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Definition of Research Targets and Algorithmic Solutions for Organizing Distributed Cooperation, Discovering and Tracking Resources, Reacting to Dynamically Changing Physical Environments, Trust and Reliable communication

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Contents

1 Introduction

Societies of tiny artefacts, such as sensor nodes, are usually deployed to an environment that is highly dynamic. Any underlying network has to adapt to the changes that are induced upon theses changes of the environment. The societies that we consider are expected to be too large to be handled in a centralized manner, and, furthermore, the environment is usually considered to be so dynamic that consistent centralized solutions are infeasible. Therefore, the main objective of the work-package at hand is to design and analyze local strategies that are capable of handling the required global tasks despite the locality of the algorithms. In this deliverable we define the future research goals and describe first results that we achieved during the first year of the FRONTS project. For each task, we first give a motivation and problem description, then we shortly discuss the state of the art and previous work. We proceed by presenting first results before defining our future research targets.

The six tasks that we work on are organizing distributed cooperation, discover and tracking resources, reacting to dynamically changing environments, trust, reliable communication, and unification of results. Organizing distributed cooperation is vital in our setting, because cooperation is needed for almost all problems that we want to solve in the societies of artefacts, and the cooperation has to be organized in a proper way. Dealing with resources is considered in the second task. Besides finding resources we also face the challenge of keeping track of them, since the environment is changing and therefore the resources might change their position in an active or passive way as well. The focus in the third task is not only to discover that the environment changes, but also to react properly to the changes by adapting the network accordingly. Another main issue is addressed in the forth task, namely the matter of trust. Common cryptographic techniques are too heavy weight for tiny artefacts. Therefore we define new notions of trust where we design mechanisms such that trust emerges over time. In the fifth task we try to enable a reliable communication within the network, despite the fact that communication links may break due to the unpredictable changes in the environment. Finally we have to unify all the joint efforts of dealing with dynamic environments in task six in order to get integrated solutions.

2 Task 3.1: Organizing distributed cooperation

2.1 Motivation and problem description

Within Task 3.1, we explore methods and techniques that allow a network of tiny artefacts to organize itself in order to be able to accomplish given tasks. Among these tasks are the setup and maintenance of a communication and cooperation infrastructures or other types of geometric formations as well as the organization of the competition for resources. We have to restrict ourselves to local strategies based on simple local rules of the nodes, resulting in a globally good solution, obeying severe energy restrictions.

Setup and maintain a communication or cooperation infrastructure We consider the general setting of sensor networks in which a large number of static sensor devices is randomly scattered on a squared-fittable terrain [BA02, ASSC02]. Our goal is to establish a reliable and efficient high level communication system in it. Such a high level communication system cannot be precomputed and encoded in the devices, but it must rather emerge from the system itself by using self-organization, self-discovery and collaborative methods. The final goal will be to have the possibility of using the best virtual topology together with the best possible algorithm for solving a problem in the most usable models of networked sensors. While this solves the problem of setting up an infrastructure, maintaining it leads to other problems and other models. Consider e.g. a group of mobile sensors in which only a few of these sensors know the trajectory of the group and move accordingly. The task of the remaining sensors in this situation is to collectively maintain a geometric formation of the group (e.g., to stay inside the convex hull of the sensors which know the trajectory). A main restriction is that the sensors can only see sensors which are close to them. We want to find local strategies for these sensors that fulfill the global common task. Our strategies should be inspired by phenomena which occur in the nature, like the behavior of birds in a flock or fishes in a swarm.

Care for energy efficiency As energy is crucial especially in this task, we have further contribution to energy awareness. One of them is known as *duty-cycling*. Hereby, sensor nodes alternate between (at least) two states: being awake and being asleep. It is generally important that the sensor nodes synchronize their activity periods. When being awake, they can perform their normal duties (e.g., monitoring the environment). When sleeping, sensors spend their time in a state that is characterized by a low energy consumption. The currently existing duty-cycling methods are engineered approaches completely managed by a central controller, which may be unfeasible when dealing with large-scale sensor networks.

Additionally, when doing *minimum energy multicast* (MEM), one node is required to transmit data to a subset of the other network nodes, spending as little energy as possible. Complete techniques, constructive heuristics and metaheuristics can be found in the literature for solving this problem. However, they mostly focus on sensor networks with omni-directional antennas. Instead, we have additionally tackled the problem for the case of nodes equipped with directional antennas.

Organizing the competition for resources Distributed cooperation arises when n independent entities are to process a set of m independent tasks and the goal is to minimize the makespan. Depending on their type and location, different entities may have different processing times for the same task. One way to persuade selfish entities to participate and report the true time it takes them to process each one of the tasks is to pay them something in return (for example in energy).

A major question of Game Theory is what kinds of payoff profiles can be induced to these agents as the equilibrium point of some dynamically evolving competition. A crucial notion for inducing a payoff point as the equilibrium of a repeated game is the so–called *threat point*.

2.2 State of the art and previous work

The setting of collective maintenance of geometric formations is related to the research area on formation and agreement problems for mobile robots. One of the basic problems investigated here is the gathering problem, where a group of robots, initially dispersed on a plane, finally gather at one chosen point [ASY95, KTI$^+$07, ITI$^+$08]. In an easier variant, we only require all robots to converge in infinite time to one point [CP04, CP05, CP02]. Further problems are the spreading problem ([CP06]), the partitioning problem [EP07] and the formation of geometric patterns ([SY99]).

Concerning the problem of scheduling distributed computation, a fundamental well-known (but still open) problem in the area of Algorithmic Mechanism Design is to determine which is the algorithm that achieves the best approximation to the goal of scheduling distributed computation. This problem has been studied in a slightly different setting (see e.g., [NR99, NR01, Hoc96, LST90]). In [NR99, NR01] a truthful n-approximate (polynomial-time) algorithm (where n is the number of machines) is given, and it is shown that no mechanism can achieve an approximation ratio better than 2 when there are at least three tasks.

We have improved the lower bound in [CKV07] for deterministic mechanisms to 2.41 (this is the best-known lower bound for 3 machines) and the one in [KV07] to 2.618 for $n \to \infty$ machines. For a fractional version of the problem, we have shown that no fractional truthful mechanism can achieve an approximation ratio better than $2 - 1/n$, and not better than $(n + 1)/2$ (tight bound) when each task is treated independently.

We note that even the problem of defining the threat point for the case of 3 players is an $NP-$hard problem ([BCI$^+$08, HHMS08]). In [LS05], it was proved that any feasible and enforceable payoff point can be induced by an equilibrium of an infinitely repeated game of 2 players; the extension to the case of more players would however be highly complicated. These results seem not to leave much space for the succinct representation of *any* payoff point above the threat point.

2.3 First results

Concerning high level communication primitives, in [ADP+08] we consider as target network a mesh of trees, which have been used for establishing hierarchical structures in which nodes form clusters, and the cluster heads are organized in a squared mesh topology [SP03]. The proposed system is energy efficient and reliable and its initialization protocol runs in sub-linear time. In our system, the balance between the throughput at which sensors emit messages and the speed these messages are transmitted through the network is adjustable.

Most existing solutions to energy harvesting are minimally adaptive and assume a priori knowledge of the energy profile of a day, which is not realistic. In [HBM+08] we presented a first study for a system that combines our self-organized duty-cycling mechanism (based on real ants' behavior) with an energy harvesting mechanism in which the periods of the duty cycles are adaptive based on the battery levels of the individual sensors and the current weather conditions. The proposed system works under static and mobile sensor networks and autonomously adapts to changing environmental conditions.

In [HBF08] we proposed a centralized ant colony optimization algorithm for minimum energy multicast and conducted an extensive experimental evaluation. The results show that our algorithm is currently a state-of-the-art method for all considered problem versions.

Concerning dynamically evolving nets, in [KS08] we have proposed a way out of the phenomenal deadlock that state of the art results suggest that there is no payoff point above the threat point. This is done by having all the (other) players consider not uncoordinated, but correlated punishment plans against any potential defector. This way we can efficiently compute the *correlated threat point* for all the players, which constitutes a credible polynomial–time computable threat for the players. Additionally, we demonstrate how to exploit this kind of threat to construct an equilibrium point for the infinitely repeated game. On the negative side, the players will have to coordinate their actions *against* any player that violates the designated behavioral plan. Finally, by means of communication complexity, our notion of equilibrium is not far from the classical Nash equilibrium.

In [CKS08b], we study the performance of approximate Nash equilibria for linear congestion games by considering how much the price of anarchy worsens and how much the price of stability improves. (Almost) tight upper and lower bounds for both measures are also given for atomic and non-atomic congestion games.

Furthermore, we generalized the state of the art results from [DS08], and in [CKV08] we gave a characterization of all (regardless of approximation ratio) decisive truthful mechanisms in terms of affined minimizers and threshold mechanisms for the case of 2 players. This characterization is about all truthful mechanisms, including those with unbounded approximation ratio.

2.4 Research targets

We will tackle some limitations to the system proposed for the virtual topologies, as for example, the lack of node mobility and fault-tolerance, where periodical re-organizations of the system may help to cope with it and may also help to alleviate the higher power consumption of the central nodes. We will also analyze the same kind of problems for other network topologies (e.g., trees, meshes of forests, cycles or cycles of trees).

For the maintenance of geometric formations, our aim is to develop appropriate local strategies and to analyze them theoretically as well as experimentally, starting with simple scenarios. For example, we are interested in knowing how fast the sensors may move so that the other sensors do not lose contact.

For energy related topics, we will enrich our systems with more technical constraints of real networks and perform experiments in SunSPOT-based and iSense-based testbeds.

In our future work on multicasting, we will consider a slightly more realistic problem version where antennas have a fixed set of transmission levels. We will also develop a distributed algorithm that adaptively changes initial multicast solutions during the operation time of the network in order to maximize its lifetime.

An interesting line of research is how to *implement* the strategies profiles described in [CKS08b] in a distributed network. It would be interesting to see how the necessary correlation device for realizing the threats could be implemented, and to see how the agents of the network could autonomously *learn* the proper threat point. Finally, as in [ADGH06], we would like to address similar issues to the case of coordinated (rather than unilateral) deviations of agents in the network.

We plan to extend on previous results about the guidance of mobile devices that employ the medial axis of an implicitly described geometric region [BGJ05, Krö08]. These results focus on routing issues in networks without localization service. We have two closely connected targets here: First, agreeing on where to spend the scarcely available communication resources provided by the mobile devices (seeking a balance between the benefit of having a supporting device in a region in need, and the cost of rearranging the devices). Second, relocating the devices to their new position, using the network for guidance.

Having already done a significant progress [CKV07, CKK07, KV07, CKV08], concerning scheduling distributed computation, we will try not only to determine which is the best approximation an algorithm can achieve here, but also to give a characterization of all possible mechanisms.

3 Task 3.2: Discovering and tracking resources

3.1 Motivation and problem description

To discover resources in an unknown terrain, we consider a group of mobile sensors exploring the terrain. We assume that they have a device to create a map of their direct surroundings. By moving, a sensor can extend its local map of the terrain. Additionally, sensors within a given communication distance can exchange their maps and use this information for cooperation in the group. The sensors start in a common home base and they have accomplished their task when they have explored the whole terrain.

A more general problem is to assign subtasks which appear in the terrain to sensors. We consider mobile sensors in the plane which have a local view only and can see tasks within their range. They have to decide which task they assign themselves to and by this cooperatively solve as many tasks as possible.

For another problem consider mobile devices moving and generating local traces. The fixed network can track these objects. We assume the absence of precise location information, yet we wish the network to predict where tracked objects are heading. Furthermore, the network should identify interesting areas (where objects move into it or appear from it) outside of its coverage. The network should then employ mobile units to extend its surveillance into such areas.

A new point of view of the problem of target tracking assumes that the tracker is mobile. The network nodes just record and judiciously spread traces about observed target presence in their vicinity; this information is then used by the tracking agent to locate the target by following the traces left at sensors. This tracking technique reduces the energy consumption of the nodes and can track single or multiple targets. The intuitive idea behind our tracking protocol is inspired by a natural model: the way a tiger tracks an antelope in a Savannah.

We will furthermore look into data propagation protocols for Wireless Sensor Networks which maximize the network's operational life and improve its performance. Network's work load should be fairly assigned to each node. Moreover, protocols must detect the different energy reserves and adapt the probabilistic data propagation scheme followed. Also, the algorithm should handle different priority of sensory data. Furthermore, we plan to investigate adaptive mobility strategies for collecting sensory data by mobile robotic sinks, in a way that ensures fairness and serves the different network regions according to their device density and the data traffic they produce. Finally, obstacles avoidance enhancements can be added to our methods in order to avoid early failures of the propagation process.

When nodes are localized and the path is built based on the geographical position of the destination and of one hop neighbors, there exist shortest path propagation protocols. We will consider the behavior of path finding algorithms in the case where there are obstacles. Because of the limitations of sensor network devices and the lack of global network knowledge, our purpose is to find in a distributed manner the shortest possible obstacle avoidance path between two points using only local geographical information. Our solution is to exploit a simple geographic routing strategy to route data while exploring the communication graph. A guaranteed delivery routing strategy is used in rescue mode to route data when the simple strategy fails. The simple geographic strategy learns about the region of the network where it is inefficient and tries to go around.

3.2 State of the art and previous work

As previous work for the exploration of unknown terrain, we analyzed strategies for tree exploration. Here the group of sensors starts in the root of the tree and in each time step each sensor may move along one edge to a neighboring node. Communication between sensors is only allowed between sensors positioned in the same node. Since the tree is unknown to the sensors in the beginning, we analyzed our strategies by means of on-line analysis. We could prove lower bounds for competitive factors and provide algorithms solving this problem [DKMS06, DKS06, DLS07, Dyn07].

The problem of assigning subtasks to sensors is related to the k-server problem. In the on-line version, requests appear as points in a metric space one after another. They have to be satisfied by moving one of k servers to this point. The goal is to choose the server moved to a request in a way that the overall traveled distance of the servers is minimized. Deterministic algorithms with competitive factors of $2k - 1$ have been developed, where k is a lower bound for this factor.

The biggest obstacle in the classical scenario of target tracking is the absence of precise location and distance information. There are results on the generation of spatial information from noisy distance and angle estimates [BGMS06], providing both impossibility results and working heuristics. Means to provide topological maps (here, triangulations) of point sets without using localization are explored in [KMS08], where a distributed Delaunay triangulation variant is introduced, which is stable even when the participating nodes disagree in what they perceive as each other's position. Finally, exploring unknown areas with actively moving devices is discussed in [FS07].

The new approach of target tracking mimicking the way a tiger tracks an antelope in the savannah leads to the design of the Tracing Handling Tracking Protocol (THTP) discussed in [MNPR08a, Pow08, MNPR08b]. The protocol defines how the intensity of the traces decreases with time and when they are spread in the network. The aim is to build an intensity gradient from nodes to the target; the mobile tracker moving in the direction of increasing traces intensity. The spreading mechanism amounts to build a tree of order two. A heuristic mechanism is suggested to ensure that the tree quickly covers the entire monitored region. Since the process is dynamic an inhibition mechanism is also suggested to reduce the number of loops.

For the energy aware data propagation problem there is a great variety of different protocols for WSN's. For the majority of these protocols the model assumes that (i) the energy capabilities of the devices are homogeneous (i.e. all devices start with the same amount of energy) and (ii) that they are monotonously decreasing (i.e. they cannot recharge their energy) (iii) the number of participating devices remain fixed for the full duration of the system (iv) the importance of data is the same over all data sources in the network.

Previous research on data propagation include: a) multi-path data propagation schemes that are probabilistically optimized to choose best paths and achieve satisfactory energy-latency trade-offs [CDNS06b] b) power saving schemes, that can be integrated with the routing algorithm, which are sensitive to incremental deployment of heterogeneous sensors and sense the local network conditions to accordingly adapt [CKN08] c) probabilistic energy-balanced data propagation schemes that appropriately trade-off cheap but slow and expensive but fast propagation patterns [ENR06] d) for networks where the sensors move, we propose in [KN08a] adaptive data dissemination protocols that basically exploit high mobility as a cost-effective replacement of flooding.

In the situation where obstacles are present, a solution consists in the detection of the obstacles and early avoidance. A first approach [MLNR08a, MLNR07] for obstacle detection is based on node's decisions' analysis. It takes place at the node level and considers the behavior of the node. The strategy is to avoid propagating data through a neighboring node that previously switch to rescue mode to guarantee delivery. Further routing decisions will avoid the paths containing the nodes that are mainly routing in the rescue mode.

A probabilistic protocol, called interacting urns process [LS08], relies on local computation and approximate the generalized eigenvector of the communication graph corresponding to the second largest eigenvalue. Spectral knowledge on the communication graph is known to be relevant to many aspects of dynamical network control. We suggest application to a) the clustering of the communication graph and b) the computation of virtual coordinates.

3.3 First results

In case of exploration of unknown terrains, we could prove better competitive factors for tree exploration under some knowledge of the tree. This is realistic in many real scenarios, since for example in buildings the number of rooms may be known in advance. First results for the assignment problem show that the problem is np-hard in most cases even if the sensors are controlled by an entity with global knowledge. We have furthermore developed a constant factor approximation algorithm for this problem using resource augmentation [BDKP09].

[CKS08a] presents three new distributed, probabilistic data propagation protocols for Wireless Sensor Networks maximizing the network's operational life and improve its performance. The keystone of these protocols' design is *fairness*. All the protocols, EFPFR, MPFR and TWIST, emerged from the study of the rigorously analyzed protocol PFR. The experiments conducted show that our proposals manage to improve PFR's performance in terms of *success rate*, *total amount of energy saved*, *number of alive sensors* and *standard deviation of the energy left*.

We have designed and evaluated a topology-sensitive and energy aware adaptive data propagation method ([AVN08]). The probabilistic data propagation algorithm considers a candidate set as forwarding nodes. The message is transmitted to the whole group and the forwarding node is chosen after transmission using a distributed algorithm. The node decides whether to transmit with a certain probability, so that the message transmission is conditioned to the individual local node decisions. An obstacle avoidance component is included according to which nodes of the candidate set are enforced to transmit messages using the flooding mechanism in order to spatially spread propagation. In this way, robustness is assured in the sense that a large propagation front is created to bypass the obstacles. Adapting the exploration idea from the reinforcement learning approaches, nodes select, under certain circumstances, a candidate from the list at random, to explore new routes towards the destination and avoid depleting the best routes.

Another result relates to adaptive random walks for collecting sensory data by mobile sinks ([KNP08]). We assume a single mobile sink and propose an algorithm for traversing the network servicing nodes in a balanced manner. The traversal is performed on a per region basis, the sink visits regions one after another. It determines the optimal stopping time needed to serve an area with respect to the whole network. In this way, we achieve fast coverage of the network and fairness in the serving time of each region.

Concerning obstacle detection and early avoidance, behavior based evaluation methods have one drawback: the dependency on incidence point of the message trajectory with the obstacle. In [MLNR08b] we avoid this dependency by introducing a new metric for evaluation: the relative position of the neighbors toward the destination. We analyze the properties of this algorithm and its impact on the optimality of the path. The evaluation method is based on the neighborhood rather than behavior: a node will mark itself as non-optimal toward a certain direction if it does not have optimal neighbors toward that direction. The impact of this method on the network is the apparition of a marked convex region along some of the faces of the object. If possible the routing strategy avoids to propagate data through the convex marked region. Data appropriately go round this region and avoid the discovered obstacle.

3.4 Research targets

Concerning the exploration on unknown terrain, we want to extend our strategies of tree exploration to geographic terrains. One idea is to cover the terrain by a graph, for example a grid with holes at positions of obstacles. This grid can then be explored by means of one of our strategies. We want to use our Smart Teams Simulator, which is developed in WP4, to experiment on these scenarios and to test whether our provably good algorithms for graphs also work well in more realistic, geographic scenarios.

For the assignment problem, future plans are to adapt the existing global algorithm to work in a local scenario. We furthermore want to consider a slightly different model: Here, each sensor can potentially be assigned to each task. Tasks have gravity forces which decrease with distance and the sensors move according to those forces.

Concerning target tracking, we will start by assuming the devices are covering the edges of a polygon that represents the environment. We will develop strategies to triangulate the polygonal area. The nodes will use the triangulation to obtain locally valid traces for objects passing by. These traces will then be used to produce an exact map of the environment. Therefore, overlaying all the traces produces a map of where the objects can go. By identifying subpaths where all objects avoid an invisible obstacle, the network can generate a floor map of the area it lives in. An important aspect is taking tracking errors into account. A physical obstacle can be deduced as all the traces do not cross it. Finally, we will develop exploration strategies that are used to extend the surveillance area

The protocol THTP proved to be efficient and suitable in many situations. However, formal analysis of the protocol is still lacking. We plan to investigate to properties of the propagation tree in terms of coverage and speed of deployment. To analyze the propagation of traces mechanism, we expect to find the quantity of information that a given trace give to the mobile tracker about the target position.

We plan to investigate alternative adaptive, resource-aware data propagation schemes that achieve additional performance gains, as well as adaptive sink mobility strategies that lead to better energy-latency trade-offs by sensing and exploiting the available resources in the network. The construction of a marked region supporting the optimal obstacle avoiding routing will be continued. Theoretical investigations are planned to prove optimality of the data path. Moreover, optimal strategies have to be designed to route data generated inside the marked region.

Concerning the spectral analysis of the communication graph based on local communications, we plan to extend our past work [LS08]. We plan to compare the new clustering method with common clustering strategies. We also plan to investigate the quality of the virtual coordinate computed with this protocol. A first step is to ponder whether simple and good routing strategies, like greedy routing, are supported by the virtual coordinate.

4 Task 3.3: Reacting to dynamically changing environments

4.1 Motivation and problem description

The general motivation for this task is to deal with an environment that develops over time. An interesting special case of this very generic setting is when the environment moves the sensor nodes, for example an ocean with currents. This leads to an unpredictable movement of the sensor nodes, which means that the communication graph changes constantly. Even the set of nodes monitoring a static event must adopt to the evolving situation.

Maintaining a communication structure: If the passive sensors (observers) are exposed to an environment which moves them, it is necessary to maintain a network infrastructure to keep the network working. Since the transmission distance of the nodes is limited, it can for example be necessary to have active moving nodes, called relays, which keep the network connected. Therefore, we need strategies for the movement of the relays. These strategies have to be local, since every node has only a limited view on the scenario and the environment is changing. A similar situation is when there exist areas with a higher communication demand than what the static network can provide. The network has to agree where to put relays, and then decide to relocate some of them when the need arises. Furthermore, the network has to collaboratively guide the relays to their new designated locations. Another problem in the same context occurs when the network has to monitor an event, which may be mobile as well. The network has to make sure that at all times nodes close to the event are monitoring it and have access to the information that was collected so far. This establishes a meme in the event's vicinity, whose position changes with the event, and which is shared by nearby nodes.

Facility Location: A second scenario we want to consider is the facility location problem in a dynamic environment. Here, a subgroup of the sensors has to be chosen to offer some service, for example a communication link to a base station, to the other sensors. It takes some persistent cost for a sensor to provide the service. The other sensors must then connect to one service provider, their cost depends on this distance. The goal is to minimize the overall cost in a scenario where all the sensors move in an unpredictable way. During the execution, the sensors providing the service might need to change.

Avoiding dynamic obstacles: Finally, we wish to investigate cases where the physical environment contains obstacles of various shapes and types that affect the connectivity of the network. Obstacle avoidance is a well-studied subject in distributed computing in general. However, there has not been much attention towards the cases where obstacles may change their size and shape during the execution of the system. For example, think of a train passing through the network deployment area, or even a road inside the deployment area that is crossed by cars. These obstacles have a temporary effect on the nodes that are situated in the area they appear. Those nodes cease to function throughout the lifespan of the dynamic obstacle by which they are capped. Such obstacles may also capture areas whose density drops significantly over time (due to physical faults, permanent or temporary, as well as software decisions, i.e., power saving schemes that put sensors to sleep).

4.2 State of the art and previous work

In our previous work on communication, we have investigated local strategies for the movement of relays in the simplest scenario where they have to connect only two observers. Only one of them was assumed to be affected by the dynamic environment [DKMS07]. For relocating and guiding relays to sparse areas of the network, previous results employ the medial axis of an implicitly described geometric region [BGJ05, Krö08]. These results focus on routing issues in networks without localization service, where the medial axis is defined via given network boundaries and the hop count metric. They can be extended for safely guiding mobile devices. In [FS$^+$06], we analyzed distributed strategies that maintain *Hovering Data Clouds*, i.e., dynamic information pieces attached to events. The network ensures that there are always carriers for the information, preferably those close to the event, even if they are moving.

The facility location problem has been extensively studied in combinatorial optimization and operations research. In general, the problem is known to be $\mathcal{NP}$-complete. For the Euclidean case, there exists a randomized PTAS [KR07]. However, the facility location problem has also been investigated in other settings, for instance in distributed [GLS06, MW05] and dynamic settings [Ind04], but not in the kinetic setting.

FRONTS researchers have significantly contributed to the state of the art research concerning the avoidance of obstacles before the start of the project. In [PN07] we have enhanced greedy methods with an inertia component that tends to propagate data in the current direction and as we show is able to bypass even hard concave obstacles efficiently.

4.3 First results

For the communication problem, we have improved our previous results and proved that the communication line between the two observers always keeps close to optimal [KM09]. Furthermore, we have considered a static scenario with several observers, which are not affected by external movement. We developed strategies for the relays to build up a communication infrastructure between the observers [MS08].

Concerning the facility location problem, we have developed an efficient global event-based algorithm using the kinetic data structure framework which computes a constant factor approximation at all times using polylogarithmic time per event [DGL08].

In [KN08b] we propose a method that senses the boundaries of an obstacle and appropriately disseminates data about it in the network so that future data propagation avoids it efficiently. An average case analysis over possible data source locations demonstrates significant performance gains, in terms of the path length followed (and thus energy and latency). Another result is a non-trivial extension of our trust-level methods in [MLNR08b] to cope with multiple source-destination-pairs and also mobile obstacles ([MLNR08c]).

4.4 Research targets

So far, our local strategies for relays to maintain a communication infrastructure worked in a synchronous time model. Now, we plan to adapt our strategies to a continuous time model and to a time model where in each time step the sensors can move a distance of ϵ. This implies different and more realistic cost measures like the traveled path lengths or the time the sensors take to build up a communication infrastructure. We furthermore plan to extend our work in the static case (observers do not move) as well as in the dynamic case, where the observers are affected by a dynamic environment. For safely guiding mobile devices, we want to extend previous results on routing issues in networks without localization service. We have two closely connected targets here: First, agreeing on where to spend the scarcely available communication resources provided by the mobile devices (seeking a balance between the benefit of having a supporting device in a region in need and the cost of rearranging the devices). Second, relocating the devices to their new position, using the network for guidance. Here, the global task of supporting network functionality comes into play again: The transition must be done in a way without consuming communication bandwidth in regions that are underequipped, as this could create a vicious circle, where sending a mobile device to re-establish connectivity somewhere breaks it in places along the way. In the event surveillance scenario, we will adopt our previous result, which specifically dealt with vehicles maintaining traffic-related information such as jam or congestion warnings. We will generalize the methodology to abstract event data in networks with passive mobility, with little assumptions on the network's and the event's behavior.

For the kinetic facility location problem, we want to adapt our global algorithm to work in a local setting.

Finally, we intend to model obstacles using stochastic processes, or deterministic recurrent patterns. We wish to use these models to investigate their effect to the performance of the data propagation mechanism used, addressing some fundamental issues that are present in sensor networks. Also, we plan to further exploit trust based methods for early obstacle avoidance under limited local knowledge and with low overhead.

5 Task 3.4: Trust

5.1 Motivation and problem description

Handling the problem of mutual trust among resource constrained devices is the core of this task. In severely resource constrained networks, trust establishment is a crucial step before for nodes of the network may start to share resources (be it energy needed to perform computation and communication, or information gathered from the environment).

We follow distinct approaches to trust. One is based on credentials and trust between two (or more) parties is derived from each party possessing the "right" credentials. The core technical problem is how credentials are distributed and how they are attested as authentic. In the game theoretical approach we consider selfish agents playing a strategic game; in this setting, the strategies of an agent determine her behavior, and we study if and when trust emerges from the solutions (i.e., the equilibria) of the strategic game. The main technical challenge is to design the system in such a way that trustful and cooperative behavior is an equilibrium and thus trust emerges as a result of rational selfish choices. Roughly speaking, in one approach trust derives from identity (as attested by the credentials) and in the other from behavior. We also use the language of first (and second) order logic to express trust properties and study the evolution of these properties as the system grows. Such a definition seems to be especially difficult to apply within the realm of the new computing paradigm that seems to have emerged over the last few years and that are of object of study of this project.

In all of our approaches, we consider a dynamic network, where agents may join and leave at any time and the trust maybe revoked. Keeping in mind the constraints imposed on agents' memory and computation capabilities we assume (not without relation to real-life scenarios) that some more powerful entities are scattered in the network (as similar approach is also taken in Task 2.3).

5.2 State of the art and previous work

There is much ongoing research on the development and analysis of new trust management models for complex and dependable computer systems. Blaze *et al.* in [BFL96] proposed the application of automated trust mechanisms in distributed systems. A number of schemes for secure information systems based on automated trust management have been proposed (see, for example, [EGB02, HBC01]).

The game theoretic approach to cooperation has been pioneered for small artefacts by the work of Buttyán et al. [BHS05]. Here the Nash equilibrium of a specific game between two sensors each wishing to communicate with its base station were investigated and it was shown that some of the Nash equilibria would lead to cooperation spontaneously (that is, without external incentives).

We have already started the study of trust within the realm of dynamically changing complex computing systems by using the first and the second order language of graphs [LMSS07a, LMSS06].

A previously published paper [KKRR07] discusses problematics of key distribution in WSN for securing node-to-node communication. A problem of maintaining internal security of the system after one sensor has been captured and key extracted was addressed. This work is a point of departure for further explorations in this domain.

5.3 First results

Key management. Based on [KKRR07], we conducted further research in the topic of multi-level key scheme. Our preliminary results in this area show that with negligible communication and energy cost, one can substantially improve resilience against attacks based on collecting the keys from corrupted devices. Given the severe constraints on memory and computation imposed on the small artefacts, we also looked at how more powerful entities might help in achieving the desired goal. First approaches to the problem of securing RFID tags with broadcast random strings resulted in a sketch of a scheme secure against very basic attacks from the queue problem. This field is currently investigated to extend this resistivity towards more sophisticated exploits.

The game theoretic approach. We have studied communication in wireless networks from a game theoretical point of view, by introducing an interesting class of games: the "Interference Games." The utility of a player is given by two factors:

the first factor depends on whether or not the node is successful in transmitting, and the other one on the energy spent for the transmission. This second factor is used to model the fact that players have limited energy, as in a scenario of interest to the project (small artefacts with limited batteries). In [AMPP08] we show that the game has no *pure Nash equilibrium* and *mixed Nash equilibria* are either unfair (in the sense that one player has a much larger expected payoff than the other players) or have social welfare 0 (that is, the sum of the expected payoff of the two players is 0 which far from the optimal). This state of things calls for the investigation of other notions of equilibrium. We show that there are *Sink* and *Correlated* equilibria with value of social welfare close to optimal. We then move to the study of Repeated Interference Games in which two players play (possibly infinitely) many instances of the Interference Game. We show that there exists a fair *Subgame Perfect Equilibrium* with maximal social welfare. This game-theoretic approach can be used also for Task 1.3-Cooperation models and algorithmic consequences (see deliverable D1.1) and Task 3.5-Reliable Communication (see next Section).

Logical and Graph-Theoretic approach. In [LMSS07b], we formally defined trust properties (that are apt for the application at hand - e.g. the separator property) and study the evolution of the property as the system grows. These properties can be written either in the first or the second order language of graphs. Based on this viewpoint, we provide a new framework for defining trust through formally definable properties that hold, almost certainly, in the limit in randomly growing combinatorial structures that model "boundless" computing systems (e.g. ad-hoc networks), drawing on results that establish the threshold behavior of predicates written in the first and second order logic.

5.4 Research targets

Local random strings. Our aims are twofold. First, we are going to investigate the concept of broadcasting random strings as means for tracking mobile devices. This can be utilized for e.g. making sure that readouts an agent is contributing are in fact coming from the surveillance area the agent claims them to be. An alternative use of this technique can be in toll gathering on motorways, where an automobile gathers random tokens from readers scattered along the road and reports them at the tollbooth.

The other track is to utilize such randomness for securing passive RFID tags from being read by eavesdroppers. This concept can be particularly interesting for solving the so-called queue problem, where tags are read at the head, but two adversaries, one at the head and the other somewhere further down the line, cooperate relaying messages between reader and some tag.

Multilevel key schemes. Using building blocks elaborated in Task 2.3, we are going to develop a security system where valid session key is easily deliverable from previous (lower-level) keys by means of simple, yet difficult to break, computation of a one-way trapdoor function. We envision a system, where agents posses keys of different "levels" and bring them to a common level for communication. Moreover, we are going to investigate the possibility of *branching* the linear structure of such keys by parameterizing the key-generation function.

This scenario should lead to a tree-like key-dependencies structure, where each key closer to the root can be derived from its child, but not the other way up. To allow top-down traversal we are planning to introduce a network of more powerful agents possessing necessary information to reverse the trapdoor function. On the whole, the system infrastructure will allow dynamic generation of new keys when needed (i.e., when a new party joins the network), but also allowing for revocation of such keys (by "cutting off" a branch of the tree with the given key) or "resetting" the whole system in case when too many keys have been captured to sustain the system's integrity.

Game-theoretic approach. We plan to continue the game-theoretic approaches to emerging trust and cooperation in complex systems. We believe that the notions of Repeated Games and Subgame Perfect Equilibria and the population protocol model [AAC+05, AAD+06, AAER07, AAE06, AAFJ05, DGFGR06, FJ06] are interesting research lines.

We also plan to continue the study of the model proposed by [BHS05] in which sensor networks owned by different authorities share the same physical space and the authorities could benefit from cooperating. We plan to augment the work of [BHS05] by considering limited battery power and required quality of service. It would be interesting to study these problems by keeping into account spatial relations between players (that is, players interact, or are more likely to interact, with players that are "close") like in [ST97] where the general Prisoner's dilemma on a lattice has been studied.

Graph-theoretic approach. One possible research direction could be the design of a kind of reductions among second order properties (which do not necessarily have a 0/1 behavior), the Kernel being the archetypal one, that can be used to show that other properties also do not have a threshold behavior (much like NP-completeness results) avoiding the complexity of the proof for the Kernel property.

Another possible direction of research is to define random graph models that seem to hinder the appearance of threshold properties written in some second order logic fragment. This would help, for instance, to define non-desirable properties (for trust) and show that they cannot possibly hold with probability 1 as the system grows.

6 Task 3.5: Reliable communication

6.1 Motivation and problem description

In any wireless system a fundamental objective is to achieve reliable communication among participating devices. Network reliability is especially important for low cost wireless devices that suffer from high failure rates and may be exposed easily to an adversarial attack due to limited physical protection. On the other hand, designers of communication protocols for wireless networks assume an idealized environment: the transmission is faultless, messages are delivered instantaneously, the devices cannot be captured by malicious parties, etc. The reality is different: messages cannot be delivered instantaneously, wireless devices cannot transmit and receive at the same time, and they need time to switch between transmission modes. Further, we have to take into account the conflict between energy efficiency and fault tolerance. They have contradictory requirements on redundancy. Moreover, there is no way to protect them physically from damage, capture, cloning, etc.

6.2 State of the art and previous work

Communication engineering offers some solutions to cope with conflicts in communication demands. One of the standard methods is “reserving” communication slots by sending a beacon signal that can be checked by other participants. Recently, we have discovered techniques that enable us to improve significantly the chance of faultless execution of this algorithm, even if the number of competing devices cannot be approximated [CKZ06], [CKZ08a]. However, one of the major remaining problems is that there are no solutions that would handle self-organization of the network when the faults are selective and independent on different links. This problem is particularly important under poor propagation conditions due to eg. an extreme environment setting. The previous research (including our contributions, e.g. [KKR06]) solves the problem of a malicious adversary, but only if the transmission faults are global, and not limited to a group of nodes. Reliable communication algorithms that trade-off energy efficiency, latency and fault-tolerance have been proposed, using probabilistically optimized redundant paths for data propagation ([CDNS06a]).

6.3 First results

Introductory research has been done in the field. Our first contribution is the paper [Kik08], where we propose an effective distributed sorting algorithm in a single-hop, synchronized radio network. In the model we assume that any message is received by the addressee with probability $p \leq 1$. Additionally, for the model with $p = 1$, a *recursive bisection ordering* algorithm is introduced which allows any station that comes out of sleep mode to establish its rank in the network using at most $4 \log n$ energy units for listening. Experimental results in the latter scenario for $p \leq 1$ were obtained.

In the paper [CKZ08b] we consider an ad-hoc network consisting of devices that try to gain access for transmission through a shared radio communication channel. We consider two randomized leader election protocols (the first one is due to Nakano and Olariu [NO00]; the second one is due to Cai, Lu and Wang [CLW03]) and introduce modifications which give us an improvement in both of them. We show that choosing a discrete starting point of transmission in a non-uniform way leads to a simple algorithm that substantially outperforms the previous techniques of resolving channel access problems. We provide methods to optimize values of parameters used.

6.4 Research targets

Adversary resistant network connection paths. Many application scenarios require setting up connections over a network of wireless nodes. For confidentiality and authentication of messages one can set up secure connections between consecutive nodes. By capturing a single node (a fair assumption is that it is not tamper-proof), an adversary can capture the entire communication going through it. To alleviate this, we envision a protocol where a communication link is implemented via dynamically altering multi-node paths and on each stage of message transmission there are at least two devices that carry the message according to a secret sharing scheme. The design guarantees that in order to break security of such a connection, one has to capture the right nodes on the same level. Apart form tailoring cryptographic tools, which partly leverages from contributions of Task 2.3, we have to provide security guarantees against an adversary and show that traffic analysis does not lead to paths discovery. For this merit, a number of probabilistic models has been tested yielding complex combinatorial problems. Solving them should provide a strong basis for designing a communication protocol.

Fault resistant basics wireless networks algorithms. Self-organization of networks necessary to set up communication framework requires executing some basic procedures such as leader election or ranking. The problem is that we cannot guarantee a common view for all participating nodes - transmission faults and diverse errors can selectively influence different nodes. They may also result from adversarial activities (even with no understanding of the roles of attacked nodes and without breaking cryptographic protection). Existing algorithms break down in this situation and produce inconsistent results leading to chaos in the network operation. In particular, the faults can be caused by an adversary aiming at destruction of network organization. In our work to date we have investigated some algorithms with the assumption that every point-to-point connection fails with a certain probability and independently of the other connections existing at the same time. Methodology used therein seems to be applicable for other basic algorithms, such as data aggregation or network management. Also, as mentioned above, for some algorithms empirical data has been gathered revealing interesting results, which require formal justification. An interesting link to research conducted in other tasks (especially Task 3.4) is that we may consider a "failed communication" case whenever the other party decides to defy rather than cooperate and hence limits eg. communication possibilities of a given node. It follows that we can in fact *estimate* the value of p given previous behavior of the node and its neighbors. Another problem of this kind is to establish a reliable communication infrastructure that is robust against temporary failures of nodes and changes regarding nodes leaving and entering the network.

Adversary resistant basics wireless networks algorithms. Smooth operation of a network can be corrupted by selfish behavior of the nodes executing the protocol without causing any faults in communication. For instance, in order to increase chances in leader election a node may emulate several nodes. The existing algorithms are not resistant against such strategies; moreover, it seems that there is no way to solve this problem without taking into account peculiarities of radio communication. We have promising results in designing an algorithm that decreases chances of a single station trying aggressively to become a leader. Further such solutions are necessary, in particular dealing with coercion between misbehaving nodes cooperating in order to gain control over the network.

7 Task 3.6: 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.

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