deliverable D4.3 “First Report on Unification of Results”.

In the list of references below, papers marked with "∗" present results of the FRONTS project.

References

[AAD+04] Dana Angluin, James Aspnes, Zoë Diamadi, Michael J. Fischer, and René Peralta. Computation in networks of passively mobile finite-state sensors. In *23rd Annual ACM Symposium on Principles of Distributed Computing (PODC)*, pages 290–299, New York, NY, USA, 2004. ACM.

[AAD+06] Dana Angluin, James Aspnes, Zoë Diamadi, Michael J. Fischer, and René Peralta. Computation in networks of passively mobile finite-state sensors. *Distributed Computing*, 18(4):235–253, 2006.

[AAE05] Baruch Awerbuch, Yossi Azar, and Amir Epstein. Large the price of routing unsplittable flow. In *37th Annual ACM Symposium on Theory of Computing (STOC)*, pages 57–66, 2005.

[ÀDP+08] Carme Àlvarez, Josep Díaz, Jordi Petit, José D. P. Rolim, and Maria J. Serna. High level communication functionalities for wireless sensor networks. *Theoretical Computer Science*, 406(3):240–247, 2008.

[AR07] James Aspnes and Eric Ruppert. An introduction to population protocols. *Bulletin of the European Association for Theoretical Computer Science*, 93:98–117, October 2007.

[ART06] D. Achlioptas and F. Ricci-Tersenghi. On the solution-space geometry of random constraint satisfaction problems. In J. M. Kleinberg, editor, *STOC*, pages 130–139, 2006.

[ASSC02] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Journal of Computer Networks*, 38:393–422, 2002.

[BB04] A. Boukerche and L. Bononi. *Simulation and modeling of wireless mobile and ad-hoc networks*. Mobile Ad-Hoc Networking. Wiley Interscience, 2004.

[BG08] Simon R. Blackburn and Stefanie Gerke. Connectivity of the uniform random intersection graph, 2008.

[BGK+06] J.C. Bermond, J. Galtier, R. Klasing, N. Morales, and S. Pérennes. Hardness and approximation of gathering in static radio networks. *Parallel Processing Letters*, 16(2):165–183, 2006.

[BKMSS08a] V. Bonifaci, P. Korteweg, A. Marchetti-Spaccamela, and L. Stougie. An approximation algorithm for the wireless gathering problem. *Operations Research Letters*, 36(5):605–608, 2008.

[BKMSS08b] V. Bonifaci, P. Korteweg, A. Marchetti-Spaccamela, and L. Stougie. Minimizing flow time in the wireless gathering problem. In *25th Symp. on Theoretical Aspects of Computer Science*, pages 109–120. IBFI Dagstuhl, 2008.

* [BKMSS08c] V. Bonifaci, P. Korteweg, A. Marchetti-Spaccamela, and L. Stougie. Minimizing verage flow time in sensor data gathering. In *4th Conf. on Algorithmic Aspects of Wireless Sensor Networks*. Springer, 2008, 2008. FRONTS-TR-2008-40.

[BMW56] M. Beckmann, C. B. McGuire, and C. B. Winston. *Studies in the Economimices of Transportation*. Yale University Press, 1956.

[BXFJ03] Binh Bui-Xuan, A. Ferreira, and A. Jarry. Computing shortest, fastest, and foremost journeys in dynamic networks. *International Journal of Foundations of Computer Science*, 14((2)):267–285, April 2003.

[BYII93] R. Bar-Yehuda, A. Israeli, and A. Itai. Multiple communication in multihop radio networks. *SIAM Journal on Computing*, 22(4):875–887, 1993.

[CBD02] T. Camp, J. Boleng, and V. Davies. Mobility models for ad-hoc network research. *Mobile Ad Hoc Networking: Research, Trends and Applications*, 2((5)):483–502, 2002.

[CD06] Xi Chen and Xiaotie Deng. Settling the complexity of two-player nash equilibrium. In *47th Annual IEEE Symposium on Foundations of ComputerScience (FOCS)*, pages 261–272, 2006.

* [CEL$^+$09] Ho-Leung Chan, J. Edmonds, Tak-Wah Lam, Lap-Kei Lee, A. Marchetti-Spaccamela, and K. Pruhs. Nonclairvoyant speed scaling or flow and energy. In *26th Symp. on Theoretical Aspects of Computer Science (STACS)*, 2009. FRONTS-TR-2009-2.

[CK05a] George Christodoulou and Elias Koutsoupias. On the price of anarchy and stability of correlated equilibria of linear congestion games. In *13th Annual European Symposium (ESA)*, pages 59–70, 2005.

[CK05b] George Christodoulou and Elias Koutsoupias. The price of anarchy of finite congestion games. In *37th Annual ACM Symposium on Theory of Computing (STOC)*, pages 67–73, 2005.

* [CKS08] George Christodoulou, Elias Koutsoupias and Paul G. Spirakis. On the performance of approximate equilibria in congestion games. Technical report, 2008. FRONTS-TR-2008-32.

[CPR08] C. Chan, M. Patrascu, and L. Rodity. Dynamic connectivity: Connecting to networks and geometry. In *Foundations of Computer Science (FOCS)*, 2008.

* [CS08] Ioannis Chatzigiannakis and Paul Spirakis. The dynamics of robabilistic population protocols. In *22nd International Symposium on Distributed Computing*, 2008. FRONTS-TR-2008-10.

[dAFN$^+$08] André L. L. de Aquino, Carlos M. S. Figueiredo, Eduardo F. Nakamura, Alejandro C. Frery, Antonio A. F. Loureiro, and Antônio Otàvio Fernandes. Sensor stream reduction for clustered wireless sensor networks. In *ACM Symposium on Applied Computing SAC08*, pages 2052–2056, 2008.

[DEGI08] C. Demetrescu, D. Eppstein, Z. Galil, and J. Italiano. *Algorithms and Theory of Computation Handbook*, chapter Dynamic Graph Algorithms, pages 250–281. 2008.

[DGP06] Constantinos Daskalakis, Paul W. Goldberg, and Christos H. Papadimitriou. The complexity of computing a nash equilibrium. In *STOC '06: Proceedings of the thirty-eighth annual ACM symposium on Theory of computing*, pages 71–78, New York, NY, USA, 2006. ACM Press.

[Dij74] E. W. Dijkstra. Self stabilizing systems in spite of distributed control. *Communications of the ACM*, 17:643–644, 1974.

* [DKMPG08] Josep Díaz, Lefteris M. Kirousis, Dieter Mitsche and Xavier Pérez-Giménez. A new upper bound for 3-sat. In *FSTTCS*, 2008. Bangalore. FRONTS-TR-2008-53.

[DMP08] J. Díaz, D. Mitsche, and X. Pérez. Walkers on the cycle and the grid. In *ACM-SIAM Simp. On Discrete Math. and Algorithmics*, pages 601–610, 2008. San Francisco.

[DPS03] Josep Díaz, Jordi Petit, and Maria J. Serna. A random graph model for optical networks of sensors. *IEEE Trans. Mob. Comput.*, 2(3):186–196, 2003.

[DPSW08] Josep Díaz, Xavier Pérez, Maria J. Serna, and Nicholas C. Wormald. Walkers on the cycle and the grid. *SIAM J. Discrete Math.*, 22(2):747–775, 2008.

[Dre69] S.E. Dreyfus. An appraisal of some shortest-path algorithms. *Operations Research*, 17:269–271, 1969.

[DS69] S. C. Dafermos and F. T. Sparrow. The traffic assignment problem for a general network. *Journal of Research of the National Bureau of Standards*, pages 91–118, 1969. Series B.

[ECPS02] D. Estrin, D. Culler, K. Pister, and G. Sukatme. Connecting the Physical World with Pervasive Networks. *Pervasive Computing*, 1:59–69, 2002.

[EGHK99] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar. Next century challenges: Scalable coordination in sensor networks. In *5th ACM/IEEE Annual International Conference on Mobile Computing (MOBICOM 1999)*, pages 263–270, 1999.

[Ell97] C. A. Ellis. Team Automata for Groupware Systems. In *International ACM SIGGROUP Conference on Supporting Group Work: The Integration Challenge (GROUP'97)*, pages 415–424, 1997.

[ES05] C. Efthymiou and P.G. Spirakis. On the existence of hamilton cycles in random intersection graphs. In *32nd International Colloquium on Automata, Languages and Programming*, pages 690–701, 2005.

[FF58] L. R. Ford and D. R. Fulkerson. Constructing maximal dynamic flows from static flows. *Operations Research*, 6:419–433, 1958.

[FKS08] D. Fotakis, A. Kaporis, and P. Spirakis. Fast, myopic and concurrent. In *1st Symposium on Algorithmic Game Theory (SAGT 2008)*, 2008. 2009.02.24.

[FSSC00] J.A. Fill, E.R. Sheinerman, and K.B Singer-Cohen. Random intersection graphs when m=(n): An equivalence theorem relating the evolution of the $g(n, m, p)$ and $g(n, p)$ models. *Random Structures and Algorithms*, 16:156–176, 2000.

[FSW+09] Sandor Fekete, Christiane Schmidt, Axel Wegener, Horst Hellbruck, and Stefan Fischer. Empowered by wireless communication: Distributed methods for self-organizing traffic collectives. Technical report, 2009.

[Gal76] R. G. Gallager. A shortest path routing algorithm with automatic resynch. Technical report, Lab. for Information and Decision systems, March 1976. Cambridge, MA.

[Gal82] R. G. Gallager. Distributed minimum hop algorithms. Technical report, Lab. for Information and Decision systems, January 1982. MIT,Cambridge, MA.

[GHSZ01] L. Guibas, J. Hershberger, S. Suri, and Li Zhang. Kinetic connectivity for unit disks. *Discrete and Computational Geometry*, 25:591–610, 2001.

[GJ02] E. Godehardt and J. Jaworski. *Studies in Classication, Data Analysis and Knowledge Organisation*, chapter Two models of Random Intersection Graphs for Classication, pages 67–82. Springer Verlag, 2002.

[GMS77] B. Gavish, P. Merlin, and A. Segall. Minimal buffer requirements for avoiding store-and-forward deadlock. Technical report, IBM, Yorktown Heights, ,NY, August 1977. RC–6672.

[Gue87] R. A. Guerin. Channel occupancy time distribution in a cellular radio system. In *IEEE Transactions on Vehicular Technology*, volume 36, pages 89–99, 1987.

[Hal77] J. Halpern. Shortest route with time dependent length of edges and limited delay possibilities in nodes. *Zeitschrift für Operations Research*, 21:117–124, 1977.

[Hek06] R. Hekmat. *Ad-hoc networks: fundamental properties and network topologies*. Springer, 2006.

[Hen96] T.A. Henzinger. The Theory of Hybrid Automata. In *11th Annual IEEE Symposium (LICS 96)*, 1996.

[Hoa81] C. A. R. Hoare. A calculus of total correctness for communicating processes. *Sci. Comput. Program*, 1(1):49–72, 1981.

[HSE03] J.S. Heidemann, F. Silva, and D. Estrin. Matching data dissemination algorithms to application requirements. In *1st International Conference on Embedded Networked Sensor Systems (SenSys 2003)*, pages 218–229, Los Angeles, California, USA, November 5-7 2003. ACM.

[JBRAS03] A. Jardos, E.M. Belding-Royer, K. Almeroth, and S. Suri. Towards realistic mobility models for mobile ad hoc networks. In *Proc. ACM MobiCom Conf.*, pages 217–229, 2003.

[Jor04] M. I. Jordan. Graphical models. *Statistical Science (Special Issue on Bayesian Statistics)*, 19:140–155, 2004.

[KLS02] E. Köhler, K. Langkau, and M. Skutella. Time-expanded graphs for flow-dependent transit times. In *ESA'02*, 2002.

[KP99] E. Koutsoupias and C. Papadimitriou. Worst-case equilibria. In *16th Annual Symposium on Theoretical Aspects of Computer Science (STACS)*, pages 404–413, Trier, Germany, 4–6 March 1999.

[KS02] E. Köhler and M. Skutella. Flows over time with load-dependent transit times. In *13th Annual ACM-SIAM Symposium on Discrete Algorithms (SODA'02)*, 2002.

[KS06] M. Kearns and S. Suri. Networks preserving evolutionary equilibria and the power of randomization. In *7th ACM Conf. on Electronic Commerce*, 2006.

[LeL77] G. LeLann. Distributed systems, towards a formal approach. In *IFIP Congress*, pages 155–160, 1977.

[LL90] L. Lamport and N. Lynch. *Handbook of Theoretical Computer Science*, volume B, chapter Distributed Computing. Models and methods. Elsevier, 1990.

[LSV01] N. Lynch, R. Segala, and F. Vaandrager. Hybrid I/O Automata Revisited. In Springer-Verlag, editor, *Hybrid Systems: Computation and Control: 4th International Workshop (HSCC'01)*, volume 2034, pages 403–417, 2001.

[Lyn96] N. A. Lynch. *Distributed Algorithms*. Morgan Kaufmann Publishers Inc, 1996.

[Mil96] I. MilchtaichS. Congestion games with player-specific payoff functions. *Games and Economic Behavior*, 13:111–124, 1996.

[MKSC99] E.R. Scheinerman M. Karonski and K.B. Singer-Cohen. On random intersection graphs: The subgraph problem. *Combinatorics, Probability and Computing journal*, 8:131–159, 1999.

[MMW07] E. N. Maneva, E. Mossel, and M. J. Wainwright. A new look at survey propagation and its generalizations. *ACM*, 54, 2007.

[MS96] D. Monderer and L. Shapley. Potential games. *Games and Economics Behavior*, 14:124–143, 1996.

[MS08] E. N. Maneva and A. Sinclair. On the satisfiability threshold and clustering of solutions of random 3-SAT formulas. *Theor. Comput. Sci.*, 407(1-3):359–369, 2008.

[Mut05] S. Muthukrishnan. *Data Streams: Algorithms and Applications*. Now Publishers Inc, 2005.

[Nag05] D. J. Nagel. Wireless Sensor Systems and Networks, 2005.

[NRS04] S. Nikoletseas, C. Raptopoulos, and P. Spirakis. The existence and efficient construction of large independent sets in general random intersection graphs. In *31st International Colloquium on Automata, Languages and Programming (ICALP)*, pages 1029–1040. Lecture Notes in Computer Science (Springer Verlag), 2004.

[NRS07] S. Nikoletseas, C. Raptopoulos, and P.G. Spirakis. Expander properties and the cover time of symmetric random intersection graphs. In *32nd International Symposium on Mathematical Foundations of Computer Science (MFCS 2007)*, 2007.

∗ [NRS09] S. Nikoletseas, C. Raptopoulos and P. Spirakis. Combinatorial properties for efficient communication in distributed networks with local interactions. In *23rd International Parallel & Distributed Processing Symposium IPDPS*, 2009. FRONTS-TR-2009-11.

[Pel00] D. Peleg. *Distributed Computing: A Locality-Sensitive Approach*. Siam Monographs on Discrete Mathematics and Applications, 2000.

[PJO95] W. B. Powell, P. Jaillet, and A. Odoni. *Handbook in Operations Research and Management Science - Network Routings*, volume 8, chapter Stochastic and dynamic networks and routing. Elsevier Science, 1995.

[PMM$^+$04] R. Di Pietro, L.V. Mancini, A. Mei, A. Panconesi, and J. Radhakrishnan. Sensor networks that are provably resilient. In *IEEE SecureComm*, 2004.

[Ros73] R. W. Rosenthal. A class of games possessing pure-strategy nash equilibria. *International Journal of Game Theory*, 2:65–67, 1973.

[Rou02] Tim Roughgarden. *Selfish Routing*. PhD thesis, Cornell University, May 2002.

[Rou05] Tim Roughgarden. *Selfish Routing and the Price of Anarchy*. The MIT Press, 2005.

[RS05] C. Raptopoulos and P.G. Spirakis. Simple and efficient greedy algorithms for hamilton cycles in random intersection graphs. In *16th International Symposium on Algorithms and Computation (ISAAC)*, pages pp. 493–504, 2005.

[RT02a] T. Roughgarden and E. Tardos. Bounding the inefficiency of equilibria in nonatomic congestion games. *Games and Economic Behavior*, 47:389–403, 2002.

[RT02b] Tim Roughgarden and Éva Tardos. How bad is selfish routing? *J. ACM*, 49(2):236–259, 2002.

[SB02] P. Santi and D.M. Blough. An evaluation of connectivity in mobile wireless ad hoc networks. In *Int. Conference on Dependable Systems and Networks*, pages 89–98, 2002.

[Sch02] C. Scheideler. Models and techniques for communication in dynamic networks. In H. Alt and A. Ferreira, editors, *19th International Symposium on Theoretical Aspects of Computer Science*, volume 2285, pages 27–49. Springer-Verlag, March 2002.

[TAGH03] S. Tilak, Nael B. Abu-Ghazaleh, and W. Heinzelman. A Taxonomy of Wireless Micro-Sensor Network Models. *Mobile Computing and Communications Review*, 2003.

[tB03] M. H. ter Beek. *Team Automata. A Formal Approach to Modeling of Collaboration Between System Components*. PhD thesis, Leiden University, 2003.

[TIM08] F. Peper Teijiro Isokawa and Masahiko Mitsui. Computing by Swarm Networks. In *LNCS*, volume 5191, pages 50–59, 2008.

[VRAC08] M. Vinyals, J.A. Roderiguez-Aguilar, and J. Cerquides. A Survey on Sensor Networks from a Multi-Agent Perspective. In *AAMAS 2008*, 2008.

[Wei95] J. W. Weibull. *Evolutionary Game Theory*. The MIT Press, 1995.

[WJ03] M. J. Wainwright and M.J. Jordan. Graphical models, exponential families, and variational inference. Technical report, Department of Statistics, Univesrity of California, Berkeley, 2003. Technical Report 649.

[WLNM08] Alan F. T. Winfield, Wenguo Liu, Julien Nembrini, and Alcherio Martolini. Modelling a wireless connected swarm of mobile robots. *Swarm Intell*, 2:241–266, 2008.