SEVENTH FRAMEWORK PROGRAMME
THEME 3
Information and Communication Technologies

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

Deliverable D3.3:

A Set of Design Rules and Technical Recommendations for Adapting to the Dynamic Environment

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

Responsible Partner: UPB
Report Preparation Date: Monday, May 1, 2011

Contents

1 Introduction

Workpackage 3 for the FRONTS project considers societies of tiny artefacts that are deployed to a dynamic environment. Therefore all algorithms and techniques developed in this workpackage have to be able to deal with a permanently changing environment. Due to this fact and the nature of wireless networks, topology, energy, robustness, and safety aspects are of concern.

This deliverable follows the line of research within WP3: In the first year, we have developed research targets and goals and identified the most important aspects to work on. The results were presented in five tasks in Deliverable D3.1. During the second year, we have developed a set of schemes for adapting to the dynamic environment which are collected in Deliverable D3.2. There, we identified four main functionalities which support the effective cooperation of tiny artifacts in dynamic environments. Those are

- Functionality A: Desirable network properties
- Functionality B: Robustness against faults and attacks
- Functionality C: Energy-awareness
- Functionality D: Task- and role- assignment

Within each functionality we proposed several schemes. In the third year we focused on four of these schemes and developed them further in order to derive a set of Design Rules and Technical Recommendations. Those are collected in the following sections. The first two schemes, considered in Sections 2 and 3, deal with large societies of mobile sensors, connected dynamically by wireless devices. Whereas WP1 explores properties of general models of dynamics like the Dynamic Sensor Field, we focus on a more problem-oriented view on dynamics. In Section 2 we consider formation problems of large societies of mobile sensors. This topic was subsumed under Functionality A in the previous deliverable D3.2. Our new focus is on energy efficient strategies, building a bridge to Functionality C. Also the next two sections deal with energy efficiency. In Section 3 we consider energy efficient data collection in mobile systems with unpredictable mobility. In Section 4, we present an important aspect of the Functionality B, namely coping with Sybil-Attacks. Finally, Section 5 focuses on static systems and extremely simple devices and explores the benefits of duty-cycling and energy efficient techniques for multi-casting.

Each section starts with an introduction in the topic based on previous deliverables, which explains its importance for the work package. Then we present a corresponding set of design rules and technical recommendations. Finally we give an overview of the technical reports within FRONTS which are relevant to the topics described in this deliverable. For an overview of the entire list of 16 publications of WP3 we refer to the FRONTS Technical Report series.

2 Building and maintaining formations of mobile sensors

2.1 Motivation and problem description

When considering large societies of mobile sensors, a basic question is which formations these sensors can build and maintain under dynamics, and which abilities the sensors must have to reach this goal. Since we deal with small sensors with limited capabilities and limited energy, we want local algorithms: each sensor has a limited range from which it gathers information. In this deliverable we focus on two formation problems. As a first problem, we want the sensors to form a line: We are given two stationary nodes and n mobile sensors with a limited viewing range. The mobile sensors form a chain between the two stationary nodes and are used to forward communication packets between the nodes. In the beginning the chain can be arbitrarily long and winding. We just assume that it is connected and each sensor knows its predecessor and successor. We design and analyze strategies to transform the chain into a shortest one in order to have a most efficient communication infrastructure. The easiest strategy is to move each mobile sensor iteratively to the midpoint between the two neighbors. Here, we consider a round based model: In each round all sensors act synchronously. First they observe the relative positions of their neighbors, and then they compute the midpoint between the two neighbors and subsequently move there. Note that, in the meantime, the neighbors also move.

A second formation problem which we considered is the gathering problem. The goal is to move all robots to one common point, which is not predetermined. Again, the robots have only a local view and should need as few capabilities as possible.

Since energy is the main critical resource in wireless settings, we are interested in strategies in order to minimize the two main energy consumers. These are the energy that is consumed for measurements, which corresponds to the number of rounds until the straight line is reached, and the energy that is consumed for travelling, which is proportional to the maximum distance a mobile sensor travels during the execution.

2.2 A Set of Design Rules and Technical Recommendations

In the first and second year we have analyzed several strategies in some models which capture several aspects of the physical world. We were able to give linear upper and lower bounds on the number of rounds for the problem of forming a line in a slightly modified model, where sensors can be excluded from chain [KM09]. For the gathering problem, we proposed a first algorithm with a quadratic bound on the number of rounds, when using an asynchronous round model and rather powerful robots [DKM10]. Here the sensors do not move to the middle of the neighbors, but calculate a new position based on the positions of all neighbors in their range. In the last year of the project we were able to achieve the bound of $O(n^2)$ even in the stronger synchronous model with weaker robots [DKL$^+$11].

For the first problem of building a chain, when moving to the middle of the neighbors, we already showed an upper bound of $O(n^2 \log n)$ [DKLM06], and also a lower bound of $\Omega(n^2)$. In the last year of FRONTS we were able to match the lower bound of $\Omega(n^2 \log n)$ [KMadH11].

The results described above relate to the number of rounds. This can be interpreted as the energy consumed for sensing the environment. However, we possibly spend too much energy for travelling, since a mobile sensor maybe moves too far, because we do not sense the neighborhood often enough. However, we were able to show that the worst case distance that a sensor moves is $\Theta(n^2)$ [BDKM10] for the Go-To-The-Middle strategy.

The distance travelled can be improved, if the step length is shortened. Letting the step length tend to 0 (a model which we call *continuous* and analyze for a similar strategy [DKKM10]), results in a worst-case maximum travelled distance of $O(n)$ [BDKM10], which is optimal for any strategy. However, the energy that is spent for sensing is not upper bounded in this case.

In order to optimize the energy consumption, we are looking for a good value for the step length. Normalizing the viewing distance to 1, the maximal step length is a value $\delta \in [0, 1]$. Note that for $\delta \to 0$, this corresponds to the continuous strategy, where the energy spent for travelling is optimized and for $\delta = 1$ this is the original strategy, where the energy for sensing is optimized. We proved that fixing δ leads to a worst case number of rounds of $\Omega(n^2 + \frac{n}{\delta})$ and $O(n^2 \log n + \frac{n}{\delta})$ when Go-To-The-Middle is performed until the straight line is reached. Furthermore, we showed that the travelled distance is bounded by $\Theta(\delta n^2 + n)$[BDKM10]. Plugging in δ reveals that $\delta = \Theta(\frac{1}{n})$ optimizes both values concurrently. An overview is given in [DFKMadH10]. This result shows that reducing the step length can be useful to reduce the overall energy consumption. We believe that this technique can also be applied to other formation problems.

Design rule: In order to cope with the changes in the environment, local algorithms are useful. The reason is that they have the property that local changes in the environment interfere only with the actions of nearby sensors, but still allow for energy efficient formation strategies.

Technical recommendation: Explore the trade-off between the step length and the number of rounds of local strategies for formation problems in order to reduce energy consumption.

2.3 Related FRONTS Technical Reports

- FRONTS-TR-2011-20 [KMadH11] A new approach of modeling local strategies for building short chains of sensors is introduced. The strategy is interpreted as a series of matrix operations, allowing to apply known results from Markov Chain theory. As a result, a lower bound of $\Omega(n^2 \log n)$ for the convergence time of the Go-To-The-Middle strategy is given.

- FRONTS-TR-2010-33 [BDKM10] We propose to bound the step length of the Go-To-The-Middle strategy to δ. We show asymptotically (almost) tight bounds for the number of rounds till convergence and the worst-case maximal distance travelled by a mobile sensor in dependence of n and δ.
- FRONTS-TR-2010-24 [DKKM10] We introduce a continuous time model, where the sensors can observe their environment all the time and adjust their movement. We analyze the strategy, where the sensors move towards the angle bisector of the neighbors, and prove that the maximal distance travelled is bounded by $O(n)$.
- FRONTS-TR-2011-5 [DFKMadH10] We review several strategies for placing sensors in geometric surroundings. We provide complexity theoretic insights and lower bounds as well as global and local approximation algorithms.
- FRONTS-TR-2011-17[DKL$^+$11] We consider the local gathering problem in the synchronous time model. Although it was known for a decade that an algorithm (based on the movement to the smallest enclosing circle) converges, no runtime bounds were known. We proved a runtime of $O(n^2)$ for n robots, which is tight.

Related first and second year FRONTS Technical Reports

- FRONTS-TR-2008-14 [MS08].
- FRONTS-TR-2009-5 [KM09].
- FRONTS-TR-2010-8 [DKM10].

3 Data collection in mobile wireless networks

3.1 Motivation and problem description

We considered wireless sensor networks where nodes have random and changeable mobility patterns. We study the problem where a particular node, called the base station, collects the data generated by the sensors/nodes. In such networks usually nodes are battery powered and it is crucial to limit the energy consumption due to the transmissions in order to increase the operability time of the network (network lifetime). In some settings, the nodes are able to transmit the messages directly to the base station by using the wireless transmissions, but it is known that the energy required to transmit a data is at least quadratic of the distance it needs to be transmitted. Therefore data collection happens in a multi hop way which significantly reduces the amount of the energy spent on transmissions. There is a large amount of research on energy aware data gathering in wireless sensor networks with static nodes, but the existing algorithms can not be applied to networks with mobile nodes without adaptation and in most cases can not be applied at all. In some applications data delivery delay is important to be small, i.e. after being generated the data should get to the base station as soon as possible. Also in mobile networks it is not possible to guarantee the delivery of all the data generated by the sensors to the base station, loss of data can not be avoided therefore it should be minimized.

3.2 A Set of Design Rules and Technical Recommendations

During the design of the algorithm we considered the above criteria (energy efficiency, data delivery delay, data delivery rate) and tried to find a trade off between them. The main idea of the proposed algorithm is to diffuse the generated data by the sensor nodes to many nodes, in such a way that the probability that at least one of the nodes, carrying the data, will get close enough to the base station and deliver the data is larger than a predefined threshold. We consider that the nodes have a limited memory and after getting their memory full, they need to drop data for saving newly generated ones. The nodes manage the memory as a FIFO queue. The main advantage of our algorithm over the existing ones is that the nodes do not use information about their positions (which is a very costly information in mobile network); they also do not need to know where the base station is located (it also can be mobile). The nodes approximate the probability that they will deliver the data contained and take the decisions whether to forward the data to another node or not by using only the count of the previously (successfully) delivered and dropped data. These counters are kept for each cell of the memory. We proceeded to the simulation of the algorithm and we showed the effectiveness of the protocol. We also compared the performance with the recent algorithm. In our simulations we used eight different types of random and changeable mobilities. The results show that the algorithm is highly scalable, all the above defined properties (energy efficiency, data delivery delay, data delivery rate) become stable when the number of nodes in network grows. The data delivery rate for the proposed protocol is shown, through the simulations, to be $97\% - 99\%$ while the recent algorithm in the same settings of the network (except it assumes that nodes know their positions) has a $70\% - 80\%$ delivery rate. The comparison of energy consumption of the algorithms shows that the proposed algorithm has an advantage in dense networks while in sparse networks the recent algorithm is preferable in terms of energy consumption. The recent algorithm has a lower data delivery delay than the proposed algorithm which is achieved by high data transmission in dense networks. The proposed algorithm has a significant data delivery rate and low energy consumption, it is highly scalable. All this holds because of highly mobile nodes of the network. In future works the networks with lower mobility will be considered.

Our work on Multiple Roomba Message Delivery with Random Walks (see Section 4.3 of Deliverable D4.6) presents first experimental results on the basic technical capabilities to use such data collection strategies.

Design rule: Data gathering protocols in highly mobile wireless networks are able to achieve good performance without having access to positions of nodes. Since the positions of nodes are expensive information, try to avoid using them.

3.3 Related FRONTS Technical Reports

- FRONTS-TR-2010-39 [ALJ10] In this paper we propose a data gathering protocol for mobile wireless sensor networks. The comparison of results of the proposed and recent algorithms show that the proposed algorithm, without using the location information of nodes, outperforms the existing one in many aspects.

Related first and second year FRONTS Technical Reports

- FRONTS-TR-2009-61 [LSR09]

4 Coping with Sybil attacks

4.1 Motivation and problem description

A device identity is a crucial concept in many wireless systems. It has a significant influence on reliability, completeness and fairness of such systems. Identity can be used to grant a device a role, some rights, data access or to exclude it in case of its malfunction.

Sybil attacks, i.e. cloning and forging identities is a common and major problem in ID-based systems, especially when we talk about heterogeneous systems with multiple providers and societies of such devices. In general it is assumed that an adversary that came into possession of an artefact can get all the information stored on it including secret keys and infect it with malicious code to make it work for the adversary. Identity of a device in systems of weak devices is usually not protected in any advanced way (certificate etc.) because of physical constraints of small artefacts (memory space, processor speed, communication bandwidth in highly populated areas, . . .). Thus malicious nodes can easily steal an identity of another node to come into possession of its privileges or produce a new one in case of being blocked or in order to simulate more devices for gaining more control of the network, and in particular a bigger share of the communication bandwidth.

4.2 A Set of Design Rules and Technical Recommendations

We followed the research line made in [GKKK09] and addressed the problem of detection and counteraction against a Sybil type attack performed in order to increase the fraction of adversarial nodes in a network. We have shown in [KK10] that in case of a Sybil attack during the execution of a leader election algorithm the chance of detection differs dramatically depending on whether we consider a model with collision detection (CD) or without collision detection (noCD). We assume that the adversary is able to construct and transmit legitimate messages. The only fraud it can perform is the frequency of its participation. We have proved that it is impossible to detect an aggressive adversary (even an extremely aggressive adversary, which participates all the time) even in very long statistical observations. On the other hand, we have shown that it is relatively easy to detect it in the CD model. Such a detection makes it possible to counteract effectively Sybil attacks.

Technical recommendation: Analyzing statistical data for detection of Sybil attacks may be skipped in the noCD model as it turns out to be ineffective. If risk analysis indicates a necessity of detection of Sybil attacks, then the hardware used should support collision detection mechanisms. Not much computational power is needed in the later case.

Another line of detection mechanism is based on physical properties of the communication channel. We have constructed protocols that enable detection of fraud even in the noCD model.

For devices working according to IEEE 802.11 standard we utilize the inability of being in transmitter and receiver mode simultaneously. Another requirement is that there is no independent channel between malicious devices (i.e. they communicate only via a shared radio channel and the communication protocol does not provide room for hidden channel messaging). For relatively small networks (of realistic size) the scheme is effective and eliminates malicious devices one-by-one. The solution is not appropriate for networks of arbitrary size as the number of messages exchanged is superlinear. The detection mechanism is based on the fact that malicious devices emulating multiple identities miss some information (state of the channel: single, noise) during transmission.

Technical recommendation: A communication protocol (in particular using any form of randomness) should be immune against building hidden channels, if Sybil attacks are to be repelled. If the risk of Sybil attack is high and the number of nodes is moderate, then the designed detection mechanism should be implemented at the expense of communication overhead.

In [KK10] we present a protocol that utilizes another physical constraint of small artefacts - their limited computational power. The main concept is that each device has to verify its identity by spending a significant amount of time for calculating a so called Proof of Work (POW) for some on-line distributively generated challenge. The time required to calculate the POW for an identity is so significant that it is impossible to calculate it for more than one identity. Fake identities without calculated POW are not considered legitimate and cannot participate in the protocol.

Two versions of the protocol are presented. One is simpler and more effective in terms of reliability, but since it requires listing of all devices it is appropriate for small size networks. The other version involves more randomness and gives the adversary some room for unfair behavior (some legitimate stations will decide not to participate – that increases the fraction of adversarial stations in the set of active devices) but can be applied for arbitrary size networks.

Technical recommendation: Utilize limited computational power of devices by designing protocols so that emulating multiple identities would require an unreachable amount of resources. In some cases the fact that energy is limited can be used in a similar way.

4.3 Related FRONTS Technical Reports

- FRONTS-TR-2010-37 [KK10] We address the problem of sybil type attacks on a leader election procedure in single-hop radio networks. We focus on the detection and counteraction possibility. We prove that it is not possible to detect adversarial behavior in the noCD model while it is relatively easy in the CD model. We propose two algorithms counteracting adversarial behavior, basing on computational constraints of the devices. To certify its identity the device has to deliver a proof of some computational effort POW. The first algorithm is very effective but more complex and thus can only be applied in networks with a small number of devices. The other one is more universal but slightly less effective.

Related first and second year FRONTS Technical Reports

- FRONTS-TR-2009-38 [GKKK09]

5 Self-synchronized duty-cycling and minimum energy multi-casting

5.1 Motivation and problem description

Nodes in mobile ad-hoc and sensor networks are generally equipped with batteries, which makes energy a scarce resource. Different techniques of *distributed cooperation* can be employed for energy saving. One of them is known as *duty-cycling*, or sleep-awake cycling. These techniques concern the use of schedules for sensor nodes to switch between (at least) two states: being awake and being asleep. When being awake they can perform their normal duties such as, for example, monitoring the environment, processing and sending data, etc. When sleeping, sensors reduce their energy spending, for example, by switching off the radio transceiver. For certain applications it may be convenient that sensor nodes synchronize their activity periods. Another aspect concerns the harvesting of energy from the environment. Increasingly many sensor network deployments use energy harvesting equipment to extend their lifetime. However, energy sources such as sun and wind power are quite variable due to changing weather conditions.

A related fundamental problem in sensor networks arises when one node is required to transmit data to a subset of the other network nodes. This scenario is known as multi-casting. Again, an important requirement when realizing a multicast request is spending as little energy as possible. This problem is known as the minimum energy multi-cast (MEM) problem. A special case of the MEM problem is the minimum energy broadcast (MEB) problem. In this specific scenario, information must be sent from a source node to all other nodes in the network. Solving the MEM, respectively the MEB, problem can be seen as a form of distributed cooperation between the sensor nodes. Unfortunately, existing problem formulations from the literature do not take into account specific aspects of radio transceivers that are nowadays used in popular hardware. More specifically, the current problem formulation allows the adjustment of the transmission power to any desired value, while most of the radio transceivers in practice only offer a limited number of discrete sending power levels.

5.2 A Set of Design Rules and Technical Recommendations

Concerning self-synchronized duty-cycling, the main aim of our research was the development of a mechanism that allows sensor networks to perform duty-cycling in an adaptive, self-organized way, without any central control. This is in contrast to the traditional fixed duty-cycling mechanisms that are commonly used in the relevant bibliography. During the last project year, we first explored the behavior of the proposed system in detail. For this purpose we used discrete event simulation, and we considered scenarios in the Euclidean plane with static as well as mobile sensor nodes. In all cases sensor nodes are equipped with omni-directional antennas. In the case of mobile networks the random way point model is used as the mobility model. Finally, it is assumed that sensor nodes are equipped with tools for harvesting energy such as, for example, solar panels. Concerning static sensor networks, the different scenarios that we considered include grid-shaped networks as well as topologies based on random geometric graphs. In addition, we considered networks with different numbers of sensors, both in the case of static and mobile networks.

The last aspect of the work on self-synchronized duty-cycling concerned the development of a protocol for real sensor networks. This protocol was implemented in Wiselib, a generic library of algorithms for sensor networks. The experiments were performed on the sensor network simulator Shawn. These experiments show that the proposed duty-cycling mechanism is able to adapt to varying energy conditions. Moreover, they indicate that the system is very robust against packet loss. This work was done in cooperation between the project partners from the Universitat Politècnica de Catalunay (UPC, Barcelona, Spain) and the Braunschweig Institute of Technology (IBR, Braunschweig, Germany).

Design rule: The mechanisms of distributed cooperation exhibited by social insects, flocks of birds and fish schools, seem to be well-suited for the development of distributed, self-organized algorithms for the management and control of networks of tiny artefacts.

Concerning the minimum energy multi-casting problem, the last year of the project was dedicated to a specific subproblem, namely the minimum energy broadcast (MEB) problem. Moreover, we considered the case of omni-directional antennas. The classical MEB problem, which is well-studied in the scientific literature, considers a transceiver model that allows the adjustment of the transmission power to any desired real value from zero up to the maximum transmission power. However, when specifically considering sensor networks, a look at the currently available hardware such as SunSPOTs or iSense sensor nodes, shows that this transceiver model is not very realistic. Therefore, we introduced a re-formulation of the MEB problem under the consideration of a realistic transceiver model. In this transceiver model transmission power levels are chosen from a finite set of possible ones. An adaptation of the best algorithms available in the literature for the classical MEB problem has shown that their relative performance changes substantially when applied to the MEB problem considering the more realistic transceiver model.

Technical recommendation: The results of the work on minimum energy broadcasting have shown that problems arising in networks of tiny artifacts should be modeled as closely as possible. As shown, it may happen that some algorithms suffer important performance losses when the problem is only slightly changed.

5.3 Related FRONTS Technical Reports

- FRONTS-TR-2010-34 [HBB$^+$10]. In this work we present a protocol for self-synchronized duty-cycling in wireless sensor networks with energy harvesting capabilities. The protocol is implemented in Wiselib, a library of generic algorithms for sensor networks. Simulations are conducted with the sensor network simulator Shawn. They are based on the specifications of real hardware known as iSense sensor nodes. The experimental results show that the proposed mechanism is able to adapt to changing energy availabilities. Moreover, it is shown that the system is very robust against packet loss.

- FRONTS-TR-2011-15 [HB11]. Ants are generally believed to follow an intensive work routine. Numerous tales and fables refer to ants as conscientious workers. Nevertheless, biologists have discovered that ants also rest for extended periods of time. This does not only hold for individual ants. Interestingly, ant colonies exhibit synchronized activity phases that result from self-organization. In this work, self-synchronization in ant colonies is taken as the inspiring source for a new mechanism of self-synchronized duty-cycling in mobile sensor networks. Hereby, we assume that sensor nodes are equipped with energy harvesting capabilities such as, for example, solar cells.
- FRONTS-TR-2010-35 [HB10]. Most, if not all, works from the literature dealing with minimum energy broadcasting in wireless ad-hoc networks such as sensor networks consider transceiver models that allow the adjustment of the transmission power to any desired real value from zero up to the maximum sensing range. However, looking at the currently available hardware shows that these transceiver models are not very realistic. In this work we therefore adapt the currently best available algorithm for minimum energy broadcasting for a more realistic transceiver model which only offers few different levels of emission power.

Related first and second year FRONTS Technical Reports

Concerning self-synchronized duty-cycling:

- FRONTS-TR-2008-34 [HBM$^+$09].
- FRONTS-TR-2009-53 [HB09c].
- FRONTS-TR-2009-54 [HB09b].

Concerning minimum energy broad/multi-casting:

- FRONTS-TR-2008-54[HBF08].
- FRONTS-TR-2008-59 [HB08].
- FRONTS-TR-2009-70 [HB09a].

References

$*$ [ALJ10] Hakob Aslanyan, Pierre Leone, and Rolim Jose. Data propagation with guaranteed delivery for mobile networks In *9th International Symposium on Experimental Algorithms (SEA 2010)*, pages 386 – 397. Springer Verlag, May 2010. FRONTS-TR-2010-39.

$*$ [BDKM10] Philipp Brandes, Bastian Degener, Barbara Kempkes, and Friedhelm Meyer auf der Heide. Building short chains of mobile robots locally with a bounded stepwidth 2010. preprint, wwwhni.uni-paderborn.de/alg/publikationen, FRONTS-TR-2010-33.

$*$ [DFKMadH10] Bastian Degener, Sándor Fekete, Barbara Kempkes, and Friedhelm Meyer auf der Heide. A survey on relay placement with runtime and approximation guarantees *Computer Science Review*, 2010. FRONTS-TR-2011-5.

$*$ [DKKM10] Bastian Degener, Barbara Kempkes, Peter Kling, and Friedhelm Meyer auf der Heide. A continuous, local strategy for constructing a short chain of mobile robots In *Structural Information and Communication Complexity, 17th International Colloquium, SIROCCO*, 2010. FRONTS-TR-2010-24.

$*$ [DKL$^+$11] Bastian Degener, Barbara Kempkes, Tobias Langner, Friedhelm Meyer auf der Heide, Peter Pietrzyk, and Roger Wattenhofer. A tight runtime bound for synchronous gathering of autonomous robots with limited visibility In *SPAA 2011: Proceedings of the 23rd Annual ACM Symposium on Parallelism in Algorithms and Architectures*, 2011. FRONTS-TR-2011-17.

[DKLM06] Miroslaw Dynia, Jarosław Kutyłowski, Paweł Lorek, and Friedhelm Meyer auf der Heide. *Maintaining Communication Between an Explorer and a Base Station*, volume 216 of *IFIP International Federation for Information Processing*, pages 137–146. Springer Boston, 2006.

$*$ [DKM10] Bastian Degener, Barbara Kempkes, and Friedhelm Meyer auf der Heide. A local $O(n^2)$ gathering algorithm In *SPAA '10: Proceedings of the 22nd ACM symposium on parallelism in algorithms and architectures*, June 2010. FRONTS-TR-2010-8.

[GKKK09] Zbigniew Golebiewski, Marek Klonowski, Michal Koza, and Miroslaw Kutylowski. Towards fair leader election in wireless networks. In *ADHOC-NOW '09: Proceedings of the 8th Interna-*

tional Conference on Ad-Hoc, Mobile and Wireless Networks, volume 5793 of *LNCS*, pages 166–179. Springer-Verlag, September 2009. FRONTS-TR-2009-38.

[HB08] ∗ H. Hernández and C. Blum. Energy-efficient multicasting in wireless ad-hoc networks: An ant colony optimization approach In *Proceedings of ISWCS 2008 – International Symposium on Wireless Communication Systems*, pages 667–671. IEEE Press, Piscataway, NJ, 2008. FRONTS-TR-2008-59.

[HB09a] ∗ H. Hernández and C. Blum. Ant colony optimization for multicasting in static wireless ad-hoc networks *Swarm Intelligence*, 3(2):125–148, 2009. FRONTS-TR-2009-70.

[HB09b] ∗ H. Hernández and C. Blum. Asynchronous simulation of a self-synchronized duty-cycling mechanism for mobile sensor networks In *Proceedings of BADS 2009 – Workshop on Bio-inspired Algorithms for Distributed Systems*, pages 61–68. ACM press, New York, NY, 2009. FRONTS-TR-2009-54.

[HB09c] ∗ H. Hernández and C. Blum. Self-synchronized duty-cycling in sensor networks with energy harvesting capabilities: the static network case In F. Rothlauf et al., editor, *Proceedings of GECCO 2009 – Genetic and Evolutionary Computation Conference*, pages 33–40. ACM press, New York, NY, 2009. FRONTS-TR-2009-53.

[HB10] ∗ H. Hernández and C. Blum. Ant colony optimization for broadcasting in sensor networks under a realistic antenna model In B. Filipic and J. Silc, editors, *Proceedings of BIOMA 2010 – 4th International Conference on Bioinspired Optimization Methods and their Applications*, pages 153–162. Jozef Stefan Institute, Ljubljana, Slovenia, 2010. FRONTS-TR-2010-35.

[HB11] ∗ H. Hernández and C. Blum. Foundations of ANTCYCLE: self-synchronized duty-cycling in mobile sensor networks *The Computer Journal*, 2011. FRONTS-TR-2011-15. In press.

[HBB$^+$10] ∗ H. Hernández, T. Baumgartner, C. Blum, M. J. Blesa, S. Fekete, and A. Kröller. A protocol for self-synchronized duty-cycling in sensor networks: Generic implementation in wiselib In S. Das et al., editor, *Proceedings of MSN 2010 – The 6th International Conference on Mobile Ad-hoc and Sensor Networks*, volume 2, pages 134–139. IEEE Press, Piscataway, NJ, 2010. FRONTS-TR-2010-34.

∗ [HBF08] H. Hernández, C. Blum, and G. Frances. Ant colony optimization for energy-efficient broadcasting in ad-hoc networks In M. Dorigo et al., editor, *Proceedings of ANTS 2008 – 6th International Conference on Ant Colony Optimization and Swarm Intelligence*, volume 5217 of *Lecture Notes in Computer Science*, pages 25–36. Springer-Verlag, Berlin, Germany, 2008. FRONTS-TR-2008-54.

∗ [HBM+09] H. Hernández, C. Blum, M. Middendorf, K. Ramsch, and A. Scheidler. Self-synchronized duty-cycling for mobile sensor networks with energy harvesting capabilities: A swarm intelligence study In *Proceedings of SIS 2009 – IEEE Swarm Intelligence Symposium*, pages 153–159. IEEE press, Piscataway, NJ, 2009. FRONTS-TR-2008-34.

∗ [KK10] Marek Klonowski and Michal Koza. Pow -based approach to sybil-type attacks in wsn FRONTS-TR-2010-37, 2010.

∗ [KM09] J. Kutylowski and F. Meyer auf der Heide. Optimal strategies for maintaining a chain of relays between an explorer and a base camp *Theoretical Computer Science*, 2009. FRONTS-TR-2009-5.

∗ [KMadH11] Peter Kling and Friedhelm Meyer auf der Heide. Convergence of local communication chain strategies via linear transformations In *Proceedings of the 23rd ACM Symposium on Parallelism in Algorithms and Architectures (SPAA)*, 4 - 6 June 2011. FRONTS-TR-2011-20.

∗ [LSR09] Pierre Leone, Nikoletseas Sotiris, and Jose Rolim. Optimal data gathering paths and energy balance mechanisms in wireless networks In *Distributed Computing in Sensor Systems, 6th IEEE International Conference, DCOSS 2010, Proceedings*, pages 288–305, 2009. best paper award.

∗ [MS08] F. Meyer auf der Heide and B. Schneider. Local strategies for connecting stations by small robotic networks In *IFIP International Federation for Information Processing*, volume 268, Biologically-Inspired Collaborative Computing, pages 95–104. Springer Boston, 2008. FRONTS-TR-2008-14.