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AEOLUS

Algorithmic Principles for Building Efficient Overlay Computers

Deliverable D5.0.3

Subproject report on the activities of months 25-36

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Contents

1 Objectives, state of the art and major achievements

The main goal of SP5 is to design, evaluate and also implement efficient algorithmic solutions for offering high quality, reliable, stable and scalable services and basic primitives to heterogeneous wireless mobile extensions of the overlay computer in global computing scenaria. During the third year, we investigated quite different wireless extensions, including wireless networks of mobile users, sensory systems of wireless tiny devices embedded in the ambient environment, mobile robots as well as fixed, fast interconnection topologies (such as radio, grid and mesh networks). To provide such algorithmic solutions we tried to study in a complementary manner several critical, strongly related issues and aspects, like the efficient management of critical resources (like energy, bandwidth, the wireless access medium) for QoS provisioning, the dynamic management of the network topology (both in the context of network design as well as on-line) and the management of mobility and failures.

Our protocols provide in fact some basic functionalities to the upper layers of the overlay computer, such as primitives for information exchange between mobile users, battery optimization for tiny wireless devices, bandwidth management for streaming high volumes of data, tracking mobile users, localization of wireless devices, routing data between wireless nodes in the presence of obstacles, collecting sensory readings by mobile robots, designing optimal fixed topology networks for wireless access, optimizing the use of smart antennas etc.

Some highlights of our work that significantly extend the relevant state of the art include: a) new combinatorial abstractions as well as non-uniform failure models (both random and worst case) for highly dynamic networks b) provably very efficient algorithms for broadcast communications that outperform previous ones in the state of the art c) efficient collaborative methods for tracking mobile entities as well as to early avoid obstacles, d) adaptive data dissemination schemes which exploit sensory mobility e) optimal wireless access network design f) near optimal methods for smart antenna optimization.

We below describe in more detail the main results in each WP. Also, deliverables D5.1.3, D5.2.3 and D5.3.3 are detailed expositions of the work in each of the three thematic aspects of the SP.

2 Description of the work carried out within each workpackage and related references

A total of 37 Technical Reports were produced during year 3. In particular, 10 TRs in WP5.1, 16 TRs in WP5.2 and 17 TRs in WP5.3 (6 of them related to more than one WPs: 3 in both 5.1 and 5.2, 2 in WP5.2 and 5.3, while 1 in both 5.1 and 5.3). It is worth mentioning that 10 reports relate to SP2 as well, 5 to SP1, 9 to SP6, 3 to SP4. Out of those, 26 papers are already published: 5 papers appeared in Journals, 20 in Conferences (including high quality ones like TCS, DMTCS, PODC, SPAA, TOCS, DCOSS, ADHOC-

NOW, GLOBECOM, 1 MSWIM, PIMRC, ICC, Computer Networks, Networking etc), 1 as a Book Chapter, while the rest 11 are currently under evaluation in both Journals and Conferences. A technical description of some characteristic results follows in the context of the WP they relate to.

2.1 WP 5.1 Resource management and quality of service

According to the SP5 objectives, our annual research activity for WP 5.1 has focused on the following issues:

- Studying different wireless network models that simulate well the heterogeneous scenarios where global computing functionalities use to work on. This task has been carried out from both analytical and experimental points of view.
- Providing dynamic-resource and role-assignment strategies that guarantee some connectivity properties of the wireless network and, at the same time, the node energy consumption is minimized.
- Designing communication protocols for mobile ad hoc networks in presence of unpredictable and non-homogeneous faults.

A novelty of our approach is that Issues 2 and 3 above have been also studied together, as a *multi-criteria* optimization problem that considers several levels of the network architecture.
We remind (see also the previous Deliverables of WP 5.1) that our approach departs significantly from standard theoretical research in ad hoc networks. This is due to the aim of implementing some particular functionalities characterizing wireless heterogeneous systems arising in the context of *Global Computing*. The main features studied in this WP concern both *(i)* the adopted network model and *(ii)* the particular techniques adopted for the design and the analysis of the proposed algorithmic solutions.

As for the first issue, the major novelty of our research lies in considering networks having *non-uniform* node fault probability, a feature that especially characterizes networks with very high dynamics. Furthermore, we consider self-organized, heterogeneous sensor networks where different roles and functionalities are assigned to nodes according to their physical wireless connectivity and sensing characteristics. We indeed identify the need of organizing a wireless/sensor network according to the tasks appropriate for each wireless node based on their initial deployment in the network.

As for the second issue, the global computing applications require the design of efficient communication protocols which are very flexible and easy to implement in order to be adapted and applied in hybrid networks where nodes may have different technology and energy power. For this reason, rather than designing very complex and involved protocols, we focus our attention on the design and performance analysis of simple, fully-distributed protocols based on simple techniques such as the greedy and divide-et-impera ones.

In particular, we provided the following efficient and robust services: (a) important communication primitives (like broadcasting) (b) mobile communication services (c) QoS provisioning and fairness (d) how to share the wireless medium (e) bandwidth management for exchange of high volumes of data.

Interacting with SP2, we have studied how to allocate the resources of bandwidth and capacity in wireless mesh topology networks, by investigating the round weighting problem that consists in computing the most efficient allocation of bandwidth to connections [7, 8, 9, 10].

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2.2 WP5.2 Network design and topology control

During the third year we focused on the following aspects: a) how collaboratively the network topology can track a moving entity as well as to early avoid obstacles b) how topology control is affected by the need to minimize wireless interference and collisions c) how broadcast protocols can handle very dynamic topology changes d) how to optimize the use of smart directional antennas e) how to design power saving schemes that adapt to topology dynamics.

A new dynamic topology control approach is proposed for solving the problem of target tracking [11, 16]. The main idea is to use passive sensors in the tracking process whose task is to generate and diffuse "traces" of the target(s) presence. The tracking agent that greedily follows trace gradients to locate the moving target performs the active role. The aim of this new approach is to broaden the scope of applications to track multiple targets moving in-group or independently.

A consistent research effort is devoted to the problem of avoiding interferences resulting from simultaneous transmissions (collisions) of nearby wireless devices. Significant results are obtained for the data gathering problem and the design of wireless mesh networks (WMN) [7, 8, 9, 10, 13, 14].

Besides appropriately scheduling the transmissions, smart directional antennas decrease interferences by reducing the number of common links of neighbour sensors. However, the configuration of the antennas has to be chosen in order to maintain the network connectivity. In [3], efficient algorithms for the connectivity problem in wireless networks using directional antennas are provided.

Efficient implementation of wireless sensor networks require to save energy and keep the network functional for as long as possible. A new modelling assumption and distributed algorithms are given in [4] that consider incremental deployment of heterogeneous nodes.

The trade-off between the energy consumption and the performances of protocols is investigated in [2]. An efficient algorithm, which provides range assignment schedule, is designed and analyzed. To take into account the time-dependence among links in dynamic networks, a new model is introduced in [4], called Edge-Markovian evolving graphs. A more general class of random graphs in introduced in [5] which is especially relevant when mobility is high.

We propose strategies that avoid to route data toward an obstacle or a void. In [15], we propose and compare different mechanisms for finding optimal paths. The basic heuristic forwarding algorithm uses the information about previous forwarded data, stored locally in nodes memory, to avoid non-optimal paths directed toward an obstacle. The algorithm uses a reputation-like mechanism.

Cooperating with SP2, we studied design aspects (regarding topology and collisions) of wireless mesh networks, a broadband and ubiquitous access network to collect information from mobile clients [7, 9, 13, 12, 14].

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2.3 WP 5.3: Mobility and Fault Tolerance

During this year, we provided additional algorithmic solutions and services relevant to the global computing scenaria addressed in SP5. In particular, our algorithms concern the following aspects: a) the efficient collection of sensory data using mobile robotic sinks, b) how to achieve QoS and fairness in mobile wireless systems, c) how to efficiently perform broadcast communications in the network and d) how to adaptively propagate information when the tiny wireless devices themselves move dynamically.

In particular, in [4, 5] we investigate broadcast communication in radio networks under very high network dynamics (especially failures and mobility). We extend our previous AEOLUS work by now studying more realistic types of dynamics, focusing on the strong dependence of wireless links on time. To capture link variability, we introduce the novel model of edge-markovian evolving graphs and investigate the efficiency of flooding by providing tight bounds for communication time.

In [1, 11] we study how to efficiently collect sensory data using a mobile robotic sink. We provide novel network dynamics descriptions based on stochastic structural network properties, as well as global indicators of dynamicity (such as network stability, connectivity and emergence of communities). We introduce the concept of rendez-vous regions, to improve performance by decoupling data dissemination from data collection

In [9] we are using balanced network traversals to combine fairness and QoS in mobile networks. We provide new randomized mobility strategies that achieve good trade-offs by distributedly employing frequency biases (to favor visiting less explored network regions) together with adaptive stop times (to probabilistically favor staying more in dense areas which tend to produce more data traffic).

In [8] we investigate information propagation in wireless networks where the sensors themselves (not just the sinks or robots) move. We focus on application scenaria when mobility is very diverse and dynamic. We propose new, local (but quite accurate) evaluations of the current mobility level in the network (wrt both speed and spatial diversity). We also provide data dissemination schemes exploiting mobility in an adaptive manner, by e.g. propagating less data when mobility is high and propagate data favoring faster nodes moving widely in the network.

In [6, 7], we provide protocols for efficient and robust broadcast services in Delay Tolerant Networks which are special types of of mobile ad hoc networks. We are also proposing a new abstract modeling (that of evolving graphs) to capture the dynamics of certain wireless networks, focusing on the construction of low cost routing paths for efficient communication. This is joint work with SP2 (in particular, with WPs 2.1 and 2.2), in the sense that the SP2 research is taking into account the crucial impact of mobility and dynamics studied in WP5.3.

Further to the above algorithmic solutions, we designed and implemented (in view of the integration work in SP6) some related simulation environments. In [3], we provide TRAILS, an ns-2 extension toolkit focusing on high network dynamics (mobility, failures, obstacles). In [2], we propose MOMOSE, a flexible and easily extendable software environment for simulating mobility models, focusing on heterogeneity of mobility profiles and obstacle presence. Also, in [14, 15, 16, 17] we worked on distributed simulations of small programmable objects, sensor-based multi-player pervasive games, as well as an extension of the WebDust architecture. Finally, in [10], we present an overlay architecture relying on a mobile ad hoc network, called Ariwheels. This is SP2 work that especially takes into account the mobility impact studied in WP 5.3.

It is worth noting that our research aims at enabling (at the algorithmic level) an integration of complementary technologies and platforms, e.g. in the complementary use of sensory devices and portable devices such as mobile phones, in the smooth integration in the network of robotic sinks, in the integration with fast, fixed topology network backbones, via radio stations. Furthermore, we emphasize a methodological shift in our work in this third year, namely considering mobility both as crucial network parameter as well as a useful algorithmic design element. In particular, our research on mobility of sensory devices themselves and how to exploit mobility to improve performance, is one of the first such attempts in the state of the art.

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3 Cooperation among workpackages and cooperation/relation to other subprojects

During the 3rd year, we tried to enhance cooperation and research interactions between the groups involved in SP5 across the various WPs. We below mention some typical examples of this cooperation.

The combinatorial properties (independence, hamiltonicity) for resource management developed in WP5.1 are relevant and can be exploited at the collision avoidance needed in the context of topology management in WP5.2, as well as the mobile data collection aspects in WP5.3. The probabilistic mobility solutions to the information propagation problems provided in WP5.3 contribute to WP5.2 towards balancing the energy loading and prolong the network lifetime. Also, power saving strategies at the device level in WP5.2 can been integrated with routing protocols in WP5.3 and contribute to the energy optimization in WP5.1. Furthermore, the smart antenna optimization in WP5.2 is complementary to range assignment in WP5.1. At a global level, it seems that the high dynamics introduced by failures, mobility and obstacles are a crucial, horizontal aspect among the WPs in SP5 which we tried to further cultivate and integrate during the third year.

There has also been cooperation between SP5 and other SPs. We tried to reinforce awareness and interactions with SP2, as pointed out by the last year's review panel report. In particular, work done in SP2 regarding e.g. wireless interconnection topologies (especially for mesh networks) and shared resources (bandwidth, capacity) are very relevant to the algorithmic optimizations designed in SP5. Also, our WP5.3 work for data dissemination among highly mobile end users in SP5 uses data replication, caching and queue management techniques that primarily originate from SP2 context. Further to SP2, SP5 research interacted with SP4, in the context of security aspects (especially tracking, during the third year) in sensor networks, and the more realistic (non-uniform) failure models and worst case (adversarial) models and obstacle presence studied in SP5.

Also, there has been significant cooperation with SP1 in using and extending powerful distributed computing techniques, randomized methods, stochastic models, combinatorial models and quantities etc. In particular, the following lines of work: a) the study of important combinatorial properties (independence, hamiltonicity) in random interesection graphs and the new model itself b) the new combinatorial model of edge-markovian dynamic graphs c) the investigation of coloring problems in various settings and d) the adaptive random walks, all of these lines above have independent combinatorial and algorithmic interest and are inspired by and extend paradigm and principles of SP1.

Furthermore, there is active cooperation and fruitful interactions with SP6 in the context of designing and implementing the experimental p2p/sensory test-bed.

Several groups involved in SP5 cooperate intensively and fruitfully, in various ways, including short and longer visits, common research and coauthorship of papers, common editorial activities (journals, books etc), organization of major relevant conferences. Members of several groups of SP5 continue successfully running ALGOSENSORS (the International Workshop on Algorithmic Aspects of Wireless Sensor Networks), which aims to strengthen the theoretical and algorithmic aspects of the wireless sensor networks research, with an emphasis on Europe. Also, it is worth noting that the 4th edition of the DCOSS (IEEE International Conference on Distributed Computing in Sensor Systems) series was held in 2008 in Greece, as a result of cooperation of several SP5 partners, like

CTI, Geneva and Rome.

To mention a few examples of SP5 interactions: J. Rolim of U. of Geneva has visited CTI, J. Rolim and S. Nikoletseas have visited Rome (Andrea Clementi), P. Spirakis has visited Josep Diaz (Barcelona). Also, Luminita Moraru (U. of Geneva) has visited S. Nikoletseas in Patras, a visit that already led to common research on obstacle avoidance between the two groups. In general, the common research and co-authorship between SP5 partners has been closer and broader (involving more partners) during the third year. It is worth noting that during the third AEOLUS year, a closer cooperation between SP2 and SP5 partners took place, in the form of exchange of visits, brainstorming, and by organizing common workshops and events. In particular, SP2 people from UoI met with CTI, while researchers from Geneva, CTI, UoP and Rome visited the CNRS team.

4 A brief description of SP management activities (coordination, integration, dissemination)

SP5 is headed by CTI, which in close, fruitful cooperation with the WP leader) periodically monitor and coordinates the overall work of SP5. There is frequent communication between groups and researchers of SP5, in several ways (email, phone, visits, informal meetings at conferences and workshops). This way the SP5 partners discuss specific plans for the WPs and coordinate cooperation and interactions needed at the SP level and between different SPs. It is worth noting that during the third AEOLUS year, a closer cooperation between SP2 and SP5 partners took place, as suggested in the review panel report. Interactions between the 2 SPs were facilitated by exchange of visits, brainstorming sessions, and by organizing common workshops and events. Several aspects considered in SP2 are inspired by SP5 related issues and contribute nicely to them, and vice versa. Also, we had a closer interaction with the SP6 partners towards a better integration of our SP5 testbed with the global AEOLUS testbed.

Dissemination activities included several actions, like participation in conferences to deliver talks on AEOLUS research, publications of relevant journal papers, delivering tutorials at relevant schools, organizing meetings, workshops and conferences. Also, strong links to leading US groups are further reinforced (like with UCLA, Berkeley, USC, Ottawa, U. of Illinois, SUNY, Johns Hopkins). Some focused dissemination actions and cooperations with relevant industries (Ericsson, Siemens) have been further cultivated. In particular, we tried to increase awareness and feedback between our algorithmic perspective and the broader networking community. Several SP5 partners (Geneva, UDRTV, CNRS, CTI) have published papers and participated to important networking conferences, like the IEEE Global Communications Conference (GLOBECOM), the ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM) and its Workshops MobiWac and PEWASUN. Also, SP5 people (CTI) organized MSWiM 07 in Greece, while CNRS people organized the 7th International Conference on Ad-Hoc Networks and Wireless (ADHOC NOW 08) in Nice. It is worth mentioning that ADHOC

NOW 08 colocated with diverse yet relevant events, like the 19th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2008) and the International Workshop on Ad hoc Ambient Computing (AdhocAmC 2008).

It is also worth noting that our SP5 p2p/sensory testbed was successfully reported and got useful feedback by the researchers of the International Workshop on Sensor Network Engineering (IWSNE) and the International Workshop on Wireless Sensor Network Deployments (WiDeploy), that were jointly organized with the DCOSS 08 Conference, as well as its Demo Session that featured demonstrations of technology, platforms, algorithms and applications of wireless sensor networks.

5 How reviewers' comments and recommendations in the second review panel report have been addressed

The review comments and our respective actions follow:

Comment: The need to address how SP5 may influence SP2 has been thought out and should generate dedicated work on year 3.

Action: During the third AEOLUS year a closer cooperation between SP2 and SP5 partners took place. Interactions between the 2 SPs were facilitated by exchange of visits, brainstorming sessions, and by organizing common workshops and events. In particular, several aspects considered in SP2 are inspired by SP5 related issues and contribute nicely to them, and vice versa. As a result, a total of 12 SP2 technical reports are also contributing to SP5 issues and are briefly reported in the 3 thematic SP5 deliverables (4 TRs WP5.1, 5 TRs WP5.2, 3 TRs WP5.3). In particular, we mention the following important aspects of thematic interaction: a) delay tolerant and vehicular networking studied in SP2 (WPs 2.1 and 2.2), are crucially affected by the presence of mobility and dynamics studied in WP5.3 b) weighted routing problems that deal with optimizing the bandwidth and capacity critical resources (WPs 2.2 and 5.1) c) WP2.2 mesh networks design aspects, that are related to the interconnection networks for wireless access studied in WP5.2.

Comment: SP5 will study during the 3rd year smart antennas which is a coming technology that can improve the utilization of the radio frequency spectrum.

Action: We indeed have studied antennas that can vary their transmission range and orientation in a wireless network. In particular, we first modeled directional antennas of the ESPAR technology, which consist of a steerable central source that can radiate in a region reasonably approximated by a cyclic sector. We also investigated the aspect of how to maintain connectivity with the minimum possible range for a given angular speed.

Comment: The integration of the SP5 testbed and components into the main AEOLUS testbed developed within SP6 is highly encouraged.

Action: We extended and further enriched the SP5 sensory testbed and demo for p2p overlays over multiple, heterogeneous sensor networks (we implemented additional functionalities and increased the sophistication of primitives used) and further integrated that testbed into the global SP6 tested.

Comment: (This one was a general comment on the entire project) The consortium should explore more dynamics issues, as a natural strategy following existing results on the static side.

Action: In several aspects of SP5 research we further investigated the impact of network dynamics. We highlight the following: a) in WP5.3 we made a fundamental shift in studying sensory networks where not just some sinks and robots but the sensors themselves move, in a very diverse and highly changing manner b) our obstacle avoidance and tracking algorithms provided in WP5.2 are especially suitable in the case when there is a high dynamics in the network (obstacles that move and change shape, and when the tracking target and mobile agent are moving fast in the network region c) in WP5.3 we study heterogeneous mobile networks with very diverse and dynamic mobility profiles d) in WP5.1 we provided communication protocols for mobile ad hoc networks in the presence of unpredictable and non-homogeneous dynamic failures e) in WP5.3 we further elaborated on evolving graphs capturing the transient behavior of dynamic networks.

Comment: (general comment on the entire project) It is strongly advisable that during the next phases of the project the consortium members focus more on integration of their research activities, and on publications resulting from such collaboration, rather than on pursuing individual external visibility.

Action: We have intensified common research, like between CTI and Geneva, between UDRTV and UDRLS, as well as INRIA and CNRS.

Comment: (general comment on the entire project) The outreach to industry and practitioners needs to be strengthened. It is currently too indirect, except in SP5 and SP6.

Action: In SP5 we tried to further increase interactions and cooperation with relevant industry. In particular, we have established strong links and exchanged short visits with Ericsson Ireland, especially in the context of potential integrations of mobile telephony and sensor networking.

Comment: (general comment on the entire project) The consortium has to assess the relevance of the work done to other communities interested in the same problems.

Action: We tried to increase awareness and feedback between our algorithmic perspective and the broader networking community. Several SP5 partners (Geneva, UDRTV, CNRS, CTI) have published papers and participated to important networking conferences, like the IEEE Global Communications Conference (GLOBECOM), the ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM) and its Workshops MobiWac and PEWASUN. Also, SP5 people (CTI) organized MSWiM 07 in Greece, while CNRS people organized the 7th International Conference on Ad-Hoc Networks and Wireless (ADHOC NOW 08) in Nice. It is worth mentioning that ADHOC NOW 08 colocated with diverse yet relevant events, like the 19th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2008) and the International Workshop on Ad hoc Ambient Computing (AdhocAmC 2008).

6 Deviations from planned work (if any)

No deviations.