07151 Abstracts Collection
Geometry in Sensor Networks
— Dagstuhl Seminar —

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Abstract. From 9.4.2007 to 13.4.07, the Dagstuhl Seminar 07151 "Geometry in Sensor Networks" was held in the International Conference and Research Center (IBFI), Schloss Dagstuhl. During the seminar, several participants presented their current research, and ongoing work and open problems were discussed. Abstracts of the presentations given during the seminar as well as abstracts of seminar results and ideas are put together in this paper. The first section describes the seminar topics and goals in general. Links to extended abstracts or full papers are provided, if available.

Keywords. Sensor networks, computational geometry, distributed algorithms, mobile computing

07151 Executive Summary – Geometry In Sensor Networks

Networks of smart sensors offer exciting new possibilities for achieving sensory omnipresence: tiny, inexpensive, untethered sensor devices can measure and observe various environmental parameters, thereby allowing real-time and fine-grained monitoring of physical spaces around us. In order to realize this vision, however, several challenging research problem must be solved, many of which involve geometry due to the embedded nature of sensor devices. The aim of this seminar, held from April 10 to April 13, 2007, was to bring together experts from several areas of computer science and mathematics for discussions and exchange of ideas on the role of geometry in the evolution of sensor networks. Enabled by recent advances in micro-electronics and fabrication, a new generation of integrated embedded devices, called *smart sensors*, has emerged that seems capable of realizing the long-cherished vision of *sensory omnipresence* or *ubiquitous awareness*. Through collaboration and *ad hoc* wireless networking, a collection of such devices can provide real-time, fine-grained sensing, monitoring, and actuation across large geographical areas. A key fact distinguishing sensor networks from other networked systems is that sensor nodes are *embedded* in the physical environment in which they function. For instance, unlike more traditional networks such as the Internet or the phone network, communication in sensor networks is dictated less by the desires of the end nodes and more by the geography of the sensor field and the associated signal landscapes, as well as the overall network task. As a result, geometry plays a fundamental and crucial role in all aspects of the sensor network, including their design and operation. In particular, the network must discover its own geometry through self-localization of nodes, construct a lightweight and self-organizing naming and routing structure using virtual or physical coordinates, exploit physical embedding to perform information aggregation and dissemination etc. Motivated by these observations, the discussion during the workshop focused largely on techniques of a geometric or topological character that are particularly relevant to sensor networks.

We give a brief roundup of the excellent presentations: Pilu Crescenzi presented Bluetooth connectivity problems stemming from unavailable neighbor information. Leszek Gasieniec discussed how to escape the quadratic lower bound in geo-routing by including pre-processed information. Erik Jan van Leeuwen exhibited better approximation algorithms for disk graphs with bounded ply. Bastian Katz presented a new sensor network localization heuristic based on recursively applying rigidity theory, and discussed noisy measurements. Andrzej Pelc surveyed results on broadcasting in radio networks. Zvi Lotker discussed the MST of random geometric graphs, and its connection to the upper box dimension. Leonidas Guibas discussed how to aggregate data from sparse events by double rulings. Anish Arora continued presenting results about data aggregation with data of nearby nodes being fresher. Jie Gao presented new sensor network localization heuristics by means of rigidity theory, similarly as Bastian Katz. Jung-Geon Park discussed localization in a mobile environment. Alex Kroeller and Sandor Fekete first showed their video on sensor networks, and then presented new results on energy constrained flow problems. Michael Elkin gave new insights into distributed sparse spanner constructions in a dynamic model. Lata Narayanan presented an impossibility result for geo-routing in 3D, and a complementing possibility result for "$2\frac{1}{2}$D." Andrea Richa and Christian Scheideler presented SIT, a new model beyond the unit disk graph, and a new algorithm for dominating sets in this model, using only constant storage. Li Erran Li investigated how much it helps to communicate with two power levels. Paolo Santi discussed new theoretical and practical insights in topology control. Shakhar Smorodinsky surveyed various results in conflict-free coloring. Alon Efrat gave a talk on sensor coverage, with a survey on the related art gallery problem.

One common and recurring theme in many talks and discussions was the lack of an appropriate model for sensor networks. For instance, many theoretically elegant results for routing in ad hoc wireless networks have been derived using the idealized unit-disk model, which fails to capture the intricate reality of radio transmission.

An open problem session was held on April 10, 2007, the first day of the workshop. Several participants (Roger Wattenhofer, Evangelos Kranakis, Li Erran

Li, Paolo Penna, Zvi Lotker, Leonidas Guibas) posed specific technical problems that have defied progress. Many of these problems elicited significant discussion among the participants, and in some cases participants even pointed to known or related results in their fields.

A general discussion forum was held on the last evening of the seminar, April 12, 2007, to speculate about the promising future directions of research in this young and emerging field. Many people felt that sensor networks are significantly different from general-purpose networks (such as the Internet) and a close coupling of applications and the networking will be important, unlike the Internet that advocates a clean separation of different layers.

In conclusion, the seminar offered a great opportunity for researchers with different, but overlapping, interests to share their expertise, and engage in intellectually stimulating discussions about the important future directions. The format of the workshop provided an ideal environment to question various assumptions in each others' work, find ideas and inspiration in their results, and get a better, more holistic, sense of how different areas of expertise can contribute to this emerging technology. Geometric approaches, through concepts and techniques, offer a number of opportunities in sensor networks to address problems at structural, functional and application levels. It is our belief that the exchange of ideas among the participants of this workshop will impact how they approach their future research in sensor networks and influence the field.

Keywords: Sensor networks, computational geometry, distributed algorithms, mobile computing

Joint work of: Suri, Subhash; Wattenhofer, Roger; Widmayer, Peter

A little geometry goes a long way: On scalable snapshots

Anish Arora (Ohio State University, USA)

We derive a distributed algorithm that periodically delivers at each node in a 2-D network a global snapshot of the state of each node, where each state has (i) distance sensitive latency, (ii) distance sensitive resolution, and (iii) distance sensitive rate. The algorithm uses constant size messages and $\mathcal{O}(\log N)$ memory at each node, where N is the number of nodes.

Keywords: Wireless sensor networks, snapshots

Joint work of: Arora, Anish; Kulathumani, Vinodkrishnan

On the Connectivity of Bluetooth-Based Ad Hoc Networks

Pierluigi Crescenzi (University of Firenze, I)

We study the connectivity properties of a family of random graphs which closely model the Bluetooth's device discovery process, where each device tries to connect to other devices within its visibility range in order to establish reliable communication channels yielding a connected topology.

Specifically, we provide both analytical and experimental evidence that when the visibility range of each node (i.e., device) is limited to a vanishing function of n, the total number of nodes in the system, full connectivity can still be achieved with high probability by letting each node connect only to a "small" number of visible neighbors. Our results extend previous studies, where connectivity properties were analyzed only for the case of a constant visibility range, and provide evidence that Bluetooth can indeed be used for establishing large ad hoc networks.

Keywords: Ad hoc network, random graph, Bluetooth

Joint work of: Crescenzi, Pierluigi; Nocentini, Carlo; Pietracaprina, Andrea; Pucci, Geppino; Sandri, Carlo

See also: P. Crescenzi, C. Nocentini, A. Pietracaprina, G. Pucci, and C. Sandri. On the Connectivity of Bluetooth-Based Ad Hoc Networks, Thirteenth International European Conference on Parallel and Distributed Computing, 2007 (to appear).

A near-optimal distributed fully dynamic algorithm for maintaining sparse spanners

Michael Elkin (Ben Gurion University, IL)

In this paper we develop a *fully dynamic* distributed algorithm for maintaining *sparse spanners*. Our algorithm improves drastically the *quiescence time* of the state-of-the-art algorithm for the problem. Moreover, we show that the quiescence time of our algorithm is optimal up to a small constant factor.

In addition, our algorithm improves significantly upon the state-of-the-art algorithm in *all efficiency parameters*, specifically, it has smaller quiescence message and space complexities, and smaller local processing time. Finally, our algorithm is self-contained and fairly simple, and is, consequently, amenable to implementation on unsophisticated network devices.

We also devise *streaming* and *fully dynamic centralized* algorithms for constructing sparse spanners that improve the respective state-of-the-art algorithms for this task.

Keywords: Dynamic distributed spanner

Discovery of Sensor Network Layout using Connectivity Information

Jie Gao (SUNY at Stony Brook, USA)

We propose a distributed algorithm to discover and recover the layout of a large sensor network having a complex shape.

As sensor network deployments grow large in size and become non-uniform, localization algorithms suffer from "flip" ambiguities—where a part of the network folds on top of another while keeping all edge length measurements preserved. We explore the high-order topological information in a sensor field to prevent incorrect flips and accurately recover the shape of the sensor network. We select landmarks on network boundaries with sufficient density, construct the landmark Voronoi diagram and its dual combinatorial Delaunay complex on these landmarks. The key insight is that when the landmarks are dense enough to capture the local geometric complexity, the combinatorial Delaunay complex is globally rigid and has a unique realization in the plane. An embedding by simply gluing the Delaunay triangles properly derives a faithful network layout, which consequently leads to a practical and sufficiently accurate localization algorithm. We prove the global rigidity of the combinatorial Delaunay complex in the case of a continuous geometric region. Simulation results on discrete networks show surprisingly good results, while multi-dimensional scaling and rubberband representation perform poorly or not at all in recovering the network layout.

Keywords: Sensor Networks, Localization, Delaunay complex, Rigidity

Joint work of: Gao, Jie; Lederer, Sol; Wang, Yue

Full Paper: http://drops.dagstuhl.de/opus/volltexte/2007/1114

Routing of single-source and multiple-source queries in static sensor networks

Leszek Gasieniec (University of Liverpool, GB)

In this paper, we introduce new geometric ad-hoc routing algorithms to route queries in static sensor networks. For single-source-queries routing, we utilise a centralised mechanism to accomplish a query using an asymptotically optimal number of transmissions $\mathcal{O}(c)$, where c is the length of the shortest path between the source and the destination. For multiple-source-queries routing, the number of transmissions for each query is bounded by $\mathcal{O}(c \log n)$, where n is the number of nodes in the network. For both single-source and multiple-source queries, the routing stage is preceded by preprocessing stages requiring $\mathcal{O}(nD)$ and $\mathcal{O}(n^2 D)$ transmissions, respectively, where D is the diameter of the network. Our algorithm improves the complexity of the currently best known algorithms in terms of the number of transmissions for each query. The preprocessing is worthwhile if it is followed by frequent queries. We could also imagine that there is an extra initial power (say, batteries) available during the preprocessing stage or alternatively the positions of the sensors are known in advance and the preprocessing can be done before the sensors are deployed in the field. It is also worth mentioning that a lower bound of $\Omega(c^2)$ transmissions has been proved if preprocessing is not allowed [F. Kuhn, R. Wattenhofer, A. Zollinger, Asymptotically optimal geometric mobile ad-hoc routing, in: Proceedings of the Sixth International Workshop on Discrete Algorithm and Methods for Mobility, Atlanta, GA, September 2002, pp. 2433].

Keywords: Wireless sensor network, Geometric routing, Communication, Design and analysis of algorithms, Memory constraint

Joint work of: Gasieniec, Leszek; Su, Chang; Wong, Prudence; Xin, Qin

Full Paper:
http://dx.doi.org/10.1016/j.jda.2006.03.012

Sparse Data Aggregation in Sensor Networks

Leonidas J. Guibas (Stanford University, USA)

We study the problem of aggregating data from a sparse set of nodes in a wireless sensor network. This is a common situation when a sensor network is deployed to detect relatively rare events. In such situations, each node that should participate in the aggregation knows this fact based on its own sensor readings, but there is no global knowledge in the network of where all these interesting nodes are located. Instead of blindly querying all nodes in the network, we show how the interesting nodes can autonomously discover each other in a distributed fashion and form an ad hoc aggregation structure that can be used to compute cumulants, moments, or other statistical summaries. Key to our approach is the capability for two nodes that wish to communicate at roughly the same time to discover each other at a cost that is proportional to their network distance. We show how to build nearly optimal aggregation structures that can further deal with network volatility and compensate for the loss or duplication of data by exploiting probabilistic techniques.

Keywords: Wireless sensor network, data aggregation

Joint work of: Guibas, Leonidas J.; Gao, Jie; Hershberger, John; Milosavljevic, Nikola

Rigid Components as Means for Direction-based Localization

Bastian Katz (Universität Karlsruhe, D)

Many applications in sensor networks require positional information of the sensors. Recovering node positions is closely related to graph realization problems for geometric graphs. Here, we address the case where nodes have angular information. Whereas Bruck et al. proved that the corresponding realization problem together with unit-disk-graph-constraints is $\mathcal{NP}$-hard, we focus on rigid components which allow both efficient identification and fast, unique realizations. Our technique allows to identify maximum rigid components in graphs with partially known rigid components using a reduction to maximum flow problems. This approach is analyzed for the two-dimensional case, but can easily be extended to higher dimensions.

Keywords: Sensor networks, direction-based localization, parallel rigidity

Joint work of: Gaertler, Marco; Katz, Bastian; Wagner, Dorothea

See also: B. Katz, M. Gaertler, and D. Wagner. Maximum Rigid Components as Means for Direction-based Localization. Proceedings of the 33rd International Conference on Current Trends in Theory and Practice of Computer Science (SOFSEM'07), pp. 330-341, 2007

A Distributed Multi-scale Positioning Scheme for Noisy Measurements

Bastian Katz (Universität Karlsruhe, D)

Positioning is one of the most fundamental problems in sensor networks: Given the network's connectivity graph and some additional local information on measured distances and/or angles, the goal is to recover the nodes' positions. Varying the assumptions regarding the nature and the quality of the measurements, there has been extensive research for both hardness results and practical, distributed, positioning schemes. This paper addresses these issues for a setting that appears to be most likely in real-world scenarios in the future – nodes can *roughly* measure distances and *relative* angles. We will show that this problem is $\mathcal{NP}$-hard like most positioning problems even for arbitrarily small errors. We will also propose an algorithm combining robustness to erroneous measurements and scalability in a completely distributed fashion and provide simulation results for networks of up to 128k nodes with varying errors.

Keywords: Sensor networks, localization, positioning, noisy measurements, multi-scale optimization, graph filtration

Joint work of: Katz, Bastian; Wagner, Dorothea

See also: B. Katz and D. Wagner. Multi-scale Anchor-free Distributed Positioning in Sensor Networks. Proceedings of the International Workshop on Theoretical and Algorithmic Aspects of Sensor and Ad-hoc Networks (WTASA'07) (to appear), 2007

The "power" of 2 power assignments in wireless sensor networks

Li Erran Li (Bell Labs - Murray Hill, USA)

Power efficient operation is very critical in energy constrained multi-hop wireless networks.

One important technique is to intelligently assign transmission powers to nodes while maintaining network connectivity. Previous work has focused on assigning a single transmission power to each node. This often leads to "power imbalance", where some nodes use much more power than other nodes. This can reduce network lifetime. In this paper, we investigate the problem of two power assignment where nodes alternate the use of these assigned powers. We rigorously formulate the problem of two power assignment under the constraint that the network connectivity is maintained. The objective here is to minimize the maximum average power used by the nodes. We show that in general the problem is not just $\mathcal{NP}$-hard but also hard to approximate. We then propose a distributed localized heuristic to compute the two power assignments. We perform extensive simulations to show that the algorithm can reduce the average power significantly when compared with algorithms that assign a single power. We also present a centralized algorithm with bounded worst case guarantees for the two power assignment problem.

Keywords: Multi-hop wireless networks, Power control, topology control

Joint work of: Bhatia, Randeep; Kashyap, Abhishek; Li, Li Erran

Full Paper:
http://www.bell-labs.com/user/erranlli/publications/Infocom07powerb.pdf

See also: R. Bhatia, A. Kashyap and L. Li, The Power Balancing Problem in Energy Constrained Multi-hop Wireless Networks, INFOCOM, 2007

Moving-Baseline Localization

Jun Geun Park (MIT - Cambridge, USA)

The moving-baseline localization (MBL) problem arises when a group of sensor nodes moves through an environment in which no external coordinate reference is available. Under this setting, each node must employ local sensing and inter-device communication to infer its spatial relationship and motion with respect to other nodes. We describe a method for estimation of motion trajectories of nodes when most or all nodes are moving. We develop a distributed solution to the MBL problem in the plane. We assume that nodes move with constant velocities within a window of observation, and that any node can make measurements of its range to certain sufficiently nearby nodes. We show that MBL in this setting involves a combination of robust hyperbola fitting, trilateration, and subgraph alignment. We implement and analyze our algorithm in a simulation informed by the performance of real UWB devices.

Keywords: Localization, Sensor Networks, Localization Algorithm, Moving-Baseline Localization, Geometry

Joint work of: Park, Jun Geun; Demaine, Erik; Teller, Seth

Broadcasting in Geometric Radio Networks

Andrzej Pelc (Université du Québec en Outaouais, CA)

We consider deterministic broadcasting in geometric radio networks (GRN) whose nodes know only a limited part of the network. Nodes of a GRN (sensors, stations) are situated in the plane and each of them is equipped with a transmitter of some range r. A signal from this node can reach all nodes at distance at most r from it but if a node u is situated within the range of two nodes transmitting simultaneously, then a collision occurs at u and u cannot get any message. Each node knows the part of the network within knowledge radius s from it, i.e., it knows the positions, labels and ranges of all nodes at distance at most s. We study the impact of knowledge radius s on the time of deterministic broadcasting in a GRN with n nodes and eccentricity D of the source.

Our results show sharp contrasts between the efficiency of broadcasting in geometric radio networks as compared to broadcasting in arbitrary graphs. They also show quantitatively the impact of various types of knowledge available to nodes on broadcasting time in GRN. In the important case of radio networks modeled as unit disc graphs (UDG), in which every node knows only its own position, we show a strict difference in complexity between two seemingly similar tasks: broadcasting and activating the network from a single source.

This presentation is based on the following papers:

1. A. Dessmark, A. Pelc, Broadcasting in geometric radio networks, Journal of Discrete Algorithms 5 (2007), 187-201.
2. Y. Emek, L. Gasieniec, E. Kantor, D. Peleg, A. Pelc, C. Su, Upper Bounds on Broadcasting Time in UDG Radio Networks with Unknown Topology, Technical report MCS06-09, The Weizmann Institute of Science, Nov. 2006.
3. Y. Emek, L. Gasieniec, E. Kantor, D. Peleg, A. Pelc, C. Su, Lower Bounds on Broadcasting Time in UDG Radio Networks with Unknown Topology, Technical report MCS07-02, The Weizmann Institute of Science, 2007.

Keywords: Radio network, broadcasting, unit disc graph, knowledge radius

Topology Control with Better Radio Models: Implications for Energy and Multi-Hop Interference

Paolo Santi (CNR - Pisa, I)

The goal of this talk is to understand the impact of simplifications done in modeling WSN on practical usefulness of the obtained theoretical results. We start with the well-know triangular inequality argument used to motivate construction of power-efficient topologies for WSN, and we show how considering realistic energy models, the conclusion drawn in classical results on power spanners (two short hops are better than a long one) is actually reversed.

We then question about practical relevance of other metrics (e.g., low degree) considered very important in the topology control literature.

Keywords: Wireless ad hoc networks, wireless sensor networks, energy consumption, multi-hop intereference, topology control

Full Paper: http://drops.dagstuhl.de/opus/volltexte/2007/1115

Constant Density Spanners for Wireless Ad-Hoc Networks

Christian Scheideler (TU München, D)

An important problem for wireless ad hoc networks has been to design overlay networks that allow time- and energy-efficient routing. Many local-control strategies for maintaining such overlay networks have already been suggested, but most of them are based on an oversimplified wireless communication model.

In this talk, we suggest a model that is much more general than previous models. It allows the path loss of transmissions to significantly deviate from the idealistic unit disk model and does not even require the path loss to form a metric. Also, our model is apparently the first proposed for algorithm design that does not only model transmission and interference issues but also aims at providing a realistic model for physical carrier sensing. Physical carrier sensing is needed so that our protocols do not require any prior information (not even an estimate on the number of nodes) about the wireless network to run efficiently.

Based on this model, we propose a local-control protocol for establishing a constant density spanner among a set of mobile stations (or nodes) that are distributed in an arbitrary way in a 2-dimensional Euclidean space. More precisely, we establish a backbone structure by efficiently electing cluster leaders and gateway nodes so that there is only a constant number of cluster leaders and gateway nodes within the transmission range of any node and the backbone structure satisfies the properties of a topological spanner.

Our protocol has the advantage that it is locally self-stabilizing, i.e., it can recover from any initial configuration, even if adversarial nodes participate in it, as long as the honest nodes sufficiently far away from adversarial nodes can in principle form a single connected component. Furthermore, we only need constant size messages and a constant amount of storage at the nodes, irrespective of the distribution of the nodes. Hence, our protocols would even work in extreme situations such as very simple wireless devices (like sensors) in a hostile environment.

Keywords: Wireless ad hoc networks, spanner, dominating set, self-stabilization

Joint work of: Kothapalli, Kishore; Onus, Melih; Richa, Andrea; Scheideler, Christian

Full Paper:
http://www14.in.tum.de/personen/scheideler

See also: The paper appeared in the 17th ACM Symposium on Parallelism in Algorithms and Architectures (SPAA), 2005.

Conflict-Free Colorings of Shallow Discs

Shakhar Smorodinsky (The Hebrew University of Jerusalem, IL)

We prove that any collection of n discs in which each one intersects at most k others, can be colored with at most $\mathcal{O}(\log^3 k)$ colors so that for each point p in the union of all discs there is at least one disc in the collection containing p whose color differs from that of all other members of the collection that contain p. This is motivated by a problem on frequency assignments in cellular networks, and improves the best previously known upper bound of $\mathcal{O}(\log n)$ when k is much smaller than n.

Keywords: Radio network, disc coloring

Joint work of: Smorodinsky, Shakhar; Alon, Noga

See also: In Proc. of the 22nd ACM Symposium on Computational Geometry, (SoCG 2006). Also accepted to the International Journal of Computational Geometry and Applications (IJCGA), (2007).

Better Approximation Schemes for Disk Graphs

Erik Jan van Leeuwen (CWI - Amsterdam, NL)

We consider Maximum Independent Set and Minimum Vertex Cover on disk graphs. A disk graph is the intersection graph of a set of disks in the plane, i.e. each vertex corresponds to a disk and there is an edge between two vertices if and only if the corresponding disks intersect. Disk graphs are frequently used to model wireless networks. The ply of a given disk graph is the maximum number of disks overlapping any given point in the plane. We propose an asymptotic FPTAS for Minimum Vertex Cover on disk graphs of bounded ply. This scheme can be extended to an Efficient PTAS on arbitrary disk graphs giving a $(1+\epsilon)$-approximation in $2^{\mathcal{O}(1/\epsilon^2)} \cdot n^{\mathcal{O}(1)}$ time, improving on the previously known PTAS by Erlebach, Jansen, and Seidel. We also introduce the notion of level density for disk graphs, a generalization of the notion of ply. We give an asymptotic FPTAS for Maximum Independent Set on disk graphs of bounded level density, which is also a PTAS on arbitrary disk graphs. The approximation schemes presented here are a geometric generalization of Baker's EPTASs for planar graphs.

Keywords: Disk graphs, independent set, vertex cover, approximation schemes, PTAS, wireless ad hoc networks

Full Paper:
http://homepages.cwi.nl/~erikjan/

See also: van Leeuwen, E.J., “Better Approximation Schemes for Disk Graphs” in Arge, L., Freivalds, R. (eds.) *Algorithm Theory - SWAT 2006, 10th Scandinavian Workshop on Algorithm Theory, Riga, Latvia, July 6-8, 2006, Proceedings*, Lecture Notes in Computer Science **4059**, Springer-Verlag, Berlin, 2006, pp. 316–327.