Final Report

ALCOM-FT

Algorithms and Complexity
Future Technologies

Project No. IST-1999-14186

January 2004

Summary

This is the final report for the ALCOM-FT project, supported by the European Commission as project number IST-1999-14186 under the Future and Emerging Technologies part of the IST programme of the Fifth Framework. The report covers the entire project period from June 1, 2000 to November 30, 2003.

ALCOM-FT has brought together eleven of the leading groups in algorithms research in Europe in a project aiming at discovering new algorithmic concepts, identifying key algorithmic problems in applications, and contributing to the transfer of advanced algorithmic techniques into commercial systems. The eleven participants of the project are listed in Table 1.

No.	*Full Name*	*Short Name*
1	BRICS, Department of Computer Science, University of Aarhus (coordinating site)	Aarhus
2	Department of Software, Polytechnic University of Catalunya, Barcelona	Barcelona
3	Department of Computer Science, University of Cologne	Cologne
4	INRIA, Rocquencourt	INRIA
5	Max-Planck-Institut für Informatik, Saarbrücken	MPI
6	Department of Mathematics and Computer Science, University of Paderborn	Paderborn
7	Computer Technology Institute, Patras, Greece.	CTI
8	Department of Computer and System Science, University of Rome "La Sapienza"	Rome
9	Department of Computer Science, University of Utrecht	Utrecht
10	Department of Computer Science, University of Warwick	Warwick
11	Department of Computer Science, University of Cyprus	Cyprus

Table 1: The participants of the ALCOM-FT project.

The focus of the project has been a combination of application oriented research in three important areas – *massive data sets*, *massive and complex communication*, and *complex problems in production and planning* – with innovative methodological work on *experimental algorithmics* and *generic algorithmic methods*.

The project has been divided into work packages, one for each of the five areas above, and one additional dealing with management and dissemination efforts. The scientific advances made by the project consortium in each of these areas have been very notable in terms of quality as well as quantity, and the goals set forth in the project description have been reached. Part I of this document gives an overview of these achievements.

All deliverables have been delivered[1], and the large majority of these were delivered on schedule. Table 2 lists all deliverables and their delivery times. Further descriptions of their contents are given in Part II of this document.

The largest deliverable is D1, which constitutes a total of 538 scientific reports produced during the project period. This high productivity has not been achieved at the cost of quality, as can be seen by the fact that at least 410 of the 538 reports have already been published in the scientific community via key conferences and journals, including the most prestigious in the world.

The set of deliverables also contains a number of software projects contributing to the transfer of advanced algorithmic methods into practice. These are: A library for external memory

[1]Except the Technology Implementation Plan, which is to be handed in by February 1, 2004

computation with a functionality similar to the widely used STL C++ library (D6, D15, D24); A demonstration package for methods in data mining (D16); A LEDA Extension Package for distributed algorithmic engineering, to facilitating simulation of large, hierarchical, or mobile networks and development of network optimization methods for resource allocation (D7, D17, D25); A BSP-style library which allows efficient implementation of BSP-style programs in dynamic distributed environments (D8, D18, D26); Software for production and transportation planning, along with a database containing real-life problem instances from the same area (D19, D27, D28); A completed software system (SCIL) for structured combinatorial optimization problems, including high-level constraints and their separation routines (D20, D23, D29); A set of tools for executing, documenting, visualizing, and reproducing algorithmic experiments (D5, D13, D21 D30).

Further dissemination efforts of the ALCOM-FT project include arrangement of eight summerschools, arrangement of several conferences and workshops (among these the 2000, 2001, and 2002 versions of ALGO, the premier algorithmic event in Europa), creation of a project web site (D2) and two web sites disseminating algorithmic knowledge (D11, D14), and industrial talks on algorithmic issues,

The project has been lead by a Consortium Board consisting of the scientific leader from each site. The following two adjustments was decided upon by the Board during the project: The algorithmics group at the University of Cyprus, headed by Prof. Marios Mavronicolas was added as an ALCOM-FT site for further strengthening of Work Packages 2 and 4, and the project was extended by six months to ensure proper finalization of some delayed deliverables (D14, D15, D19, and D21).

The rest of this document is organized into three parts. The first describes the progress achieved within the six work packages of the project. The second lists details of each deliverable of the project. The third lists all scientific reports published as part of the project.

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D1	Research reports	Cont.	Cont.
D2	Project Presentation	3	3
D3	Dissemination and Use Plan	6	6
D4	Guidelines for algorithmic experiments (internal release)	6	12
D5	Testbed for experimental algorithmics (specification)	6	6
D6	External memory experimental platform (design)	12	12
D7	Distributed algorithmic engineering software package (prototype)	12	12
D8	BSP-style library for dynamic distributed environments (prototype)	12	12
D9	Production and transportation planning modeling report	12	12
D10	Guidelines for algorithmic experiments (external release)	12	36
D11	Algorithm Forum web site	12	12
D12	First progress report	12	12
D13	Testbed for experimental algorithmics (internal release)	18	18
D14	PR web-pages for algorithmics	18/36	36
D15	External memory experimental platform (prototype)	24/36	36
D16	Data mining demonstration package	24	24
D17	Distributed algorithmic engineering software package (beta version)	24	24
D18	BSP-style library for dynamic distributed environments (beta version)	24	24
D19	Production and transportation planning software prototype	24/36	36
D20	Description language for high level constraints in optimization	24	24
D21	Testbed for experimental algorithmics (external release)	24	26
D22	Second progress report	24	24
D23	Library of separation routines for ABACUS	30/36	36
D24	External memory experimental platform (final release)	36/42	42
D25	Distributed algorithmic engineering software package (final release)	36/42	42
D26	BSP-style library for dynamic distributed environments (final release)	36/42	42
D27	Production and transportation planning software user evaluation report	36/42	42
D28	Production and transportation planning problem instance database	36/42	42
D29	Complete software system for structured combinatorial optimization problems (SCIL)	36/42	42
D30	Testbed for experimental algorithmics (final release)	36/42	42
D31	Technology implementation plan	36/42	–
D32	Third progress report	36/42	42
D33	Final report	36/42	42

Table 2: The deliverables of the project. The notation 18/36 denotes the planned delivery month before and after the extension.

Contents

Part I Work Packages

WP 1: Massive Data Sets

Participants: Aarhus, Barcelona, INRIA, MPI, Paderborn, CTI, Rome, Warwick
Coordinating site: Barcelona
Work Package Leader: José L. Balcázar
Number of technical reports: 80, of which 61 also appear in other work packages

Presentation

Traditional algorithm design is based on the von Neumann model, which assumes uniform memory access costs. However, our current state-of-the-art machines increasingly deviate from this model. From the registers, through very fast caches and a bit less fast internal memories, to increasingly complex secondary or even tertiary storage structures such as systems of parallel hard drives or robotized racks of CD-ROM units, algorithms that process large datasets need an awareness of where the accessed data is stored, and must take into account that the cost of memory accesses depends on the characteristics of the memory support. Typically, each level of this complex memory hierarchy, compared to its preceding level, has slower access time, larger capacity, and cheaper per-bit costs. For instance, an operation on registers in a modern but humble machine, operating at around a gigahertz as clock speed, takes a few cycles, whereas a memory access takes microseconds, or about 1000 times longer, and a disk access takes milliseconds, or one million times longer. These rough estimates give a hint of the problem faced, but actual computations with actual times of actual machines give even more daunting differences.

Even the constantly growing capacity of disk drives cannot satisfy the ever growing demand for flexible and efficient storage systems. Increasingly, commercial database systems offer support for including, as fields of the records in their tables, so-called BLOBS (Binary Large OBjectS) corresponding to e.g. images or music, which means single fields of typically 50Kb to 500Kb for a jpeg-encoded image or 1Mb to 4Mb for an mp3-encoded rock-and-roll song; and this, repeated over and over for all the tuples in the corresponding relation, and adding up to impressive quantities of memory usage.

A simple way to provide almost unlimited storage capacity is the use of many disk drives in parallel. RAID systems offer a handful of hard drives together, appropriately interconnected, but much bigger systems of parallel disk will be in use in the near future. The underlying architecture of such a *storage network* may vary significantly, and its design and use is far from trivial.

The smooth acceptance by the end user of such large storage systems depends on the employment of effective algorithmic techniques able to extract peak performances of such complicated systems without the user having to care about how. The record of the research in algorithms along the XX century proves that algorithmic work at different abstraction levels and target tasks has been able to meet the expectations of the user regarding computing power: we must do the same for virtually unlimited storage. Considering how Computer Science has coped with the situation in the past, we chose to organize our contribution to this future vision along three lines: the algorithms that have to be employed internally by the storage structures proper; algorithms that run on top of them to solve basic combinatorial problems, such as those found in our successful internal memory algorithmic library LEDA; and the algorithms themselves, on top of these, that solve user-oriented, industry-relevant or scientific tasks. Thus, the remainder of this report is structured in three sections, corresponding to these views.

A touchstone of the latter view is the analysis, not feasible up to now, of very large combinatorial structures, which we have chosen to perform as a testbed of our algorithms and their implementations. Along this line, we are also studying a number of problems that are popular in the Data Mining community, and believe that our results will contribute to the progress of this discipline, both in the layer of understanding and the layer of applications.

This report will neither present details of the contributions, nor include a discussion of the research that we feel yet as not so mature as to be very relevant (but which is necessary anyhow): see the yearly reports or the archive of technical reports for this. We concentrate instead on the most novel contributions and their significance.

Use of External Memory

Massive data sets need not only to be processed efficiently but also to be stored in a flexible manner. Such a storage scheme has to permit fast access to data elements even if the access pattern is not known in advance. This is necessary because even the large efforts to find good external memory algorithms for fundamental problems (like graph or geometric problems) did not result in many practical solutions for real-life problems.

From the first year of the project we studied the algorithmic support for parallel disks, where we have contributed innovative algorithms based on randomization, combined with redundant storage and sophisticated scheduling algorithms and a newly discovered duality between writing to disks and prefetching. Descriptions of the algorithms and their analysis are in [371], [496], [493], where a variety of practical situations such as data streams or variable-length blocks are considered.

However, we are aware that current storage systems lack the flexibility to adapt to a growing space demand. One way of meeting capacity and performance requirements is the usage of dedicated storage networks. These networks abstract from and generalize the parallel-disks model in that they consist of a number of arbitrary storage devices, connected by an arbitrary network. A number of requirements, like data distribution, balance of data accesses, heterogeneity, or adaptivity, have to be met to exploit the full potential of storage networks. In particular, whereas simple schemes are able to cope with homogeneous systems, where all the storage devices are essentially identical, and static, so that the full system is known in advance [122], we need solutions for the practical cases of heterogeneous (i.e. storage devices have different capacity and/or transfer rate) and adaptive (i.e. storage devices may enter or leave the system) settings. We developed two new placement schemes: SHARE and SIEVE [123]. Both of them are the first storage algorithms that permit an optimal adaptation to changing space requirements. In [491] we give an overview of existing techniques and introduce some more techniques for the efficient handling of many of these conditions simultaneously.

Altogether, we find ourselves in a position where it is realistic to pursue the implementation of a storage virtualization, where the storage units are extendable with little technological conditions and usable without the end user having to care too much about how: this has prompted us to suggest a new storage management environment, based on our new concepts, that is able to significantly reduce management costs and increases the performance and resource utilization of the given SAN infrastructure [121].

Basic Combinatorial Algorithmics

Cache-oblivious algorithms represent an excellent exponent of the approach to computer science research within the ALCOM consortium. Indeed, this work takes its starting position from the abstraction of technological issues, defines crisply a computation model so that formal analysis of the computational parameters of the algorithms is possible (though sometimes only feasible through strenuously hard mathematical work), and allows us to compare with more standard models and thus identify which aspects of the development have the potential for a practical impact; then we can concentrate on these and thus obtain deeply relevant contributions, such as the Lazy Funnelsort algorithm that, in most current machines, compares favorably in practice with the sorting algorithms that are usually considered best. Thus a sound, abstract, theoretically mathematical approach ends up providing an advance in the state-of-the-art practical systems.

Cache-oblivious algorithms are optimized algorithms in the usual I/O model, except that one optimizes to a block size B and a memory size M which are *unknown*. This seemingly simple change has significant consequences: since the analysis holds for any block and memory size, it holds for *all* levels of the memory hierarchy. In other words, by optimizing an algorithm to one unknown level of the memory hierarchy, it is optimized to each level automatically. Also, the characteristics of the memory hierarchy do not need to be known to the algorithm, thereby increasing portability, which is important in situations such as the production of software libraries and code delivered over the web.

Sorting is a basic task in information processing, and is also one of the few currently known tools for designing cache oblivious algorithms. Improving the practicality of sorting algorithms, as we do in [133], is therefore important, and, indeed, our advances provide cache oblivious algorithms for a number of problems in computational geometry.

A fundamental question is whether there is a *separation* in power between cache-oblivious algorithms and algorithms in the standard two-level model; we have contributed important results to this question. For instance, still with respect to sorting, we have proved that our algorithm Lazy Funnelsort is optimal, by proving a matching lower bound, and that therefore the cache-oblivious model is essentially different from the standard two-level model. This is one of the ways we have found of solving the separation question, and in a way that is practically important; other related contributions study permuting and searching problems [125], [83]. On the basis of the knowledge gained through this work, in [128] we describe how a fine tuning of our cache-oblivious algorithms can leverage the overhead imposed by the cache-obliviousness into a large number of advantageous characteristics, and still be competitive with the best practical algorithms for the same tasks. We see this contribution as, again, one more of the most influential work in the theory of algorithms.

Graph Algorithms

Hardly any other area of combinatorial algorithms is of wider practical use than graph algorithms. From layout and placement problems in the construction of the actual circuits that run our programs, through the identification of useless code by compilers, to facility location or operational transport and delivery problems in industrial logistics, the classical graph traversal problems breadth first search (BFS), depth first search (DFS) and single-source shortest-paths (SSSP) are more and more applied to larger and larger graphs.

Whereas BFS and DFS are easily solved sequentially using linear time on internal memory, fast and efficient external graph explorations were one of the big algorithmic challenges at the start of ALCOM-FT. The best external-memory algorithms then known for BFS and DFS required $\Omega(n)$ I/Os on general graphs. This was even true for *semi-external computing*, where it is assumed that node-related data can be stored internally. In [445] we gave the first external memory BFS algorithm which achieves $o(n)$ I/Os on arbitrary undirected graphs of bounded degree, or even of unbounded degree for planar embedded graphs [26], and extended the results to other problems such as DFS and SSSP. The idea of starting from suboptimal parallel algorithms gave an important progress for DFS [27]. Finally, as a landmark achievement, in [439] we presented the first external-memory BFS algorithm, fairly simple and likely to be practical, that achieves $o(n)$ I/Os on arbitrary undirected graphs.

A similar development was followed for SSSP problems. Various algorithms, focusing on the optimization of some or another aspect, were designed; some of them were obtained as follow-ups of algorithms for other traversals and appear in the previously cited reports, whereas others were described in [446], [448], [444], [447] and, finally, [449], which gives the best algorithm known for some specific applications (namely, for the ubiquitous case of sparse graphs with weights not too large, where our algorithm saves factors close to the square root of the block size). The specific advantages of each of the algorithms designed are briefly summarized in the corresponding yearly reports.

Applications

We have studied as well a number of algorithms and problems driven by more specific applications. Originated on the scientific interest in the combinatorial properties of graphs that appear in reality, such as call graphs or the WWW, and which are too large for treatment with internal memory algorithms, we have studied the power-law graphs that model them using our external-memory graph algorithms. We have found algorithms that, for the specific case of these graphs, became the first work-efficient $o(n^{1/4})$ average-case time SSSP algorithms [446]. In [514] we give a set of heuristics which allow to perform semi-external DFS for directed graphs in practice. The heuristics have been applied to models of the web graph and some call graphs, with impressive speed improvements, sometimes 100-fold better than any other alternative. Also, the topological properties of web-like graphs, including a real fragment of the WWW consisting of 200M HTML pages and 1.4 billion edges, have been studied thanks to our new algorithms for external or semi-external computation: [412] and [258]. This research has been facilitated by the `<STXXL>` library described below.

Approximation and Sampling

An important problem in the handling of large data sets is that of extracting relevant information from largely unstructured data, where the treatment often has to be based on statistical decisions. One then needs to be able to recognize what are statistically unavoidable regularities and distinguish these from the observed events that are likely to be meaningful. It is to be noted that classical probabilistic methods do not readily provide answers to these questions, while the original combination of formal and analytic approaches developed in the project enables us to attack the analysis of significance thresholds for an extremely wide class of complex patterns [306], [243].

A major new result is the LogLog Counting algorithm of [269] presented at ESA'03. The problem addressed is that of accurately estimating cardinalities, in particular the number of *distinct* records satisfying a given criterion. The algorithm proposed can estimate cardinalities in massive data sets of up to gigabytes of data in a single pass, using only one or two kilobytes of data, in which case, the estimates it provides are normally with 1% or 2% of the actual value.

On relational data, a central problem in Data Mining applications is the computation of frequent sets from a given family of subsets of a fixed universe. This is actually a version of the problem of computing the transversal hypergraph of a given hypergraph, implicitly described by the frequencies of occurrence of items from the universe in the dataset, and is solved usually in practice by the so-called Apriori Algorithm. We proposed in [47] an alternative scheme based on a best-first strategy. Besides being efficient, it has the main advantage of combining naturally with adaptive sampling schemes, developed by our own researchers, which decide whether the sample size is sufficient for a given approximation quality, instead of using a batch sampling, i.e. a fixed sample size obtained from a standard Hoeffding-Chernoff analysis.

In fact, with respect to such (widely used) batch sampling, which is frequently inapplicable due to the extremely demanding sample sizes required, adaptive sampling maintains the same theoretically well-founded statistical guarantee of representativeness; simultaneously, in the vast majority of practical cases, it requires a reasonably small sample size. Therefore, as promised in the initial work plan, we have developed and programmed versions based on adaptive sampling of Data Mining and Machine Learning tasks, namely, the frequent sets problem as described above (where the standard schemes for frequent sets algorithms, like the Apriori method, are unable to take profit from the advantage of adaptive sampling, so that an alternative algorithm was developed), the construction of decision trees, and the construction of boosting-based weightings of decision stumps. These programs must be considered as research prototypes only and are accessible through our website. Finally, we should mention that we developed a general unified framework [347] to study such adaptive sampling schemes, ready for implementation and allowing also to prove limitations of the approach in the form of lower bounds.

With the additional ingredient of letting the underlying probability distribution, according to which the sampling is done, evolve in time, we have been able to apply sampling strategies to the training of Support Vector Machines (SVM) for classification problems; these algorithms are becoming another central topic in the datamining community. In [52] we provided an alternative randomized decomposition algorithm for which we could prove a strong bound on the expected completion time: it is the first (and so far the only) SVM training algorithm for which subquadratic expected running time bounds exist. An extension to regression problems appears in [53].

Software Libraries for External Memory

As planned, we have devoted considerable effort to making our most basic algorithms useful to persons outside the project. Initially we developed a single-disk external memory library [197] consisting of a low level block manager that allows the use of file systems and raw devices interchangeably and a higher level part that implements numerous algorithms and data structures such as sorting, matrix arithmetics, simple graph algorithms, priority queues, B-trees, buffer trees, and suffix arrays.

On the basis of this experience, and of wide previous experience in the design of algorithmic libraries, as explained in the initial proposal, we have implemented a first version of a platform for the experimentation with external memory algorithms, with a view to practical uses: our two main requirements were, therefore, very high performance and easy migration from existing software.

Based on an inexpensive Linux system that sustains full bandwidth I/O from up to eight disks, and using Posix threads and ordinary synchronous file system I/O calls, we could implement a novel I/O layer that supports both parallel disks and overlapping of I/O and computation. On top of this, a highly portable library is being built; by now it has support for almost all the STL of C++, while at the same time guarantees close to optimal use of all disks. Our implementation is two to three times faster than previous algorithm libraries, and is extremely innovative in that it is the first time that so many theoretical optimizations reach a fully practical, ready-to-use system. As a token of the outcomes of the experimentation made possible by this library, we can mention a new parallel disk sorting algorithm [226] that for the first time guarantees optimal overlapping of I/O and computation.

The part of this library relative to external memory graph algorithms is also growing fast; we already have an implementation for minimum spanning trees and connected components of massive graphs and there are ongoing implementation projects of external BFS, search trees, suffix tree construction, and other algorithms from [145, 386, 443]. More significantly, our library, called `<STXXL>`[2] has already suggested three possible cooperations outside our group, involving computer graphics, image processing, and geographic information systems. We see this interest of external potential cooperators as the best indicative of the appropriateness and timeliness of our whole developments.

WP 2: Networks and Communication

Participants: INRIA, MPI, Paderborn, CTI, Rome, Warwick
Coordinating site: CTI
Work Package Leader: Christos Kaklamanis
Number of technical reports: 216, of which 139 also appear in other work packages

The principal aim of the work within WP2 is to design, theoretically analyze and experimentally validate efficient and robust solutions to selected fundamental optimization issues in modern network communications. The work related to WP2 within the project has focused on two central issues:

- *Efficient communication in modern networks*
- *Distributed dynamic environments.*

In the rest of this section we overview important related results focusing on the theoretical developments. We cover the following specific research areas: Wavelength optimization in all-optical networks, algorithms for wireless networks, modelling of telecommunication networks, network routing, non-cooperative networks, graph partitioning and load balancing, scheduling problems, data management in networks, and BSP algorithms.

[2] `http://www.mpi-sb.mpg.de/~rdementi/stxxl.html`

Wavelength optimization in all-optical networks

Our work in this area focused on *Wavelength Division Multiplexing* (WDM) all-optical networks. In such networks, communication requests are ordered pairs of nodes to be thought of as transmitter-receiver pairs and the WDM technology establishes connectivity by finding paths connecting transmitters to receivers and assigning wavelengths (or colors) to the paths so that paths sharing the same fiber are assigned different wavelengths. Since the number of wavelengths is limited, an important (and hard) optimization problem to be solved is to minimize the number of wavelengths used. This is known as the *wavelength routing* problem.

Within the project, we considered the wavelength routing in trees and proposed novel methods for wavelength optimization. These include the use of randomization and the exploitation of fractional path colorings for approximating the minimum number of wavelengths. In the first approach, we extended the notion of deterministic greedy algorithms to randomized ones, we studied their limitations, and we obtained new upper bounds for the problem which beat the known lower bounds for deterministic algorithms. For the analysis, we developed tail inequalities for hypergeometrical-like distributions. The relevant results are reported in [36, 163, 164].

In the second approach, we showed how to compute almost optimal fractional path colorings (these are relaxations of wavelength routing solutions) in bidirected trees of bounded degree, and we proposed new randomized rounding methods which, combined with known deterministic or randomized algorithms, yield solutions with substantially better approximation ratios. The second approach is general; it allows to improve the known approximability bounds for the wavelength routing problem for all networks where fractional path colorings can be computed efficiently. Furthermore, it can be applied in the case of multi-fiber WDM networks. In [154, 155], we apply this approach to (multi-fiber) bidirected trees and undirected rings. In the analysis, we use new tail bounds for interesting generalizations of classical occupancy problems. Other investigations related to wavelength optimization are reported in [152].

Algorithms for wireless networks

In the context of wireless networks, we have mainly considered ad hoc wireless networks (i.e., networks in which no infrastructure exists and communication is achieved by direct message exchanges between the nodes) with omnidirectional transmitters. We have studied issues related to their modelling, their dynamics and mobility, frequency assignment, and energy consumption.

Many reports were devoted to modelling of ad hoc networks. In [451], we studied the problem of path selection in static ad hoc networks on the two- and three-dimensional space. Measures of interest are the congestion, dilation and energy, while we took interferences between links into consideration. Our results provided interesting trade-offs between congestion, dilation and energy expressed in terms of the network size and the number of interfering links. We have also extended our investigations in the case of unidirectional transmission model where we allow communication in parallel sectors [253]. Other problems related to modelling and basic operations in mobile ad hoc networks were studied in [110, 179, 181, 183–185, 189, 465].

In particular, *smart dust* (or *sensor networks*) is a set of a vast number of ultra-small fully autonomous computing and communication devices, with very restricted energy and computing capabilities, that co-operate to quickly and efficiently accomplish a large sensing task. Smart dust can be very useful in practice, e.g., in the local detection of a remote crucial event and the propagation of data reporting its realization. The work [186] opened the basic algorithmic research on smart dust systems, by providing a simple and realistic model for smart dust, and by giving a set of simple and very efficient protocols for local detection and propagation along with a rigorous average case performance analysis. Subsequent studies are reported in [25, 111, 174, 175, 180, 188, 274, 458].

Concerning dynamics of ad hoc wireless networks, we compared the ability of several topologies to handle dynamic changes where radio stations appear and disappear [359]. For this, we measured the number of involved radio stations and presented distributed algorithms for repairing the network structure. It turned out that some of the models studied combined good performance in terms of interferences, energy and congestion. Additionally to this kind of dynamics, stations may move freely and unpredictably. In [505] we investigated distributed algorithms for ad hoc networks with moving stations in worst case scenarios (by defining models which restrict worst case mobility in a reasonable way). Our results showed that it is possible to maintain persistent routes with nice communication properties. Another recently studied [257] combinatorial notion, the *infection time* of graphs, may also be useful in estimating the information propagation time in mobile ad hoc networks.

Frequency assignment is important in wireless networks utilizing frequency division multiplexing (FDM) technology. These may be ad hoc networks consisting of transmitters which can communicate directly among them, or networks of base stations aiming at supporting communication for mobile phone users. FDM assigns different frequencies to users or transmitters so that users or transmitters which are close to each other are assigned different frequencies. Since, usually, the spectrum of available frequencies is limited, it is important to minimize the number of frequencies used, or given the available spectrum, to maximize the number of connections.

These problems can be formulated as coloring (also known as radio labelling and radiocoloring) or independent set problems in graphs. In this context, in [21, 328–330, 460] we studied the *radiocoloring problem* (RCP). Among other results, we obtained complexity and algorithmic results for hierarchical and periodic planar graphs. Besides their inherent combinatorial interest, these graphs are motivated by large, structured wireless networks and can model periodic frequency assignment requests. New coloring algorithms for efficiently coloring squares of planar graphs were presented in [22–24]. We also studied another version of the problem in [97] where some nodes may have a pre-assigned frequency, and we obtained several algorithmic, combinatorial, and complexity-theoretic results.

We also considered online versions of the independent set problem in *cellular wireless networks* in [159–162]. These are planar networks with specific structure modelling interferences between base stations with equivalent transmitters uniformly distributed on the plane. We presented improved competitive ratios and competitiveness lower bounds for the problem of approximating the maximum independent set when the network nodes (representing users wishing to connect to base stations) appear on-line. Our algorithms are very simple and make competitive decisions using only a constant number of random bits or comparable weak random sources.

Energy is another scarce resource for ad hoc networks. In [78, 338] we studied energy-efficient routing in radio networks using advanced data structures from algorithmic geometry. Suppose we have n radio stations whose position is known and we assume that the energy consumption for communication between two stations is bounded by their Euclidean distance raised to some constant. In this situation, the energy consumption can be reduced by using intermediate stations as relay stations. We developed a linear space data structure that can be precomputed in time $O(n \log n)$ and allows constant time queries for k-hop paths whose energy consumption is within a factor $1 + \epsilon$ from optimal for any constant $\epsilon > 0$.

In [157, 158], we addressed the issue of supporting typical communication patterns like broadcasting, multicasting, and gossiping in wireless networks using the minimum amount of energy. We formulated a series of *wireless network design problems* which are shown to be NP-hard. Roughly speaking, these problems can be generally stated as computing an energy assignment to the nodes of the networks so that the supported connections maintain a connectivity property and the total energy is minimized. We considered the problems of minimum-energy broadcasting, multicasting, and gossiping in networks with symmetric and asymmetric edge-cost functions (representing required energy for communication between pairs of nodes). In asymmetric graphs, we obtained optimal logarithmic approximations for broadcasting and gossiping, and polylogarithmic inapproximability results for multicasting. For networks with symmetric edge-cost functions, we obtained logarithmic approximations for multicasting and constant approximations (and inapproximability results) for group communication problems. Our results exploit the relations of these wireless network design problems to node-weighted versions of famous combinatorial problems like directed/undirected steiner tree/forest, connected dominating set, and more.

Modelling of telecommunication networks

In this context, we aimed at investigating the basic features of mathematical models describing telecommunication networks. Our objective was firstly to give a precise description of the impact of the basic algorithms controlling the telecommunication networks and secondly to optimize the choice of their parameters. The equilibrium properties and transient behavior of the stochastic models of networks and telecommunication protocols were analyzed through Markovian methods. The renormalization (Euler's scaling) was the main fundamental tool used to investigate the behavior of complex multi-dimensional Markov processes involved.

Our research work includes fundamental studies of the renormalized processes involved in the stochastic models describing telecommunication networks [214, 334, 335], studies of bandwidth allocation problems in TCP-like networks [265, 267], investigation of the behavior of TCP congestion avoidance mechanisms [263, 360, 361] and admission control for Diffserv networks [264, 266, 377], stochastic modelling of TCP flows in ADSL traffic [82], and studies of the interactions of long and short TCP flows in IP networks [119, 362].

We have analyzed the *fluid limits* of Markov processes describing a telecommunication system. The fluid limits approach is a first order analysis of the state of complex systems and one of the most promising methods to tackle these difficult problems. Roughly speaking, a stochastic process is almost reduced to a deterministic dynamical system. Basic questions concern the relation between the initial process and the dynamical system. Our results showed that an old conjecture concerning the non-randomness of fluid limits in a classical Markovian model of a telecommunication network is wrong. Randomness implies that deterministic differential equations cannot describe completely the first order behavior of the network. We also showed that, in some specific cases, the limiting dynamical system involves products of random matrices. A complete characterization of such stochastic processes was achieved with the help of the dynamical system.

The study of AIMD (Additive Increase Multiplicative Decrease) algorithms is important since such algorithms are used in the congestion avoidance phase of TCP networks. An AIMD algorithm can be quickly described as follows: a source transmits W packets and, if an acknowledgement of reception is received, it then sends $W + 1$ packets (additive increase). Otherwise, a packet loss is detected and the source then sends δW packets (multiplicative decrease). The analysis focused on the evolution of the variable W (called the *congestion window size* for a very long connection: a source is sending a large file and the network losses packets from time to time. In our analysis we considered two models: a simplified one in which packet losses are independent (this model provides useful lower bounds on the behavior of AIMD algorithms), and another model where packet losses occur in groups. Our analysis of the second model showed that the simplified model underestimates the real performance of AIMD algorithms. For a fixed loss rate, correlation of packet losses improve the performance of the protocol (the higher the variability of the loss process, the better the throughput).

At the entrance of a network, admission control mechanisms determine whether new requests can be accepted or not. Connections are classified in several types according to their requirements (throughput, load, etc.) and the purpose of admission control is to accept the maximum number of connections and, simultaneously, to guarantee that each accepted connection will have a probability of packet loss less than ε (guaranteed quality of service). Algorithms based on a parameter called *effective bandwidth* are known to be very efficient if there is only *Assured Forwarding* traffic. In the context of Diffserv networks, there is also an additional class of traffic, the *Expedite Forwarding* traffic, which has absolute priority over every other traffic. Previous algorithms underestimate severely this high priority traffic. By considering a new stochastic model as a stochastic upper bound of the initial model, we proposed a new connection admission control algorithm. It uses effective bandwidths as well, but also considers the high priority traffic so that quality of service is guaranteed.

The aim of [82] was to characterize the Internet traffic in order to get realistic traffic models. After an extensive study of trace captures on an Internet backbone link connecting ADSL users, an approximation model was proposed and mathematical expressions for the stationary behavior of the system were obtained. The theoretical results were partially validated with the ADSL traces.

We also investigated the performance of a network link supporting long elastic flows which may abort. The model consists of a network link crossed by elastic traffic with a transmission capacity assumed to be shared according to the processor-sharing discipline which is the ideal bandwidth sharing achieved by TCP. The basic queueing system considered in this analysis is the M/G/1 processor-sharing (PS) queue with or without impatience and with finite or infinite capacity. We remark that it is generally difficult to get explicit results concerning queues with impatience. Under some assumptions, our estimations shed light on fairness issues concerning long flows.

Network routing

In the context of packet routing, we have produced several new results for fundamental routing problems. These problems have been intensively studied before because they form major building blocks for the efficient use of parallel computers. The results cover not only low level primitives but also more complex operations. Some of the results we obtained are remarkable since most important questions seemed to be largely closed for a decade. A simple randomized permutation routing algorithm for hypercube networks [534] closes a long standing gap between the best known algorithm and the trivial lower bound. A similar improvement for the problem of broadcasting a long message from one processor to all others is described in [498]. For gossiping (a natural generalization of broadcasting), powerful heuristics have been developed that can be applied to any specific network as well as a new algorithm for butterfly networks that breaks a long standing barrier for very large networks. Generalizations of these problems have been studied in [492]. Many of the algorithms designed work robustly on the emerging main-stream architecture of clusters of symmetric multiprocessors.

We also investigated the possibility or impossibility, and the corresponding costs, of devising *bufferless packet-routing algorithms* for communication networks that achieve nice performance guarantees with respect to the *congestion* C (the maximum number of packets that simultaneously cross a link of the network), and the *dilation* D (the maximum number of links a packet needs to traverse from *source* to *destination*). In [147, 148], we studied two restrictions of bufferless routing algorithms, namely *hot-potato routing algorithms* and *direct routing algorithms*. In hot-potato routing, nodes in the network have no buffers for packets in transit, and packets may instead be deflected, while direct routing is a special case of bufferless routing in which packets must be routed *without conflicts* along specific paths. For both problems, we derived algorithms which guarantee routing time within logarithmic factors of the obvious $\Omega(C + D)$ lower bound. Our results for hot-potato routing apply to trees, while the results on direct routing apply to a variety of commonly used network topologies such as trees, meshes, hypercubes and butterflies and are complemented by related hardness statements.

Adversarial Queueing Theory is a currently major arena in which to study the *worst-case* performance of routing and contention-resolution protocols for communication networks. The worst-case setting is much more natural and realistic than settings making probabilistic assumptions about the injection of packets into the network and their associated delays (with classical queuing theory being the prime example for the latter settings). Our research activity in this arena has attempted to classify protocols and networks according to the *stability* inherited to the network–the property that the number of packets in the network remains *bounded* at certain rates of injection. Within the project, we made substantial progress in several stability-related questions. We have shown the smallest injection rate that leads to instability when used on a certain FIFO network and the largest injection rate that guarantees stability when used on *any* FIFO network. We have shown that certain contention-resolution protocols that are stable in isolation are not so when composed together in a heterogeneous network with sufficiently large injection rate. We have addressed the question of how network structure (size, diameter, maximum node degree, minimum number of node-disjoint paths, network subgraphs) affects the stability properties of networks, for various greedy protocols. We have also investigated the effect of dynamically changing the capacities of a network on its stability and instability properties and have proved lower and upper bounds for the instability and stability thresholds, respectively, for several natural greedy protocols such as SIS (shortest-in-system) and LIS (longest-in-system). The related results are reported in [11, 19, 20, 246, 397–401] and push much forward the current front of research on stability issues in the context of Adversarial Queueing Theory.

In the virtual circuit routing problem, we are given a graph and a sequence of routing requests between node-pairs in the graph. The goal is to connect all pairs via a path in the network so that the congestion is minimized. Previous work on this problem mainly focuses on the online or offline version of this problem, where a routing decision may depend on other requests. In [88, 485], we have shown that for undirected networks there exist also an efficient *oblivious* algorithm for this problem, i.e., an algorithm that does not use any knowledge of the request sequence for its routing decisions. Such an algorithm can be implemented very efficiently in a distributed environment since it only requires static routing tables at the network nodes. Our approach is based on a hierarchical decomposition of the network with certain properties. We obtained existential and constructive results for such decompositions which yield competitive oblivious algorithms with polylogarithmic (in the size of the network) competitive ratios with respect to the network links.

Non-cooperative networks

Our work in this area has considered three different models for a non-cooperative network. These are the *KP Model,* the *Hybrid Model* and the *Restricted Links Model.* In the KP model, a single source and a single destination are connected by m parallel links. Each of n users chooses a strategy, that is, a probability distribution over all links, trying to minimize its private cost to send its traffic from source to destination. The private cost is defined as the maximum expected latency over all links the user has chosen with positive probability. This definition of private cost often contradicts the social cost, defined as maximum expected latency on a link, which measures the global performance of the network. A Nash equilibrium is a state of the system such that no user can decrease its private cost by unilaterally changing its strategy.

In [208] we proved that the worst-case coordination ratio (defined as the maximum possible value over all Nash equilibria of the social cost over the *social optimum* which represents the best achievable social cost) on links with possibly different speeds is $\Theta\left(\frac{\log m}{\log\log\log m}\right)$ generalizing a previous result of [434]. In [402], the notion of Nash equilibria was extended to that of approximate equilibria. We also presented the first study [203] of the price of selfish routing under general monotone families of cost functions and cost functions from Queueing Theory. In particular, a precise characterization of cost functions having bounded/unbounded coordination ratio was given. For example, cost functions that describe the expected latency in queueing systems have unbounded coordination ratio. We also focused on cost functions describing the behavior of Web servers that can open only a limited number of TCP connections. We concluded that web servers that are allowed to reject requests can guarantee a high quality of service for every individual request stream even under relatively high injection rates.

In [327], we presented the first complexity results concerning the KP model. We proved that it is hard to compute the maximum social cost for any given Nash equilibrium, or to compute the best or worst Nash equilibrium. Providing algorithms to compute a pure Nash equilibrium from a given schedule without increasing the social cost, we obtained a polynomial-time approximation scheme (PTAS) to approximate a best-case pure Nash equilibrium for the model of identical links [342] and related links [301], respectively.

In [342, 424], we have also given structural results providing substantial evidence for the Fully Mixed Nash Equilibrium Conjecture, henceforth abbreviated as FMNE Conjecture, which states that the worst Nash equilibrium with respect to the social cost is the fully mixed Nash equilibrium, where each user chooses each link with positive probability. For a survey on results in the KP-model we refer to [302].

In [423] we considered the Hybrid model (which combines in an interesting way features of the KP model and the *Wardrop* model), and we evaluated the performance of Nash equilibria with the help of *quadratic social cost* as the sum of the expectations of the squares of the incurred link latencies. We presented a comprehensive collection of combinatorial expressions for the computation of quadratic social cost. These expressions readily imply some polynomial algorithms to compute quadratic social cost in several special cases, and a corresponding *general,* pseudopolynomial, dynamic programming algorithm. Furthermore, we proved that, for the model of identical users and identical links, the worst-case Nash equilibrium is the fully mixed Nash equilibrium. Finally, we presented a comprehensive collection of (usually tight) constant (that is, independent of m and n) lower and upper bounds on the coordination ratio.

In [341] we considered the *Restricted Links Model* which is the variant of the KP model in which each user may only be routed on a link from a certain set of *allowed links* for the user. Our study of the Restricted Links Model has led us to the development of new techniques for the computation of Nash equilibria and for proving bounds on the coordination ratio under this model.

In a similar context [77], we studied algorithmic questions concerning a congestion game in which there is a single provider that offers a service to a set of potential customers. Each customer has a particular demand of service and the behavior of the customers is determined by utility functions that are non-increasing in the congestion. Customers decide whether to join or leave the service based on the experienced congestion of the offered prices. If the prices of services are fixed, then the customer behavior leads to a pure, not necessarily unique, Nash equilibrium. In order to evaluate marketing strategies, the service provider is interested in estimating its revenue under the best and worst customer equilibria. For the case in which the provider has perfect knowledge of the behavior of all customers, we presented a complete characterization of the *complexity of computing optimal pricing strategies* and of *computing best and worst equilibria*. Basically, we showed that most of these problems are inapproximable in the worst case but admit an "average-case FPAS". We extend our analysis to a more realistic model in which the provider has *incomplete knowledge* and show that the worst-case complexity of the problem increases with the precision of the available knowledge.

Scheduling problems

We have addressed several scheduling problems focusing on their on-line variants, where information about tasks is not known in advance. In [393] we studied the problem of assigning independent tasks to uniformly related machines when only limited online information is provided to the scheduler. This is an elementary scheduling problem having many applications in areas where the communication is costly and a scheduler should require the minimum online information in order to achieve a fixed performance, such as online allocation of decentralized resources. The setting studied in [393] is a general framework whose special cases are the classical multiple-choice games for the assignment of independent tasks to identical machines. The latter case has been the subject of intensive research for the last decade. The problem is intriguing in the sense that the natural extensions of the greedy oblivious schedulers, which are known to achieve near-optimal performance in the case of identical machines, have been proved to perform quite poorly when distinct machine speeds come into play.

We presented a rather surprising lower bound stating that any oblivious scheduler that assigns an arbitrary number of tasks to n related machines would need $\Omega\left(\frac{\log n}{\log\log n}\right)$ polls of machine loads per task, in order to achieve a constant competitive ratio versus the optimum offline assignment of the same input sequence to these machines. On the other hand, we showed that the only missing information for an oblivious scheduler to perform asymptotically optimally is the amount of tasks to be inserted into the system by providing a new oblivious scheduler that uses only $O(\log\log n)$ polls, along with the additional information of the size of the input sequence, in order to achieve a constant competitive ratio. The nature of the proposed scheduler is quite different from the existing schedulers for identical machines (which are mainly greedy schedulers) and is based on the concept of giving higher priority to the least favourable machines. This oblivious scheduler was used as the core of an adaptive scheduler that does not require the knowledge of the input sequence and yet achieves similar performance.

In [74, 75] we considered the problem of efficiently serving on-line requests submitted by interactive users to a distributed server system. This setting is modelled in a very general way, as the problem of on-line scheduling jobs on a set of identical machines to minimize some function of time. In [74] we studied the quality of service (QoS) that is achievable by semi-clairvoyant online scheduling algorithms, which are algorithms that only require approximate knowledge of the initial processing time of each job on a single machine. It was an open question whether it is possible for a semi-clairvoyant algorithm to have constant competitive ratio with respect to average flow time on one single machine. We settled this open question by giving a semi-clairvoyant algorithm that is $O(1)$-competitive with respect to average flow time on one single machine. We also presented a semi-clairvoyant algorithm on parallel machines that achieves up to constant factors the best known competitive ratio for clairvoyant on-line algorithms. It is known that the clairvoyant algorithm SRPT is optimal with respect to average flow time and is 2-competitive with respect to average stretch. Thus, it is possible for a clairvoyant algorithm to be simultaneously competitive in both average flow time and average stretch. In contrast we showed that no semi-clairvoyant algorithm can be simultaneously $O(1)$-competitive with respect to average stretch and $O(1)$-competitive with respect to average flow time.

In [75] we introduce the notion of smoothed competitive analysis of online algorithms. Smoothed analysis has been proposed to explain the behaviour of algorithms that work well in practice while performing very poorly from a worst case analysis point of view. We apply this notion to analyze the Multi-Level Feedback (MLF) algorithm to minimize the total flow time on a sequence of jobs released over time when the processing time of a job is only known at time of completion. A direct consequence of our result is also the first average case analysis of MLF. We show a constant expected ratio of the total flow time of MLF to the optimum under several distributions including the uniform distribution. A randomized version of the MLF was studied in [72] and was shown to perform well from a worst case analysis point of view.

A survey of recent work on on-line scheduling to minimize average response time or related metrics, on single and parallel machines is given in [76]. Other works reporting on related results can be found in [65, 69, 71, 219, 298, 393, 416].

Graph-partitioning and load balancing

Within the project, we extensively studied the k-partitioning problem. The task is to divide the set of vertices of a graph equally into a given number of parts while keeping the number of crossing edges between vertices belonging to different parts as small as possible. We refer to such a number of edges as the *cut size* of the partition. The special case of partitioning the graph into 2 parts is called a *bisection*, and the minimal cut size of all balanced bisections of a graph is called its *bisection width* (*k-section width* in the general case). Its calculation is NP-hard for arbitrary graphs and remains NP-hard for regular graphs. We obtained several new bounds on the bisection width of regular graphs [209, 244, 455]. Results for 3- and 4-regular graphs are of special interest because these are the lowest non-trivial degrees. Moreover, there are some direct applications of these results, e.g., upper bounds on the bisection width of 4-regular graphs have successfully been applied to the configuration of transputer systems. In [513] we considered the graph-partitioning problem by relaxing the balancing constraint. We presented new and generalized lower bounds for the k-section width within this model.

As we mentioned above, there are graph-partitioning problems in a wide range of applications. For example, when executing processes on parallel computer systems, inter-processor communication is a major bottleneck. One way to address this problem is to minimize the communication between processes that are mapped to different processors. This translates to the k-partitioning problem of the corresponding process graph, where k is the number of processors. In [280], we proved new relations between the structure and the eigenvalues of a graph and we presented a new method to get tighter lower bounds on the k-section width related to classical spectral bounds previously known. Our method makes use of the level structure defined by the k-section. We defined some global expansion property and proved that for graphs with the same k-section width the spectral lower bound increases with this global expansion. These results were enhanced and generalized in [281, 283].

Another research topic was the study of the relation between the properties of a graph and its suitability as interconnection network. One of the fundamental properties of a graph is the number of distinct eigenvalues of its adjacency or Laplacian matrix. Graphs with small spectra exhibit many symmetry properties and are well suited as interconnection topologies. In particular, load balancing can be done on such topologies in a small number of steps. In [278, 279], we constructed families of graphs with bounded or polylogarithmic maximum degree with a small number of distinct eigenvalues.

In the same line of research, we studied the *distributed load-balancing* problem. Distributed load-balancing is often done in two separated phases: *Flow Computation* and *Load Migration*. Concerning the first phase, a well known approach is based on diffusion algorithms. Several different diffusion schemes had previously been developed, especially for load-balancing on homogeneous processor networks.

In [284], we generalized existing schemes in order to deal with heterogeneous networks. The generalized schemes may operate efficiently on networks where every processor can have arbitrary computing power. [285] concentrates on heterogeneous networks where the capacities of the edges varying. It is shown that the convergence rate of diffusion algorithms can be improved using edge-weighted graphs without deteriorating the flows quality. Moreover, in the same work, we considered common interconnection topologies and demonstrate, how optimal edge weights can be calculated for the *First and Second Order Diffusion Schemes*. Using theoretical analysis and practical experiments, we showed that improvements can be achieved on selected networks.

[425] investigates how to schedule a flow on a synchronous distributed network. In this way, we concentrated on the second phase of the two step approach described above. The goal is to use the minimum number κ of rounds to reach the balanced state. Although this flow scheduling problem trivially leads to a formulation as a linear program which is solvable (in a centralized way) in polynomial time, the best distributed scheduling strategy so far needs at most $O(\sqrt{n})$ times the minimum number of rounds. We have shown that every distributed scheduling strategy requires at least $\frac{3}{2}$ times the minimum number of rounds, and, furthermore, we presented a distributed algorithm for scheduling flows on tree networks, which requires at most two times the optimal number of rounds.

In [537] *evolving tree computations* on circulant (rings with chords) and related graphs are analyzed. In an evolving α-ary tree computation, a complete tree grows level by level, i.e., every leaf generates α new nodes that become the new leaves. The load-balancing task is to spread the new nodes on a network of processors in the moment they were created in such a way that the accumulated number of nodes per processor, i.e., its load, is as close as possible to the average number of nodes per processor. In [478], we studied the load-balancing problem with respect to a demand-driven parallelization of a ray tracing algorithm.

Data management in networks

We studied static and dynamic data management problems in computer systems connected by networks. A basic functionality in these systems is the interactive use of shared data objects that can be accessed from each computer in the system. Examples for these objects are files in distributed file systems, cache lines in virtual shared memory systems, or pages in the WWW. In the static scenario, we are given read and write request frequencies for each computer-object pair. The goal is to calculate a placement of the objects to the memory modules, possibly with redundancy, such that a given cost function is minimized. We considered the following problems.

A hierarchical bus network uses hierarchically, tree-like connected buses as a communication network. New communication technologies like SCI (Scalable Coherent Interface) make such networks very attractive, because they allow their easy construction and guarantee reasonable communication performance. Such networks can be modeled as tree networks: leaves correspond to processors, inner nodes to buses, edges to switches, and bandwidths of inner nodes and edges are related to bandwidths of buses and switches, respectively. For these hierarchical bus networks, we investigated in [450] the static data management problem with the goal to minimize the congestion, i.e., the maximum load of all edges and inner nodes induced by the read and write frequencies, divided by the bandwidth of the edge or inner node, respectively. We showed that the problem is

NP-hard and presented an algorithm that calculates a 7-approximate placement of all objects on a hierarchical bus network in polynomial time.

With the widespread use of commercial networks, as, e.g., the Internet, it is more and more important to consider commercial factors within data management strategies. The goal in previous work was to utilize the available resources, especially the bandwidth, as good as possible. In [404], we presented data management strategies for a model in which commercial cost instead of the communication cost is minimized, i.e., we considered a metric communication cost function and a storage cost function. We introduced new deterministic algorithms for the static data management problem on trees and arbitrary networks aiming at minimizing the total cost. This was the first analytic treatment of this problem which is NP-hard on arbitrary networks. Our main result was a combinatorial algorithm that calculates a constant factor approximation for arbitrary networks in polynomial time. Furthermore, we presented an algorithm that calculates an optimal placement of all objects on a tree in polynomial time.

An important aspect of dynamic data management is data tracking. Consider an arbitrary distributed network in which large numbers of objects are continuously being created, replicated, and destroyed. A basic problem arising in such an environment is that of organizing a distributed directory service for locating object copies. In [484], we presented a new data tracking scheme for locating nearby copies of objects in arbitrary distributed environments. Our tracking scheme supports efficient accesses to data objects while keeping the local memory overhead low. We also have shown that the new tracking scheme adapts well to dynamic changes in the network.

BSP algorithms

Within the project, we focused on two main activities in the context of bridging-models for parallel computing, in particular, in the investigation of the so-called BSP (bulk-synchronous parallel machines) model. On the one hand, a programming environment where one can actually execute BSP programs efficiently was implemented. On the other hand, BSP algorithms for combinatorial problems were developed and analyzed and the impact of the model used on the design of these algorithms was investigated.

In the context of the first activity, Paderborn implemented a platform-independent programming environment continuing our previous work. Virtual processors were introduced and it was realized that their execution can be stopped on the current processor and resumed at a different one. This is implemented on a Linux workstation cluster. A prototypical load-balancing mechanism was integrated into this system. The current release of the implementation of the Paderborn University BSP library can be inspected on the web page

`http://www.upb.de/~pub/alcom-ft/` .

In the context of the second activity, we developed algorithms for the broadcast problem [380] that obey locality constraints of the parallel machine where it is intended to be executed. The running time of this method was proved to be optimal for a wide range of BSP parameters and locality assumptions. An overview of further impacts of the used model on the design of efficient parallel algorithms was presented in [452] where we showed how the aspects "latency" and "critical block-size" influence the development of fast algorithms for solving the multisearch problem.

Also, an automatic configuration approach for implementing complex parallel BSP algorithms was investigated. [109] reports on the results of this approach. Here, a parallel algorithm is described by a sequence of instructions and of subproblems that have to be solved by other parallel algorithms called as subroutines, together with a mathematical description of its own running time. There may also be free algorithmic parameters that have an impact on the running time. As the running time of an algorithm depends on several machine parameters, the actual composition of the parallel program for an actual parallel machine given all these ingredients is a difficult task. Such a configuration system has been implemented using the Paderborn University BSP library. As an instructive example, we chose to implement a collection of sophisticated minimum spanning tree algorithms on two parallel machines, using the PUB library. The results of these implementations can be found in [109].

Other topics

Finally, within the project, there has also been work in some other important topics related to WP2. These include investigation of network fault-tolerance issues, Web-related problems and algorithms, distributed algorithms, networked data structures, properties of random network models, network design, algorithms for graph coloring problems, algorithms for dynamic networks, contention resolution protocols, and other fundamental network problems.

WP 3: Production and Transportation Planning

Participants: Cologne, Paderborn, MPI, Utrecht
Coordinating site: Utrecht
Work Package Leader: J.A. Hoogeveen and Jan van Leeuwen
Number of technical reports: 34, of which 20 also appear in other work packages

The goal of WP 3 was to explore novel algorithmic issues in the area of production and transportation planning. Here we have focused on the development of algorithms for solving or finding good solutions to problems that arise in industry and which require both practical algorithm design and fundamental research.

The large fraction of WP3 reports that also appear in other work packages emphasizes the fact that we were aiming at a combination of practical and fundamental research. Almost all of the reports have appeared in conference proceedings like ESA, ALENEX, ICALP, and CP-AI-OR or have appeared in/been accepted for journals like INFORMS Journal on Computing, Math Programming, OR Letters, and Journal of Heuristics. Researchers participating in WP3 have been active in the program committees of many international conferences like ESA, IPCO, ICALP, COCOON, and CP-AI-OR.

Below we give an overview of the work done and results that have been established in WP3 in ALCOM-FT. We distinguish between research that is targeted at specific problems in this area and research that is more generic, in the sense that it aims at improving algorithms that can be used to tackle different problems in this field. We start with the problem-specific research.

Planning, Rostering, and Scheduling Problems

Planning

The seat reservation problem deals with the question of deciding which seat to issue to a customer given that he can be accommodated. It is a typical example of a planning problem that is complicated by a lack of knowledge about the future: each customer has to be served if possible, although later it may turn out that he had better been ignored. We have studied two variants of this problem: the fully on line version, in which a specific seat has to be issued immediately ([43], [117]), and the partially on line version, in which passengers are told that they will get a, yet unspecified, seat when they get on the train. We have developed several algorithms with optimal competitive ratio for a number of scenarios of the first variant and an algorithm that solves the second problem to optimality.

Network planning

Within WP3 we have analyzed a number of problems involving network optimization (see [441], [511], [94], [89]). In the latter two reports we present and compare several metaheuristic algorithms, one of which is the rather new technique of Ant Colony Optimization; it turns out that this technique not only works well, but it is well suited for dealing with dynamic networks as well.

Rostering

A major component in WP3 is the study of complex crew rostering problems. We have looked at problems in the airline industry ([512], [295], [358]) and in home health care (Deliverable D9 and report [86]). These problems are highly difficult to solve in practice as the basic assignment problem is perturbed by difficult rules and regulations reflecting legal aspects, contracts, preferences, etc. Moreover, rules and regulations may vary significantly from one company to another making it thus evident to focus on general models that can incorporate various rule structures. In close cooperation with our industrial partners, we have dealt with problems concerning the integration of yield management and fleet assignment facilities and the integration of the airline fleet assignment and aircraft rotation building phases. These have been tackled by applying a combination of column generation and constraint programming and through local search, and integer programming; this has led to encouraging results.

In close co-operation with industrial partners we have developed a compact model for the home health care problem that is flexible enough to break down most real-world home health care problems of different characteristics. Especially, in [86] we describe the core optimization components of the software that we have produced. In the optimization kernel, a combination of linear programming (LP), constraint programming (CP), and (meta-)heuristics for the home health care problem are used, and we show how to apply these different heuristics efficiently to solve home health care problems. The overall concept can be adapted to various changes in the constraint structure, thus providing the flexibility needed in a generic tool for real-world settings. The industrial software-prototype is currently undergoing intensive user evaluation, where solutions generated by our optimization methods are competing in real-world scenarios. In a further step, requests for additional legal and company constraints, or credit point systems (contributed by researchers from ergonomics) will be integrated into our algorithmic framework.

Scheduling

Our work on different kinds of machine scheduling problems has led to a large number of reports (see Deliverables 9, 27, 28 and reports [369], [370], [6], [288], [287], [216], [7], [4], [368], [5], [532]). The deliverables concern a scheduling problem originating from the pharmaceutical industry. We have come a lot closer to solving this problem, but the algorithms need to be tested in practice. Then we can also see the effect of the randomness of the processing times, which has been studied in [4].

Methodological research

In this part we describe the generic research that has been conducted on algorithms that are used to solve planning problems.

Constraint programming and column generation are two very important techniques, which are used in many of the algorithms that we have presented to solve the real-life problems. In many applications we have to solve some subproblem then, which usually is some kind of constrained standard problem, like a shortest path problem or knapsack problem. We have developed several algorithms to solve these quickly, either to optimality of approximately (see [441], [506], [293], [220], [297]).

Moreover, many of the algorithms we have proposed are enumerative of nature, and thus depend on how well the search space can be reduced. We present several methods to reduce the search space in the reports [296], [293], [510], [511], [509], [294], [297]; these all are very effective.

Finally, we have developed the package SCIL (Symbolic Constraints in Integer Linear Programming), which enables the user to define high-level constraints, which often occur in the problems encountered in WP3 (see Deliverable D20).

WP 4: Generic Methods

Participants: Aarhus, Barcelona, Cologne, INRIA, MPI, Paderborn, CTI, Rome, Utrecht, Warwick (all sites)
Coordinating site: Warwick
Work Package Leader: Mike Paterson
Number of technical reports: 358, of which 178 also appear in other work packages

Of the 358 reports produced within the WP4 work package over the life of the ALCOM-FT project, at least 181 are in the published proceeding of conferences and workshops, at least 71 others appear in, or are about to appear in, journals, while another 7 are in other published forms such as book chapters.

Generic Methods have a central role in ALCOM–FT, providing new algorithms and analysis techniques, and supporting the more applied research within each of the other work packages. This Final Report will summarize the major themes addressed during the last $3\frac{1}{2}$ years with a few illustrative examples from different areas. More information appears in the three Annual Progress Reports and full details are to be found in the Report Series, the major deliverable of this work package, which is available on-line in our Project's web pages.

Analytic combinatorics and random structures

Randomized algorithms are of enormous importance in computer applications today. One strand of research within WP4 is the precise analysis of discrete models of randomness. This is essential in providing tools to predict the practical complexity of probabilistic algorithms. There has been a major change of emphasis in the design and analysis of algorithms from worst-case performance to an appropriate average-case "typical" behaviour. Further, there have been greater efforts to estimate run-times and resource bounds more precisely than with the traditional "big-O" analysis. This developing area of "random combinatorics" arising from algorithmic design may be seen as a largely European endeavour, and the work done in ALCOM–FT is recognised world-wide.

Finite-state and context-free models arising from finite Markov chains, formal verification and other sources are analysed systematically in [310]. Applications of this analysis to communication protocols and RNA structure are provided in [265, 376]. An important kind of question concerning large databases of texts or biological sequences concerns the significance or otherwise of the occurrence of some given pattern. This arises also in such contexts as intrusion detection and filtering large traces of concurrent events in computer systems. The analytic techniques to predict the number of occurrences of such patterns in sequences obeying rather general randomness properties are provided in [112, 306], and applications are considered in [243, 488].

Probabilistic tools are needed for the design and analysis of protocols for the reliable transmission of information in distributed communication networks. ALCOM–FT research has concerned such important features as routing strategies [246, 434], data management [404], load balancing [85], contention resolution (as in Ethernet) [351], stability [214], reservation policies [334], and tradeoffs between density and robustness in interconnection networks [307, 459, 464]. Formal models representing some naturally-arising graphs are established in [248, 475].

Some examples from this "random combinatorics" work are [56, 60] in which the "kernel method" yields closed-form formulae and asymptotics for some constrained random walks, with applications to uniform random generation problems from combinatorics and algorithmics. A further example is [500], which investigates overlapping file allocation problems for disks and uses the Lambert function to bound the degree of overlap.

Two major publications [311, 312] establish a basis for combinatorial enumeration of random discrete structures and a corresponding asymptotic theory. The approach is founded on formal generating functions and their complex-analytic properties. The objects of study, such as words, trees, graphs, and permutations, arise in diverse applications from statistical physics, computational biology, probability theory, and the analysis of algorithms.

The techniques are illustrated in [262,303,309,313,487], with examples investigating connectivity in random graphs, patterns in random texts, divide-and-conquer algorithms, and the expected complexity of balanced trees. Applications range from data mining to intrusion detection and the interpretation of genomic sequences.

GCD algorithms arise in many important practical applications and their characteristics have been extensively studied. New results in [50] give very a precise formulation of their distributional properties.

Optimization and on-line algorithms

Substantial contributions in this area have been made by several groups within ALCOM–FT during the period of the Project. These range from methodological studies of the measures used to evaluate on-line algorithms to very detailed analysis of particular situations.

The quality of on-line algorithms is often measured by comparing them with (off-line) algorithms which have all of the input data available at the start of their operation. The *competitive ratio* of an on-line algorithm is the worst case ratio of the performance of the on-line algorithm and the performance of an optimal off-line algorithm. Although the competitive ratio is a popular analytic tool, in many cases it does not differentiate satisfactorily between different on-line algorithms.

In [113], a new measure, the *relative worst order ratio*, is defined which allows a direct comparison between different on-line algorithms, instead of comparing each with an optimal off-line algorithm. This measure is applied to the paging problem in [115]. Commonly used deterministic algorithms, such as LRU (Least Recently Used) and FWF (Flush-When-Full), cannot be distinguished by their competitive ratios, both achieving the best possible ratio for deterministic algorithms. We introduce a novel algorithm and show that in relative worst order ratio terms this is strictly better than LRU, which is strictly better than FWF. A different approach to the paging problem, using locality of reference, provides a useful comparison of algorithms using the *fault rate* and gives results closer to reality than those obtained for the competitive ratio [10].

We made advances in the classic problem of on-line job scheduling, where a sequence of jobs arrives on-line to a number of identical machines. We investigated scheduling algorithms to minimize latency and optimize the “quality of service” as perceived by the end user, in the scheduling model where jobs can be pre-empted (i.e., suspended and resumed). We considered the metrics of average flow time and average stretch (where the *stretch* of a job is the ratio of its flow time to its processing time), as well as a rather general combination of the two. *Clairvoyancy* means that a new job’s processing time is known on arrival, whereas in *semi-clairvoyancy* there is only approximate knowledge of this. Results obtained include upper and lower bounds on average stretch for randomized algorithms in the clairvoyant case [69], tight bounds for the randomized Multi-level Feedback algorithm (which is used in the Windows NT and the Unix operating systems) in the non-clairvoyant case [72], and a semi-clairvoyant algorithm that is $O(1)$-competitive with respect to average flow time [74]. Results for the more general objective functions appear in [73] and [315].

We have new results in another classic problem domain: on-line bin packing. In [42], we show that the competitive ratio of the well-known First-Fit algorithm can be improved by rejecting some items of input even when there is space for them. In further studies of bin-packing [116,286], we show that some natural algorithms achieve constant competitive ratios when restricted to sequences that can be packed completely by an off-line algorithm.

An interesting twist to on-line scheduling is to consider the effect of introducing a *sorting buffer*, a random-access buffer which can be used to rearrange the input sequence before processing. For example, in [486] we consider a service station with a sorting buffer with storage capacity k. The input items to be processed may have different attributes. The service station benefits from having consecutive items with the same attribute and seeks to use the buffer to minimize the number of attribute changes in the sequence it processes. The problem is motivated by applications in computer science and economics. Our main result is a deterministic strategy with a competitive ratio of $O(\log^2 k)$.

A fine example of the successful combination of Constraint Programming with Operations Research is given in [295, 512]. A new approach to the Crew Assignment Problem uses complex rule systems and shortest path algorithms to provide a powerful optimization algorithm.

Smoothed analysis

Several ALCOM sites are involved in this new approach to measuring on-line performance, seeking to explain how algorithms can work well in practice while performing poorly from a worst-case point of view. The idea is to avoid the sharp peaks of worst cases by some local averaging and to determine whether the worst instances are rare exceptions in the "complexity landscape" of the algorithm.

Smoothed competitive analysis of online algorithms was introduced in [75] to analyze the *Multi-Level Feedback* (MLF) algorithm. MLF tries to minimize the total flow time on a sequence of jobs in the non-clairvoyant case. The exponential worst-case performance of MLF contrasts dramatically with its good behaviour in practice. Our smoothed competitive analysis explains this contrast and gives the first average-case analysis of MLF.

Online problems, such as the paging problem, the static list-accessing problem and the k-server problem, can be modelled as *metrical task systems*. The *work function algorithm* (WFA) of Borodin, Linial and Saks has a tight competitive ratio of $2n - 1$ for metrical task systems of size n. We give in [501] a smoothed competitive analysis of WFA, showing it to be much better than its worst-case competitive ratio suggests. Other successes for our applications of smoothed analysis are to the knapsack problem [80], and to the *motion complexity* of systems of moving objects [210].

Applying an analogous approach to algorithms running on *discrete* data structures leads to the concept of *discrete smoothed analysis* [59]. Classical algorithms such as Quicksort and shortest-path algorithms in weighted graphs are analysed in models where the role of local averaging is played by *partial permutation* (of the instances) or *partial randomization* (of some bits of the instances).

Property testing

A decision problem is to verify whether a given object possesses a certain property or not. A *property testing algorithm* has just to distinguish between the case when a given object has the property and the case when the object is far away from any object having the property. Sometimes this can be done much more quickly than the corresponding (exact) decision problem, e.g., in time independent of the object description size.

The decision problem for proper ℓ-colouring of a hypergraph is known to be NP-hard, however in [205] we give a testing algorithm that can distinguish between the hypergraph having a proper ℓ-colouring and being "far" from having such a colouring in time independent of the size of the hypergraph.

Approximate data structures for sets of moving points are called *soft kinetic data structures* in [204]. A property testing algorithm can be used to check whether the data structure is "far from correct" and if so then it is repaired. Soft kinetic data structures are presented for sorted arrays, balanced search trees, heaps, range trees and Euclidean minimum spanning trees.

The efficiency of property testing algorithms depends on the queries available to the algorithm. It is shown in [206] how the introduction of range queries allows much faster testing algorithms for some properties concerned with convexity and clustering.

Approximation methods.

An important goal is to find fast approximation algorithms with constant worst-case ratio. We outline a few examples of progress in this direction, reported over the period of ALCOM–FT.

One graph-theoretic problem arising from applications such as transportation, warehousing and networking, bandwidth minimization and radio labelling, is the *k-clustering* problem. An efficient approximation algorithm making use of an advice structure, the *d-octopus* of the graph, is described in [316].

A polynomial-time algorithm for a constant-factor approximation of a partition of a sequence into a minimum number of increasing or decreasing subsequences, or of a partially ordered set into chains and antichains, is described in [317].

A polynomial-time constant-factor approximation to the *time-dependent orienteering problem* (a dual to the time-dependent traveling salesman) problem is obtained in [318].

A parameter affecting the performance of a communication network based on a given undirected graph G, is the oriented diameter of G (the smallest diameter of any strongly connected orientation of G). A linear time algorithm for chordal graphs is given in [319] which either finds that no strongly connected orientation exists, or approximates the oriented diameter to within a factor of about two. Unless P=NP, there can be no polynomial-time algorithm giving better than a $\frac{3}{2}$-approximation to the oriented diameter of a chordal graph.

Randomized algorithms

The problems of approximately counting combinatorial structures and of sampling the structures almost uniformly at random are closely related. A popular method for sampling is to simulate an appropriate Markov chain, the chief technical difficulty being to bound the *mixing time* of the chain (the time required before the stationary distribution is (nearly) reached). Such bounds are studied in a number of different areas: counting unlabelled combinatorial structures [352], modelling the iterated Prisoner's Dilemma [271], contingency tables [198], H-colourings of graphs [198, 270], and 3-colourings of the planar grid [349].

Randomized algorithms are particularly important in many practical applications involving sorting and selection. Appropriate use of randomization is very successful in giving simple efficient algorithms which avoid their worst-case scenarios with high probability.

The Quickselect algorithm finds the m^{th} smallest element from n. Simple variants are investigated in [433], such as the *proportional-from-s* method, where at each stage the pivot is chosen from a random sample of size s as the element with the same relative rank as the element sought. Our analysis shows that even the simple proportional-from-3 algorithm is often better than the conventional median-of-3. We investigate in detail the strategy ν-find, which is a generalization of proportional-from-3. Experimental and theoretical results support the contention that ν-find should be the method of choice in practice.

When only the first m elements in the sorted order of n elements need to be determined, a simple variant of Quicksort gives a more efficient algorithm [429], which is shown to outperform the commonly-used partial-sort function in C++'s Standard Template Library.

The report [211] analyses an extension of the recent randomized primality test proposed by Grantham. Grantham's test has a smaller probability of error than the classic Miller-Rabin test, in the worst case. Our new algorithm gives an improvement in the average case, which is more relevant in many applications, such as the generation of random primes in cryptography. The worst-case performance is also improved, by using the efficient cubic residuosity test from [213].

Complexity bounds.

Tradeoffs and similarities

Determining relationships between different complexity measures is important in understanding the intrinsic complexity of computational problems.

In low-level circuit complexity the apparently very different notions of depth-restriction and width-restriction are shown in [367] to be closely related, by locating width-restricted classes within the hierarchy defined by constant depth circuits between $\mathbf{AC}^0$ and $\mathbf{ACC}^0$. Further work [366] led to an alternative characterisation of $\mathbf{ACC}^0$ in terms of constant-width polynomial-size planar circuits.

A classic example of a tradeoff between time and space arises from sorting. The time–space product required for sorting integers over a given domain is known to be $\Omega(n^2)$, even for non-comparison-based sorting. For times less than $\Theta(n \log n)$, no matching upper bound was known. This was improved to cover time down to $\Theta(n(\log \log n)^2)$ (and down to $\Theta(n \log \log n)$ with high probability using a randomized algorithm) in [470].

Another time-space trade-off, for deciding whether any pair elements are "close", was shown for branching programs in [473], extending a result by Ajtai.

In external memory models, where time is measured by the number of I/O operations (accesses to external memory), techniques for deriving I/O-space trade-offs from time-space trade-offs are presented in [404], giving examples from sorting and the "element distinctness" problem.

The complexity of proofs by resolution is often measured in terms of *resolution-width*. We show in [34] how to use pebble games to characterize resolution-width. Using this approach we can show that resolution-width is always at most the resolution-space, solving a well-known open problem.

Hard problems

Approximate counting is considerably easier than exact counting in the context of the polynomial hierarchy. The #P-hard problems of exact counting (introduced by Valiant) are as hard as the whole polynomial hierarchy, whereas approximate counting is not much harder than NP. However, little is known in detail about the complexity of approximate counting. The relation of *approximation-preserving reducibility* is used in [272] and begins to reveal some of the landscape of approximate counting problems. Between the expected equivalence classes which are the "hardest" and "easiest" problems in #P, there is an interesting natural class represented by the problem of counting the number of independent sets in a bipartite graph.

The continuing efforts to locate more precisely the phase transition from nearly-all-satisfiable to nearly-all-unsatisfiable for random 3-SAT formulae is continued in [382]. An improved upper bound of 4.571 is given for the critical clause-to-variable ratio.

When formulae are converted between CNF and DNF forms the size may increase "exponentially". A more precise quantification of this sheds some light on the complexity of satisfiability algorithms. Results relating the size of the increase to the numbers of variables and clauses is given in [453].

The NP-complete problem of finding the chromatic number of a graph is known to be also hard to approximate. An improved algorithm for solving this problem exactly, running in time $O(2.4023^n)$, is presented in [150].

Constraint satisfaction problems

The complexity of a constraint satisfaction problem can be greatly reduced by the imposition of restricted tree-width on the constraint graph. Previous results of this kind were limited to constraint programs over finite domains. In [437], we show that a similar restriction, *k-consistency* for tree-structured problems with algebraic constraints permits backtrack-free algorithms. Further width notions are studied which give backtrack-free solution algorithms for more general classes of constraint systems. In particular, some new classes of efficiently solvable 0-1-programming problems are derived.

Allen's *interval algebra* is concerned with binary relations such as "precedes or overlaps" on time intervals. It is used in artificial intelligence research for temporal reasoning about the time intervals associated with sets of events. In general, it is NP-complete to decide whether some collection of binary qualitative constraints on a set of intervals is satisfiable. A long-standing open question has been to classify the complexity of this decision problem according to the restricted types of allowed temporal constraints. This was solved in [406] and further extended in [405].

New data structures.

ALCOM–FT has been very productive of ingenious new data structures for a wide variety of algorithmic problems.

Dictionaries

Dynamic *dictionaries* support search, insert and delete operations. There are many well known data structures for them, such as binary search trees (BSTs, for short) and skip lists. BSTs perform poorly when they are skewed, so many notions of balanced BSTs have been devised. The method presented in [489] achieves logarithmic worst-case cost by using the sizes of the subtrees as balancing information. It is simple, easy to implement and fast in practice, provides worst-case guarantees, and allows for rank operations. Empirical evidence suggests that it should be considered among the first choices when constructing a BST.

Relaxed balance is the term used for search trees where the rebalancing has been uncoupled from the updating. This has advantages in some real-time applications and in shared-memory architectures. In [292], a search tree with relaxed balance having a height bound of $c \log n$ for any $c > 1$ is presented. The previous best bound had $c = 1.44$. In [410], B-trees with relaxed balance are enhanced to include group updates, and in [374] we present variants of B-trees with relaxed balance with improved space utilization.

In many dictionary applications, the access probability of any given key is not fixed, but decreases with the time since the last access to that key. In [290, 291], a *lazy update* scheme is supported by a new data structure, the *biased skip list* (BSL). The lazy update scheme gives optimal search and insert/delete times in terms of the bias of the input distribution, and is shown to have advantages in practice on real and synthetic data.

Another important technique for the dictionary problem is *hashing*. In [468, 469, 471] we have both theoretical and practical contributions: a characterization of optimality in terms of the number of memory locations accessed, a new idea for a deterministic algorithms, and a practically promising new hashing algorithm, *Cuckoo Hashing*.

At the extremes of speed versus storage, a randomized dictionary can be constructed so that each query only accesses a single word of memory [199] and gives the correct answer with a high probability. The storage required is just $O(n \log \frac{2u}{n})$ for a dictionary of n elements from a universe of size u.

String processing

For index structures on strings and sequences, both suffix arrays and suffix trees have been commonly used. Important advances have now been made in the efficient construction of suffix arrays. The linear-time algorithm given in [386] matches that previously known only for suffix trees, thus strengthening the appeal of the simpler, more space-efficient suffix arrays. The algorithm is also readily parallelizable to an efficient implementation on several varieties of parallel machine. A related algorithm [145], which is comparison-based however, constructs suffix arrays in $O(n \log n)$ time. It is space-efficient and competes well in practice with all previous algorithms.

An important problem in text compression and computational biology is to count the number of occurrences of some given pattern in a fixed string. It is shown in [131] that a string of length n can be preprocessed in time $O(n \log n)$, following which any pattern count can be found in time linear in the pattern length.

Other data structures

Many operating systems use a memory management system which allocates and deallocates memory blocks whose sizes are powers of two. The *buddy system* requires time which is logarithmic in the memory size. A new scheme is given in [132] which requires only constant time per operation.

Refined Buneman trees are a favoured way of generating evolutionary trees from bioinformatic data. The new algorithm for their construction given in [127] requires time only $O(n^3)$ and space

$O(n^2)$. This marked improvement over previous algorithms allows the investigation of refined Buneman trees for realistically sized data sets.

Graph and network algorithms

We mention just a few of the many results obtained during the life of ALCOM–FT in the area of graph algorithms.

New techniques, described in [227, 235], allow the construction of a deterministic algorithm to maintain explicitly the fully dynamic transitive closure of a graph as a Boolean matrix, supporting updates in $O(n^2)$ amortized time, and queries in unit worst-case time, or, in the case of deletions only, supporting updates in $O(n)$ amortized time. We also construct a randomized Monte Carlo algorithm which breaks through the $O(n^2)$ barrier on the single-operation complexity of fully dynamic transitive closure by supporting updates in $O(n^{1.58})$ and queries in $O(n^{0.58})$ worst-case time.

In [234, 237, 238], we have studied algorithms for maintaining all-pairs shortest paths in a dynamic graph. We use a completely new approach which yields a fully dynamic algorithm for general directed graphs on n vertices with real edge weights that supports any sequence of operations in $O(n^2 \log n)$ amortized time per update and unit worst-case time per distance query. This is the first algorithm that solves the dynamic all-pairs shortest paths problem in its full generality, and our bounds improve substantially over previous results. For more complex queries, such as "What is the shortest path from vertex x to vertex y avoiding a failed link (u, v)?", but for static graphs only, we have a compact data structure with $O(n^2 \log n)$ space which supports a query time of $O(\log n)$ [242].

In many applications, the graphs and networks which arise may have only small values of some parameter such as cutwidth, treewidth, or degree, and efficient algorithms can be designed to take advantage of this. Examples of our work in this area are linear-time algorithms when the cutwidth is small [521], and polynomial-time algorithms when the treewidth and degree are small [522], and efficient algorithms for computing the minimum dominating set and related problems on planar graphs [9].

Experiments on computing the treewidth of networks, with applications to decision support systems and telecommunication, are reported in [395]. The modular decomposition of a network can be used to efficiently compute the treewidth [104], and a variant of treewidth to measure the cost of a tree decomposition is introduced [101], where algorithms to compute tree decompositions of minimum cost are given.

Other work on graph algorithms includes a deterministic algorithm for maintaining a t-spanner of a general weighted undirected graph under a sequence of edge insertions and deletions [41], and simple combinatorial algorithms for the minimum feedback-arc set and minimum feedback-vertex set problems that achieve an approximation ratio bounded by the length of a longest simple cycle of the digraph [241].

Randomized algorithms to compute the bisection width of random cubic graphs with n vertices are presented in [245], giving an asymptotic upper bound of $0.174039n$. We also obtain an asymptotic lower bound of $1.325961n$ for the size of the max bisection. The tight analysis is based on the differential equation method.

In [140, 141] we perform a detailed study of the computational complexity of the problem of colouring a planar graph with the minimum number of colours such that each colour class avoids one or more forbidden graphs as subgraphs. Results include a complete answer for the case of a single forbidden connected subgraph, and many results on *subcolourings* (where each colour class consists of a disjoint union of cliques).

WP 5: Experimental Algorithmics

Participants: Aarhus, Barcelona, Cologne, INRIA, MPI, Paderborn, CTI, Rome
Coordinating site: MPI
Work Package Leader: Peter Sanders
Number of technical reports: 93, of which 64 also appear in other work packages

The main goal of WP 5 was to strengthen the role of experimental techniques in algorithmic research in order to increase the practical impact of algorithmic results and to speed up their dissemination. We will begin with high level activity into this direction.

Rudolf Fleischer (MPII), Bernard Moret (U. New Mexico), and Erik Meineche Schmidt (Aarhus) organized a Dagstuhl Seminar on Experimental Algorithmics in September 2000. The result was deliverable D10, a volume [483] in the Springer LNCS series which possibly contains the most comprehensive collection of articles about algorithm engineering methodology. There were summer schools on algorithm engineering and algorithm library design organized by the Rome site and MPII in September 2001 and September 2003 respectively. The Workshop on Algorithm Engineering (WAE) was organized by MPII in 2000, by the Aarhus site in 2001, and became the "Engineering and Applications" track of the European Symposium on Algorithm in 2002 that was organized by the Rome site.

Of the 93 ALCOMFT reports produced in WP5, at least 76 have appeared in conference proceedings or journals, or are scheduled to do so soon. The large fraction of reports listed with at least one other work package underlinings the fact that algorithm engineering is an integral component of algorithmic research.

In the following we highlight some areas where we have worked very intensively and obtained interesting results that are easy to explain. It should be kept in mind however that this is an incomplete list. In particular, algorithm engineering permeates all work packages so that you will find several results in other sections of this report. For example, the work on cache efficient algorithms that was listed as part of WP 5 in the proposal turned out to have a larger theoretical component than anticipated and also significantly overlaps with WP 1 so that we want to refer to this section in particular.

Dictionary Data Structures

Dictionaries maintain a set of elements supporting fast search, insertion, and deletion of elements. Although from a theoretical perspective this area looked largely settled since the mid 1980s, an algorithm engineering perspective led us to a number of interesting results [83, 135, 225, 290, 331, 374, 471, 494] For example, priority queues [134] and search trees [83, 135] can also be implemented to run efficiently on all levels of the memory hierarchy simultaneously using the simple concept of cache oblivious algorithms. For more details refer to the description of WP 1.

We could also demonstrate that search trees that exploit integer keys [225] can achieve practical speedup over comparison based data structures.

Rasmus Pagh and Fleming Rodler received the best student paper award for a practical hash table data structure that has worst case constant access time [471]. A simple generalization of this *cuckoo hashing* approach additionally leads to highly space efficient hash tables [225].

Optimization Problems on Graphs

We have studied many optimization problems of graph that have many applications. For example the feedback arc set problem and its application to graph drawing [228] and local search algorithms for coloring and their application to timetabling and frequency assignment [22, 166, 167].

Here we report on three results in more detail that help to close gaps between theory and practice:

Previously, the best implementations of the maximum weighted matching problem uses suboptimal algorithms since the required data structures (mergable priority queues) for asymptotically better algorithms were considered too expensive. An implementation at MPII, that is now part of the LEDA library, shows that this is not the case — our asymptotically efficient algorithm outperforms previous implementation on almost all instances measured [440].

Steiner trees are one of the most widely studied network design problems with many applications ranging from VLSI design to bioinformatics. Reports [480–482] describe parts (new preprocessing and bounding heuristics) of a large program that can solve real world Steiner tree problems optimally although the problem is NP-hard. Our system is among the world leading systems in the sense that it is the fastest program for most instances from the well-established benchmark library SteinLib and that for some large instances it is the only program finding optimal solutions.

Many NP-hard problems can be solved efficiently for graphs with small treewidth. Although there are many theoretical result based on this observation, there were few practical implementations so far. One of the main problems was that it is nontrivial to find good tree decompositions. Reports [102, 103, 275] address this problem. Tests on networks derived from applications like decision support systems and frequency assignment have shown that the methods are usually very effective.

Dynamic Graph Algorithmics

In the last 15 years, many interesting theoretical results have been obtained on the practically interesting question how to maintain solutions to fundamental graph problems when only a few edges change. However, there have been few implementations and it was not always clear whether simple minded solutions would not outperform sophisticated worst case efficient algorithms for practical inputs. We have therefore conducted several experimental studies on transitive closure [337], single-source shortest paths [233], all pairs shortest path [237, 239], and minimum spanning trees [172]. A detailed survey was prepared in [539]. Our experimental data suggest that some of the dynamic algorithms and their algorithmic techniques can be really of practical value in many situations.

Algorithm Visualization

Our most influential contribution to algorithm visualization so far is Leonardo, an integrated environment for visualizing C programs [229]. Leonardo is distributed with a collection of more than 60 animations of algorithms and data structures including approximation, combinatorial optimization, computational geometry, on-line and dynamic algorithms. Leonardo has been widely disseminated on CD-ROM in computer magazines and is available for download in several software archives over the Web. It has received several technical reviews and more than 18,000 downloads over the last two years. A newer extension is Leonardo Web, a tool for building animated presentations that also work over the Internet.

We are also studying advanced aspects of algorithm visualization. CATAI (Concurrent Algorithms and data Types Animation over the Internet) [173] allows multiple users to watch a visualization and interact.

In [108] we describe a cross-platform virtual machine that provides advanced facilities for implementing directors, i.e., reactive systems that monitor the run-time environment and react to the emitted events. Typical examples of directors are debuggers and tools for program analysis and software visualization.

Interactive Rendering of Highly Complex Scenes

In [389, 536] we present a new rendering algorithm. The *randomized z-buffer algorithm* uses a sampling technique to achieve interactive frame rates even for huge scenes with up to 10^{14} (implicitly defined) triangles. In contrast, traditional z-buffer algorithms have a running time proportional to the scene size and are thus unable to process huge scenes. Our system is also able to handle scenes that are so large that they can only be stored on a local or remote hard disk.

Report [479] presents a prototype of an e-commerce system that simulates realistic lighting of large scenes on high performance parallel computers.

Uniform Random Generation of Combinatorial Objects

Uniform random generation allows to study experimentally the behavior/complexity of algorithms by running them with thousands of randomly generated inputs.

The article [261] explains how to generate combinatorial objects of size between n and $n*(1+\epsilon)$ in linear time using a rejection method. In contrast, the best known algorithms that produce objects of size exactly n take quadratic time.

The report [262] proposes a new approach to the structure of random objects like constrained sequences, trees, graphs, or permutations, based on the idea of Boltzmann models from statistical physics. Most of these algorithms are of subquadratic or even linear complexity and can be automatically generated from specifications. Implementations indicate that objects of size 100.000 can now be generated where only size 100 was previously possible.

Engineering Distributed Algorithms

Mobile ad-hoc networks [176, 178, 181, 183, 184] and sensor networks [25, 174, 175, 180] are a challenging new area for distributed algorithms. Since these models are very complex, simulations of new algorithms are an essential part of algorithmic research in this area. Our approach is based on a lightweight simulation environment using C++ and LEDA, which allows us to make extensive simulations runs involving thousands of nodes.

We have also studied attacks in computer networks [461] and routing torus-connected processor arrays.

WP 6: Project Management, Dissemination, Evaluation

Participants: Aarhus, Barcelona, Cologne, INRIA, MPI, Paderborn, CTI, Rome, Utrecht, Warwick (all sites)
Coordinating site: Aarhus
Work Package Leader: Erik M. Schmidt

Project Management

Overall, the management of the project has run very smoothly, and few problems have been encountered. Scientific productivity has been high, work has progressed as expected, funds have been used in good accordance with the budget, and communication within the consortium, as well as between the consortium and the EC, has worked well.

The Consortium Board, consisting of the scientific leader of each of the eleven participating sites and chaired by the Coordinator, has carried the overall responsibility for the management of the project. The work at each site has been organized by the site leader in question, with the help of one or more assistants. The coordination of the activities within each of the six work packages has been the responsibility of the Work Package Leaders, who have also conducted the reporting on the work done.

The Board has met at least once a year, monitoring the progress of the work and the use of the financial funds. Among the key decisions taken by the Board during the project is the inclusion of the algorithms group at the University of Cyprus, headed by Prof. Marios Mavronicolas, and the application to the EC for a six month extension in order to ensure proper finalization of some delayed deliverables (D14, D15, D19, and D21). Both steps proved successful: Site Cyprus has been well integrated in the consortium, as witnessed by the amount of cooperation between site

Cyprus and other ALCOM sites, and all deliverables have been delivered according to their new schedule.

Each year has featured an ALCOM-FT review meeting with participation of the EC project officer and review team. In connection with each review meeting, a consortium-wide scientific workshop has taken place, featuring talks on select work from each site.

Dissemination

The principal means of dissemination for the ALCOM-FT project is scientific reports describing the research done. In total, 538 scientific reports have been produced as part of the ALCOM-FT project. At least 410 of these[3] have already been published in the scientific community via key conferences and journals, including the most prestigious in the world. All 538 reports have also appeared in the ALCOM-FT Technical Report Series, which is available online.

A total of eight summerschools/workshops aimed at Ph.D.-students and young researchers have been organized using project funds, all with contemporary subjects in areas related to ALCOM-FT. The events were: *Advanced Course on the Foundations of Computer Science* (Saarbrücken, September 2000), *ALCOM Spring School on Dynamic Algorithms* (Paderborn, May 2001), *2nd Max-Planck Advanced Course on the Foundations of Computer Science* (Saarbrücken, September 2001), *ALCOM-FT Summer School on Algorithm Engineering* (Rome, September 2002). *Models and Algorithms for the Web* (Udine, 2002) *3nd Max-Planck Advanced Course on the Foundations of Computer Science* (Saarbrücken, September 2002) *Workshop on Parallelism in Algorithms and Architectures* (Paderborn, March 2003) *4th Max-Planck Advanced Course on the Foundations of Computer Science*(Saarbrücken, September 2003). All events had a high attendance, with participants from many European countries as well as from outside Europe.

Members of the ALCOM-FT project organized several internationally renowned conferences in areas highly relevant for the work of the project. These include ESA'00, WAE'00, APPROX'00 (site MPI), STOC'01, ICALP'01, SPAA'01 (site CTI), ESA'01, WAE'01, WABI'01 (site Aarhus), ESA02, APPROX'02 and WABI'02 (site Rome), CCC'03 (site Aarhus). Additionally, many smaller conferences and workshops were arranged by various ALCOM-FT sites, including two Dagstuhl meetings on algorithmic engineering.

An ALCOM-FT website (`http://www.brics.dk/ALCOM-FT`) has been set up, containing a description of the objectives of the project, the sites participating, and the deliverables produced. The website also contains the online version of the ALCOM-FT Technical Report Series. Several further deliverables have separate websites describing the work performed and reachable through the ALCOM-FT website. Two of these websites are directly concerned with dissemination, namely a site with PR-pages for algorithmics (among other things reporting success stories on collaboration among theorists and practitioners), and a website facilitating the sharing of lecture notes among lecturers within computer science.

To increase the awareness of algorithmics in research communities outside ALCOM-FT, we have also set up an algorithmic competition based on finding worst case instances for graph algorithms from the LEDA library (see `http://www.mpi-sb.mpg.de/~schaefer/MLLB/index.html`. Unfortunately, the competition has failed due to lack of entries submitted. Apparently, this venue of dissemination is not efficient, at least not in the form attempted here.

Dissemination of algorithmic awareness has also been fostered by talks given by partners to audiences in industry. In particular, the Paderborn site has established a forum called *Industrie trifft Informatik* (Industry meets Computer Science), where university and business cultivate their dialog in the field of information technologies and where possibilities for new cooperations are launched.

The consortium has maintained a high profile in Ph.D. education, illustrated by the fact that during the project, 47 persons obtained an ALCOM-FT related Ph.D.-degree.

[3] Based on the reporting from the authors. This is a lower bound, as it is quite possible that some publications have not been reported.

Evaluation

The ALCOM-FT project has been very successful. All deliverables have been completed. Scientific productivity has been high, and a substantial number of Ph.D.'s have been educated. The international standing of ALCOM-FT is illustrated by the large fraction of research reports which have been published, or been accepted for publication, at the most prestigious conferences in the field.

Part II Deliverable Overview

Below, we list the deliverables of the ALCOM-FT project grouped by work package. Deliverable D1 (538 research reports delivered continuously across the entire project period) is not included, as it pertains to all work packages.

The notation 24/36 denotes the planned delivery month before and after the six month extension of the project.

Deliverables of WP1

External Memory Experimental Platform

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D6	External memory experimental platform (design)	12	12
D15	External memory experimental platform (prototype)	24/36	36
D24	External memory experimental platform (final release)	36/42	42

Description: Deliverables D6, D15, and D24 constitute the development of the `<STXXL>` library. The core of `<STXXL>` is an implementation of the well-known C++ standard template library STL for external memory computations, i.e., `<STXXL>` implements containers and algorithms which can process huge volumes of data that only fit on disks. The `<STXXL>` library is already used by several projects. Although still evolving, `<STXXL>` is by now a substantial piece of software with 14.000 lines of code and a number of statements comparable to the standard STL library. More information can be found at the `<STXXL>`-homepage at `www.mpi-sb.mpg.de/~rdementi/stxxl.html`.

Sites involved: MPI

Data Mining Demonstration Package

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D16	Data mining demonstration package	24	24

Description: Deliverable D16 consists of programs that use our adaptive sampling techniques to scale up methods from Machine Learning and Data Mining. It contains four stand-alone programs (our algorithm for frequent sets as per [49], the scaled-up version of that algorithm as per [347], a program to experimentally evaluate association rules as per [170], and the scaled-up versions of the decision tree and decision stumps algorithms as per [347]) and two extensions (scaled-up weighted majorities of decision stumps and scaled-up K-Means) of Weka, a well-known and widely used open source data mining package. All the programs can be retrieved on the web from `http://www.lsi.upc.es/~gcasas/alcom/alcom_software.html`.

Sites involved: Barcelona

Deliverables of WP2

Distributed Algorithmic Engineering Software Package

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D7	Distributed algorithmic engineering software package (prototype)	12	12
D17	Distributed algorithmic engineering software package (beta version)	24	24
D25	Distributed algorithmic engineering software package (final release)	36/42	42

Description: Deliverables D7, D17, and D25 are the Distributed Algorithms Platform (DAP). This is a software platform supporting the implementation, simulation, and testing of distributed algorithms. Its focus is on implementing distributed algorithmic ideas developed for wired and mobile wireless network systems. It is implemented in C++ using LEDA. To transfer the full power of LEDA to distributed experiments and implementation of distributed algorithms, DAP is provided as a LEDA Extension Package. The main strengths of DAP are:

- The user develops in a standard programming language (C++) and the programs can be easily and efficiently ported to a real distributed environment.
- A modular model is used, powerful enough to represent diverse distributed environments, yet simple enough to hide unnecessary details.
- A user is able to control, monitor, and visualize the simulation of his/her algorithm through a Graphical User Interface (GUI).
- Many users can simultaneously monitor and visualize (through a lighter version of the GUI) the simulation of some algorithm from remote locations.
- The execution of the simulation can be distributed among several hosts (if required).
- Randomness can be introduced in all areas of the simulated distributed system.
- Scenarios can be defined for repetitively simulation of particular situations.

More information can be found at the homepage of DAP at `ru1.cti.gr/~LEP-DAP/`.

Sites involved: CTI

BSP-Style Library for Dynamic Distributed Environments

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D8	BSP-style library for dynamic distributed environments (prototype)	12	12
D18	BSP-style library for dynamic distributed environments (beta version)	24	24
D26	BSP-style library for dynamic distributed environments (final release)	36/42	42

Description: Deliverables D8, D18, and D26 constitute a contribution of the ALCOM-FT project to the further development of the Paderborn University BSP software library (PUB) for parallel computing. The PUB library is a BSP-style library that allows the efficient implementation of BSP-style parallel programs in dynamic distributed environments. Specifically, the deliverables embody work resulting in stable process migration procedures, load balancing routines, and the possibility for realizing any customized load-balancing methods. The ALCOM-FT funded final release 8.0 of the PUB library can be downloaded from `www.upb.de/~pub/` together with a comprehensive documentation.

Sites involved: Paderborn

Deliverables of WP3

Production and Transportation Planning Modeling Report

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D9	Production and transportation planning modeling report	12	12

Description: D9 are two reports describing ways to model and solve optimization problems from two complicated real-life domains, namely scheduling multipurpose batch processes and rostering in home health care.

Sites involved: Paderborn, Utrecht

Production and Transportation Planning Software

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D19	Production and transportation planning software prototype	24/36	36
D27	Production and transportation planning software user evaluation report	36/42	42

Description: D19 and D27 are two steps in the development of software for solving job scheduling problems with no-wait constraints.

Sites involved: Utrecht

Production and Transportation Planning Problem Instance Database

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D28	Production and transportation planning problem instance database	36/42	42

Description: Deliverable D28 is a database of real life instances of the job shop scheduling problem. The instances stem from the pharmaceutical industry, and are here made accessible for research purposes. Because these instances come from an actual industrial company and may provide insight into their internal production methods, we cannot publish the described material on the web. If you are interested in this material, please write an e-mail to Peter Lennartz (`peterl@cs.uu.nl`).

Sites involved: Utrecht

Deliverables of WP4

Software System for Structured Combinatorial Optimization Problems

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D20	Description language for high level constraints in optimization	24	24
D23	Library of separation routines for ABACUS	30/36	36
D29	Complete software system for structured combinatorial optimization problems (SCIL)	36/42	42

Description: Deliverable D29 is the completion of a software system for Symbolic Constraints in Integer Linear programming (SCIL). The system consists of a modeling language (developed as deliverable D20) together with standard symbolic constraints (developed as deliverable D23), the documentation, and examples. The system is now available as an easy to install software system which can be downloaded at `www.mpi-sb.mpg.de/SCIL/scil.tar.gz`. Further information can be found at the SCIL homepage at `http://www.mpi-sb.mpg.de/SCIL/`.

Sites involved: Cologne and MPI

Deliverables of WP5

Guidelines for Algorithmic Experiments

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D4	Guidelines for algorithmic experiments (internal release)	6	12
D10	Guidelines for algorithmic experiments (external release)	12	36

Description: Deliverable D10 is a volume [483] in the Springer LNCS series, and is the outcome of a Dagstuhl Seminar on Experimental Algorithmics arranged by Rudolf Fleischer (MPII), Bernard Moret (U. of New Mexico), and Erik Meineche-Schmidt (Aarhus) in September 2000. It contains a comprehensive collection of articles on algorithm engineering methodology and algorithm engineering cases studies. Deliverable D4 was the table of contents of the (at that time) still unpublished volume.

Sites involved: Aarhus, MPI

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D5	Testbed for experimental algorithmics (specification)	6	6
D13	Testbed for experimental algorithmics (internal release)	18	18
D21	Testbed for experimental algorithmics (external release)	24	26
D30	Testbed for experimental algorithmics (final release)	36/42	42

Description: Deliverable D5, D13, D21, and D30 constitute ExpLab, a set of software tools for executing, documenting, visualizing, and reproducing algorithmic experiments. The main goals of this tool set are:

- To provide a simple way to set up and run computational experiments.
- To provide a means of automatically documenting the environment in which an experiment is run so the experiment can be easily rerun (provided the same environment is still available) and the results can be more accurately compared to the results of other computational experiments.
- To eliminate some of the tedium involved in collecting and analyzing output by providing basic text output processing tools.

In particular, the point is not to replace existing tools that already provide useful functionality for computational experiments (such as gnuplot, make, perl, python). Rather, ExpLap extends the functionality already available, and provides new tools giving a more comfortable and productive experimentation environment with more easily reproducible results, thereby promoting scientific integrity. The software can be downloaded from ExpLaps web site `sourceforge.net/projects/explab/`.

Sites involved: MPI

Deliverables of WP6

Progress Reports

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D12	First progress report	12	12
D22	Second progress report	24	24
D32	Third progress report	36/42	42
D33	Final report	36/42	42

Description: Deliverables D12, D22, D32, and D33 are the three progress reports and the final report for the ALCOM-FT project. They describe the work performed during the three periods June 1, 2000 to May 31, 2001, June 1, 2001 to May 31, 2002, and June 1, 2002 to November 30, 2003, as well as the entire project period June 1, 2000 to November 30, 2003.

Sites involved: All sites.

Project Presentation

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D2	Project Presentation	3	3

Description: Deliverable D2 is the main ALCOM-FT web site, which contains a description of the project, a list of the participants, online access to all deliverables of the project, and information on further activities like summerschools. The web site can be found at `http://www.brics.dk/ALCOM-FT/`.

Sites involved: Aarhus

Web Sites for Dissemination of Algorithmic Knowledge

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D11	Algorithm Forum web site	12	12
D14	PR web-pages for algorithmics	18/36	36

Description: Two websites launched as part of the dissemination effort of the ALCOM-FT project. Deliverable D11 is a site facilitating the sharing of lecture notes produced by members of the scientific community (inside as well as outside ALCOM). It can be found at `http://www.brics.dk/ALCOM-FT/LNC/`. D14 is a site aiming at describing algorithmic problems and solutions in a way which is easily understood by non-scientists, e.g. people from industry. It does so by reporting success stories on collaboration among theorists and practitioners, and by providing a repository of descriptions of problems and techniques. It can be found at `http://www.mpi-sb.mpg.de/~spyros/pr-www/`.

Sites involved: Aarhus and MPI

Dissemination, Use, and Technology Implementation Plans

No.	*Deliverable*	*Month Planned*	*Month Delivered*
D3	Dissemination and Use Plan	6	6
D31	Technology implementation plan	36/42	–

Description: Two required deliverables for IST projects. The documents delineate the consortiums plans for dissemination, use, and technology transfer of the results achieved in the project. The Technology Implementation Plan is due February 1, 2004.

Sites involved: All sites

Part III Scientific Reports

In the following, we list all 538 scientific reports (and two further ALCOM-FT related references [443, 483]) which have been published in the ALCOM-FT Technical Report Series. All reports are available online at `www.brics.dk/ALCOM-FT/TR`.

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