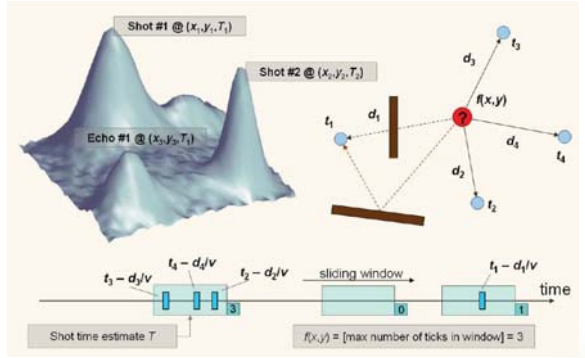




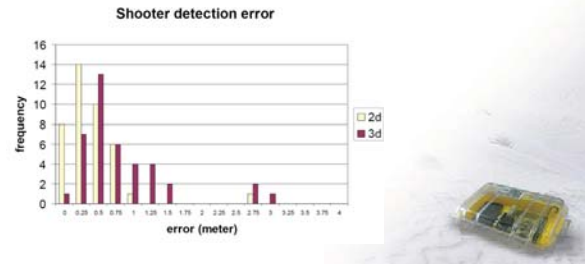
# Positioning

## Chapter 10




# Acoustic Detection (Shooter Detection)



- Sound travels much slower than a radio signal (331 m/s)
- This allows for quite accurate distance estimation (cm)
- Main challenge is to deal with reflections and multiple events



# Rating

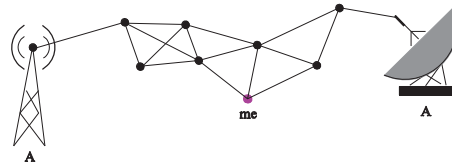
- Area maturity
  - First steps  Text book
- Practical importance
  - No apps  Mission critical
- Theory appeal
  - Booooooring  Exciting

# Overview

- Motivation
- GPS, Geodetics, etc.
- Measuring Distances or Angles
- Rigidity Theory
- Anchors & Virtual Coordinates
- Embeddings, Theory and Heuristics
- Boundary Recognition

## Motivation

- Why positioning?
  - Sensor nodes without location information are often meaningless
  - Avoid having “costly” positioning hardware
  - Geo-routing



- Why **not** GPS (or Galileo)?
  - “Heavy, large, and expensive”
  - Battery drain
  - Not indoors
  - Accuracy?

- Solution: equip small fraction with GPS (**anchors**)



## GPS

- A lot of recent progress, so attaching a GPS receiver to each sensor node becomes an alternative.

- Example, u-blox
  - footprint size: down to 4x4mm
  - Power supply: 1.8 - 4.8V
  - power consumption: 50 mW
  - power on: < 1 second
  - update rate: 4Hz
  - support for Galileo!

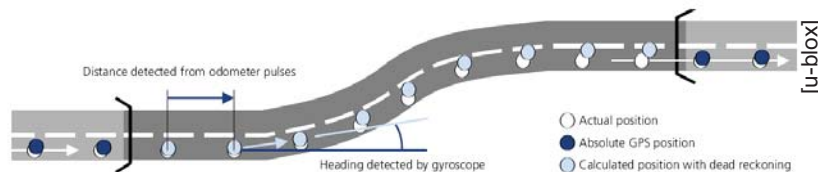


- So GPS is definitely becoming more attractive; however, some of the problems of GPS (indoors, accuracy, etc.) remain.



## GPS Extensions

- GPS chips can be extended with other sensors such as gyroscope, direction indications, or tachometer pulses (in cars). With these add-ons, mobile devices get continued coverage indoors.



- Affordable technology has a distance error of less than 5% per distance travelled, and a direction error of less than 3 degrees per minute.



## Geodetic Networks

[Geodesy pics by Rainer Mautz]

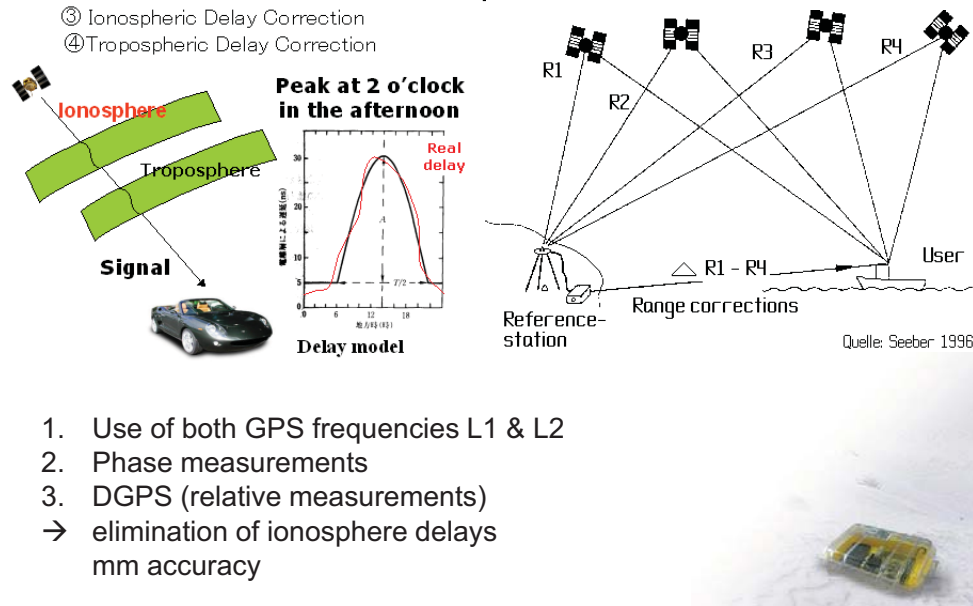
- Optical Sensors
  - Positions through reference points and object points
  - Very accurate (mm)



- GNSS
  - Global Navigation Satellite System
  - Allow phase measurements



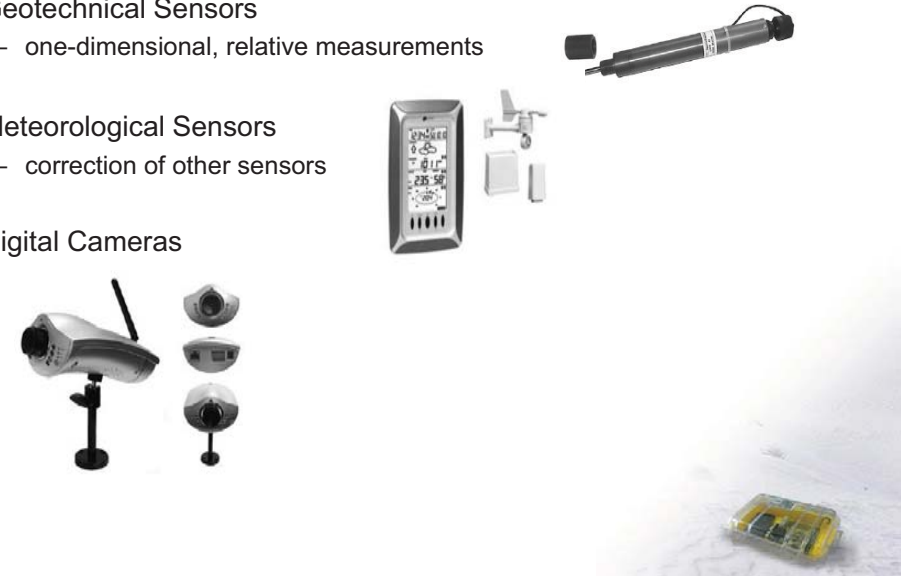
## GPS meets Geodesy



Ad Hoc and Sensor Networks – Roger Wattenhofer – 10/9

## More “Distance” Sensors

- Geotechnical Sensors
  - one-dimensional, relative measurements
- Meteorological Sensors
  - correction of other sensors
- Digital Cameras



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## Geodesy vs. Sensor Nodes

availability:	high
timeliness:	real time
reliability:	no failures
hybrid systems:	to be avoided
local installations:	none
accuracy:	mm - cm
coverage:	global

... but:

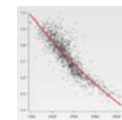


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## Measurements with reasonably priced hardware

### Distance estimation

- Received Signal Strength Indicator (RSSI)
  - The further away, the weaker the received signal.
  - Mainly used for RF signals.
- Time of Arrival (ToA) or Time Difference of Arrival (TDoA)
  - Signal propagation time translates to distance.
  - Routing trip time measurements with specific hardware: accuracy 2-3m
  - Better: Mixing RF, acoustic, infrared or ultrasound.



### Angle estimation

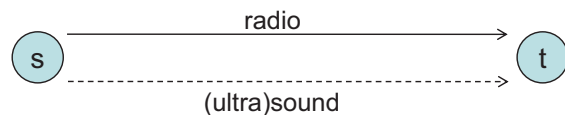
- Angle of Arrival (AoA)
  - Determining the direction of propagation of a radio-frequency wave incident on an antenna array.
- Directional Antenna
- Special hardware, e.g., laser transmitter and receivers.



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## Example: Measuring distance with two radios

- Particularly interesting if the signal speed differs substantially, e.g. sound propagation is at about 331 m/s (depending on temperature, humidity, etc.), which is of course much less than the speed of light.

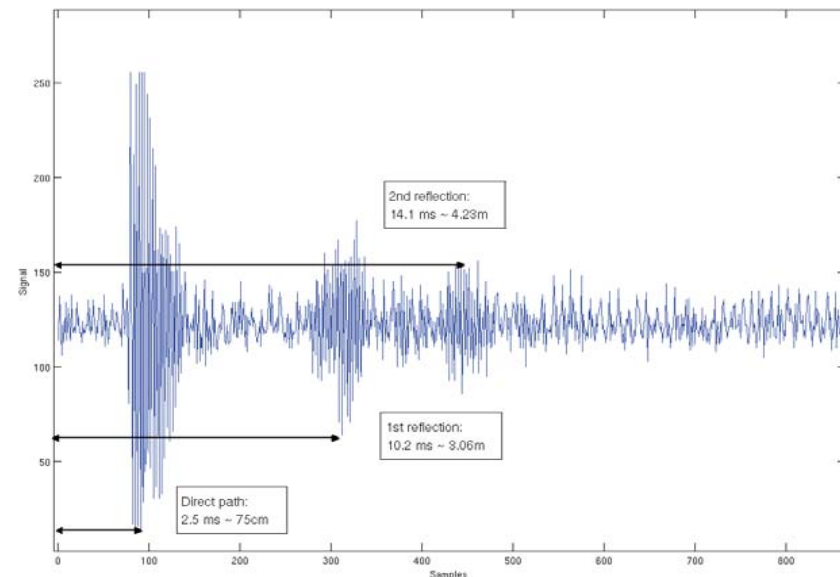


- If you have line of sight you may achieve about a 1cm accuracy. But there are problems
  - (Ultra)sound does not travel far
  - For good results you really need line of sight
  - You have to deal with reflections



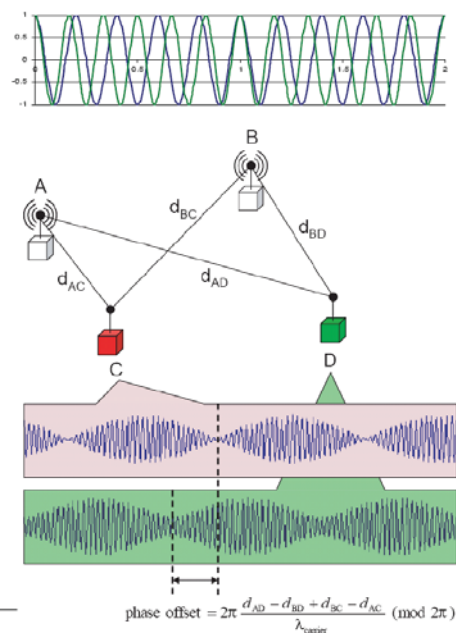
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## Ultrasound Lab Example: Multipath



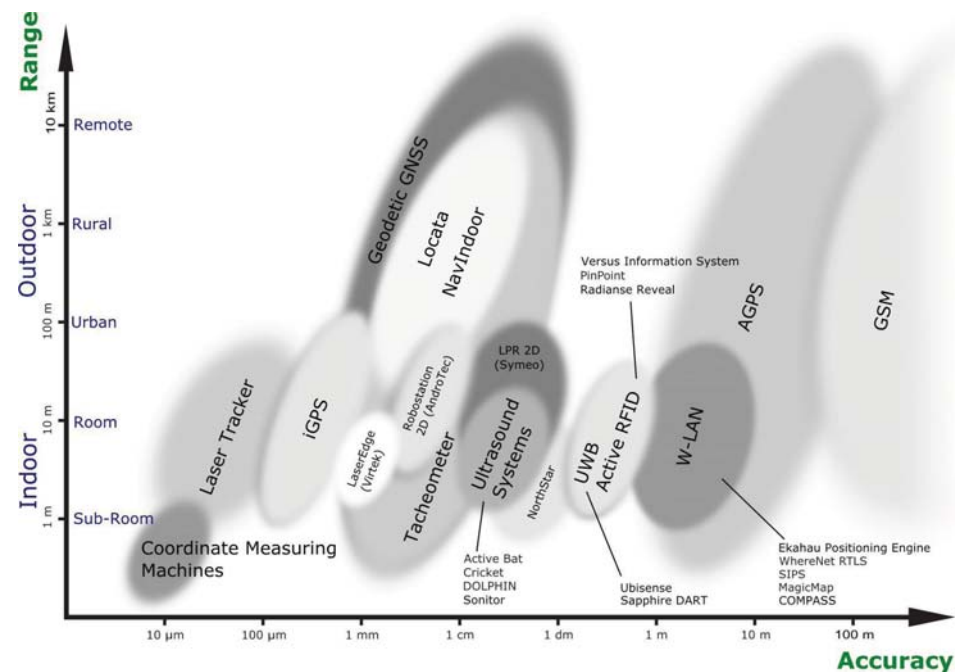
## Interferometry

- Interferometry is the technique of superimposing (interfering) two or more waves, to detect differences between them
- Signals transmitted with a few hundred Hz difference at senders A and B will give different phase offsets at C and D. Using this, one can compute the total distance of the four points A, B, C, D.
- However, one needs to solve a linear equation system, and one needs very accurate time synchronization ( $\mu\text{s}$  order)



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## Positioning Systems: An Overview



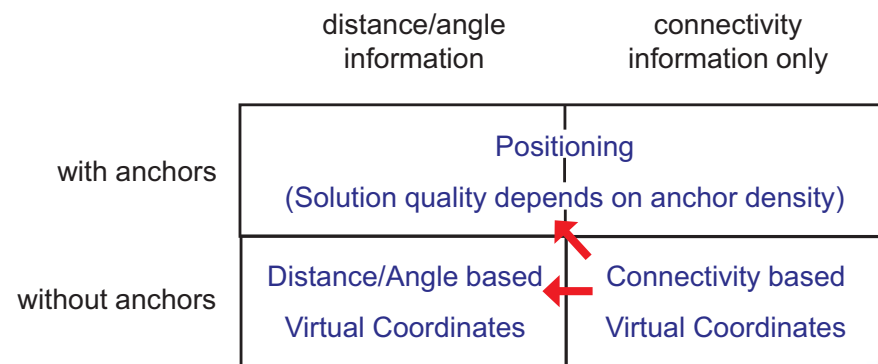


## Positioning in Networks

- Task: Given distance or angle measurements or mere connectivity information, find the locations of the sensors.
- **Anchor-based**
  - Some nodes know their locations, either by a GPS or as pre-specified.
- **Anchor-free**
  - Relative location only. Sometimes called virtual coordinates.
  - Theoretically cleaner model (less parameters, such as anchor density)
- **Range-based**
  - Use range information (distance or angle estimation)
- **Range-free**
  - No distance estimation, use connectivity information such as hop count.
  - It was shown that bad measurements don't help a lot anyway.

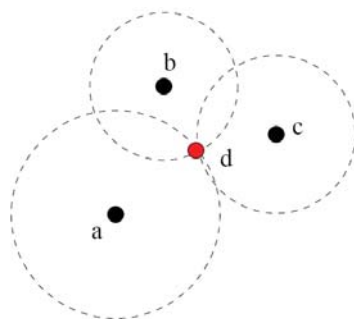


## Overview

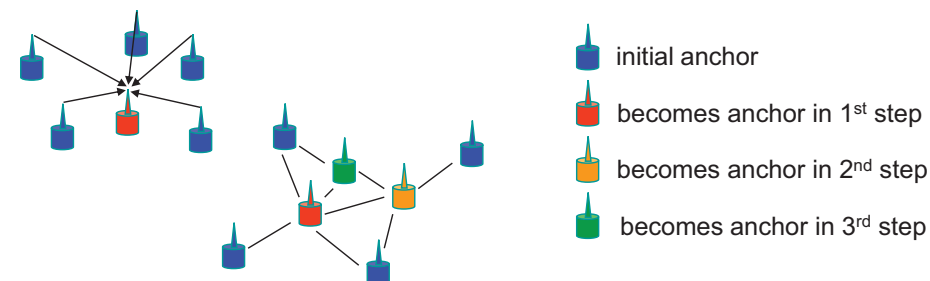


## Trilateration and Triangulation

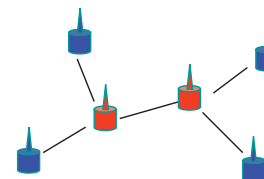
- Use geometry, measure the distances/angles to three anchors.
- **Trilateration**: use distances
  - Global Positioning System (GPS)
- **Triangulation**: use angles
  - Some cell phone systems
- How to deal with inaccurate measurements?
  - Least squares type of approach
  - What about strictly more than 3 (inaccurate) measurements?



## Iterative Multilateration



### Cooperative Multihop Multilateration:

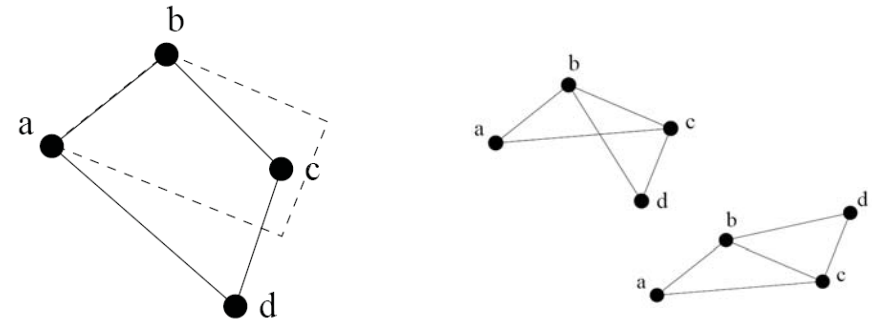


## Problems with Distance Measurements

- No information
  - Pair of nodes simply too far apart
  - Physical obstacles: Line-of-sight needed for ultrasound, laser, infrared, ...
  - Limitations of ranging hardware: Might not be omni-directional.
- Not enough information
  - Too sparse deployment to determine a “globally rigid” structure
- Inaccurate information
  - Measurement errors will sum up
  - Idea: Reduce “depth” of iterative multilateration
  - Trying to get an over-constrained system (to decrease errors)
  - Problem well known in mobile robotics



## Rigidity Theory



[Jie Gao]

- Given a set of rigid bars connected by hinges, rigidity theory studies whether you can move them continuously.
  - Continuous deformations, or flips



## Rigidity Theory

- Theory concerned with when we are guaranteed uniqueness of structures in 2D or 3D (or higher D).
  - Applications to structural engineering, molecular structures
- Definition: An  $n$ -point formation  $P$  in  $d$ -space consists of:
  - Coordinates in  $d$ -space for points  $p_1, \dots, p_n$ , and
  - A set of edges between some points (indices).
  - In other words, a graph embedded in  $d$ -dimensional space.
- Definition: An  $n$ -point formation  $P$  in  $d$ -space is **globally rigid** provided that any other  $n$ -point formation  $Q$  with the same edges and the same distances on those edges is the same as  $P$ , up to translation, rotation, and reflection.
  - Flips are at least locally rigid. Local rigidity makes sense in e.g. structural engineering
  - Continuous deformations are not rigid at all



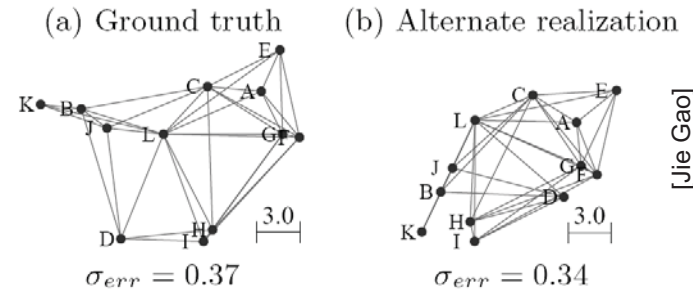
## Global Rigidity

- There are some simple rules that guarantee global rigidity:
- In **2D**, a triangle with distances between all pairs is globally rigid. Starting with a triangle, if we repeatedly add a node and edges (with distances) to at least 3 non-collinear points, it results in a globally rigid point formation.
- In **3D**, a tetrahedron (with all 6 distances) is globally rigid. Starting with a tetrahedron, if we repeatedly add a node and edges (with distances) to at least 4 non-coplanar points, it results in a globally rigid point formation.



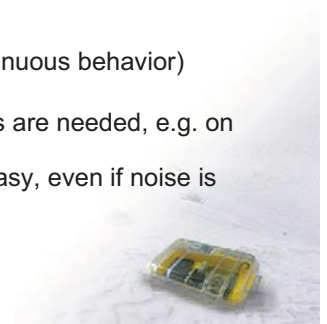
## Noisy distance estimates

- Noise can introduce anomalies
  - We might no longer get exact solutions, but may have some error (difference between given and computed distances). Tolerable, unavoidable.
  - Solutions may no longer be unique, even allowing for small errors: varying the measurements a tiny amount could yield drastically different best solutions.
  - Errors caused by noisy measurements can become compounded through an iterative coordinate assignment procedure.



## Coping with noisy measurements

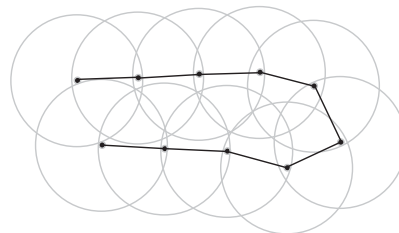
- Idea: Robust quadrilaterals
  - Robust with respect to a bound  $\epsilon$  on error in distance calculations.
  - 4 nodes in 2D, edges (and distances) between all pairs.
  - Nodes spaced so, even with errors, only one realization is possible.
- Method
  - Parameterized by bound  $\epsilon$  on measurement error.
  - Start with a robust quadrilateral, and then add nodes iteratively.
- Discussion
  - Avoids certain kinds of ambiguities (“flip”, discontinuous behavior)
  - But not enough to guarantee global rigidity
  - To guarantee global rigidity, additional constraints are needed, e.g. on angles
  - Intuitively: if angles are too small, then flips are easy, even if noise is bounded



## Rigidity alternative: Simple hop-based algorithms

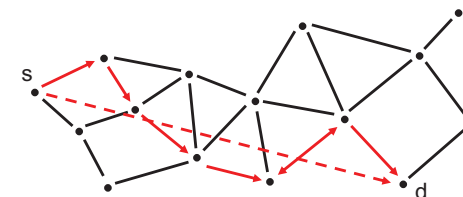
- Algorithm
  - Get hop **distance h** to anchor(s)
  - Intersect circles around anchors
    - radius = distance to anchor
  - Choose point such that **maximum error is minimal**
    - Find **enclosing circle** (ball) of minimal radius
    - Center is calculated location

- In higher dimensions:  $1 < d \leq h$ 
  - Rule of thumb: **Sparse graph**
  - bad performance



## How about no anchors at all...?

- In absence of anchors...
  - ...nodes are clueless about **real coordinates**.
- For many applications, real coordinates are not necessary
  - **Virtual coordinates** are sufficient
  - Geometric Routing requires only virtual coordinates
    - Require no routing tables
    - Resource-frugal and scalable



## Virtual Coordinates

- Idea:
  - Close-by nodes have similar coordinates
  - Distant nodes have very different coordinates

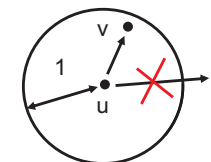
→ Similar coordinates imply physical proximity!

- Applications
  - Geo-Routing
  - Locality-sensitive queries
  - Obtaining meta information on the network
  - Anycast services („Which of the service nodes is closest to me?“)
  - Outside the sensor network domain: e.g., Internet mapping



## Model

- Unit Disk Graph (UDG)** to model wireless multi-hop network
  - Two nodes can communicate iff Euclidean distance is at most 1

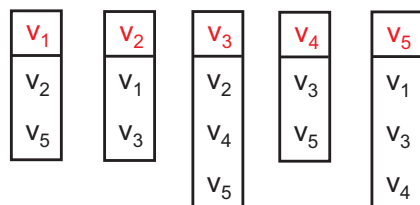


- Sensor nodes may not be capable of
  - Sensing directions to neighbors
  - Measuring distances to neighbors
- Goal: Derive topologically correct coordinate information from **connectivity information** only.
  - Even the simplest nodes can derive connectivity information



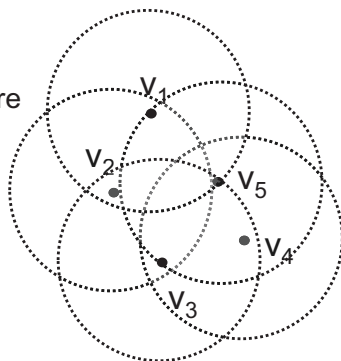
## Virtual Coordinates ↔ UDG Embedding

- Given the **connectivity information** for each node...



...and knowing the underlying graph is a UDG...

...find a UDG embedding in the plane such that all connectivity requirements are fulfilled! (→ Find a realization of a UDG)



**This problem is NP-hard!**

(Simple reduction to *UDG-recognition* problem, which is NP-hard)

[Breu, Kirkpatrick, Comp.Geom.Theory 1998]

## UDG Approximation – Quality of Embedding

- Finding an exact realization of a UDG is NP-hard.
  - Find an embedding  $r(G)$  which **approximates a realization**.
- Particularly,
  - Map adjacent vertices (**edges**) to points which are close together.
  - Map non-adjacent vertices („**non-edges**“) to far apart points.
- Define **quality of embedding**  $q(r(G))$  as:

Ratio between longest edge to shortest non-edge in the embedding.

Let  $\rho(u,v)$  be the distance between points  $u$  and  $v$  in the embedding.

$$q(r(G)) := \frac{\max_{\{u,v\} \in E} \rho(u,v)}{\min_{\{u',v'\} \notin E} \rho(u',v')}$$



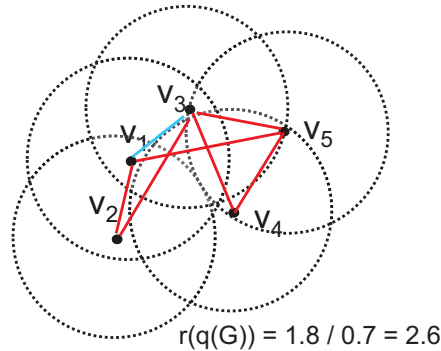
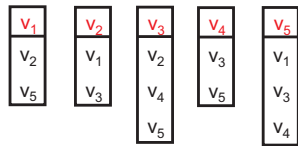
## UDG Approximation

- For each UDG  $G$ , there exists an embedding  $r(G)$ , such that,  $q(r(G)) \leq 1$ . (a realization of  $G$ )

$$q(r(G)) := \frac{\max_{\{u,v\} \in E} \rho(u,v)}{\min_{\{u',v'\} \notin E} \rho(u',v')}$$

- Finding such an embedding is NP-hard
- An algorithm ALG achieves **approximation ratio  $\alpha$**  if for all unit disk graphs  $G$ ,  $q(r_{\text{ALG}}(G)) \leq \alpha$ .

- Example:



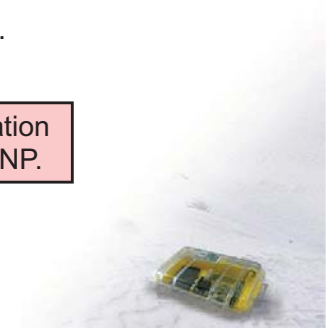
## Some Results

- There are a few virtual coordinates algorithms
- Almost all of them evaluated only by **simulation on random graphs**
- In fact there are very few **provable approximation algorithms**

There is an algorithm which achieves an approximation ratio of  $O(\log^{2.5} n)$ ,  $n$  being the number of nodes in  $G$ . [Pemmaraju and Pirwani, 2007]

Plus there are lower bounds on the approximability.

There is no algorithm with approximation ratio better than  $\sqrt{3}/2 - \epsilon$  unless  $P = NP$ .



## Approximation Algorithm: Overview

- Four major steps

1. Compute **metric** on MIS of input graph  $\rightarrow$  **Spreading constraints** (Key conceptual difference to previous approaches!)

UDG Graph  $G$  with MIS  $M$ .

Approximate pairwise distances between nodes such that, MIS nodes are neatly spread out.

2. **Volume-respecting**, high dimensional **embedding**

Volume respecting embedding of nodes in  $\mathbb{R}^n$  with small distortion.

3. **Random projection** to 2D

Nodes spread out fairly well in  $\mathbb{R}^2$ .

4. Final embedding

Final embedding of  $G$  in  $\mathbb{R}^2$ .

## Lower Bound: Quasi Unit Disk Graph

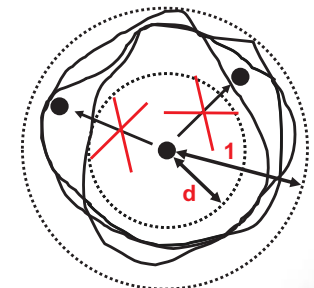
- Definition **Quasi Unit Disk Graph**:

Let  $V \in \mathbb{R}^2$ , and  $d \in [0, 1]$ . The symmetric Euclidean graph  $G=(V,E)$ , such that for any pair  $u,v \in V$

$$\text{dist}(u,v) \leq d \Rightarrow \{u,v\} \in E$$

$$\text{dist}(u,v) > 1 \Rightarrow \{u,v\} \notin E$$

is called  **$d$ -quasi unit disk graph**.



Note that between  $d$  and  $1$ , the existence of an edge is unspecified.



## Reduction

- We want to show that finding an embedding with  $q(r(G)) \leq \sqrt{3/2} - \epsilon$ , where  $\epsilon$  goes to 0 for  $n \rightarrow \infty$  is NP-hard.
- We prove an equivalent statement:

Given a unit disk graph  $G=(V,E)$ , it is NP-hard to find a realization of  $G$  as a  $d$ -quasi unit disk graph with  $d \geq \sqrt{2/3} + \epsilon$ , where  $\epsilon$  tends to 0 for  $n \rightarrow \infty$ .

- Even when allowing non-edges to be smaller than 1, embedding a unit disk graph remains NP-hard!
- It follows that finding an approximation ratio better than  $\sqrt{3/2} - \epsilon$  is also NP-hard.



## Reduction

- Reduction from 3-SAT (each variable appears in at most 3 clauses)
- Given a instance  $C$  of this 3-SAT, we give a polynomial time construction of  $G_C=(V_C, E_C)$  such that the following holds:

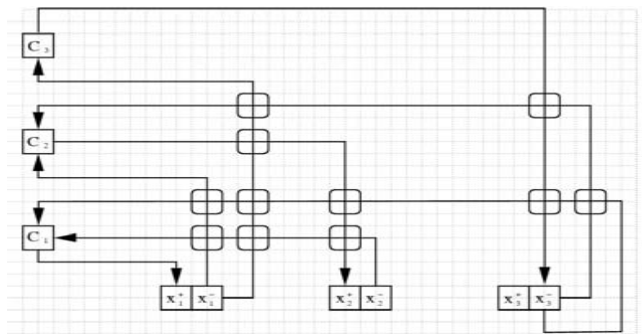
- $C$  is satisfiable  $\Rightarrow G_C$  is realizable as a unit disk graph
- $C$  is not satisfiable  $\Rightarrow G_C$  is not realizable as a  $d$ -quasi unit disk graph with  $d \geq \sqrt{2/3} + \epsilon$

- Unless  $P=NP$ , there is no approximation algorithm with approximation ratio better than  $\sqrt{3/2} - \epsilon$ .



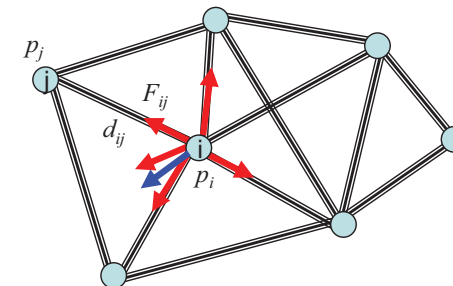
## Proof idea

- Construct a grid drawing of the SAT instance.
- Grid drawing is *orientable* iff SAT instance is satisfiable.
- Grid components (clauses, literals, wires, crossings,...) are composed of nodes  $\rightarrow$  Graph  $G_C$ .
- $G_C$  is *realizable as a  $d$ -quasi unit disk graph* with  $d \geq \sqrt{2/3} + \epsilon$  iff grid drawing is orientable.



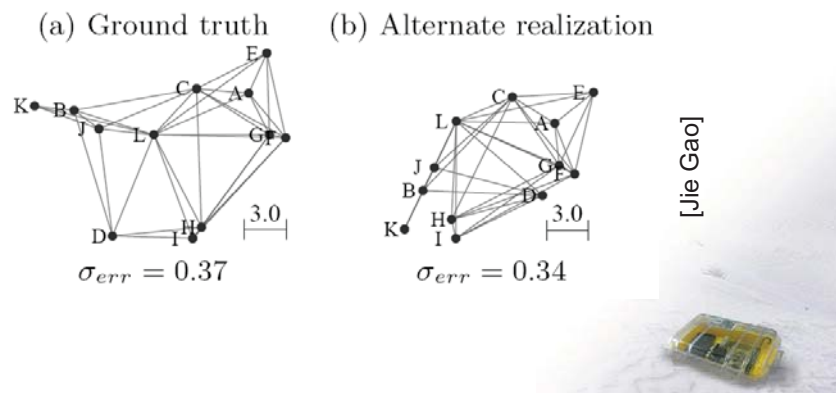
## Heuristics: Spring embedder

- Nodes are “masses”, edges are “springs”.
- Length of the spring equals the distance measurement.
- Springs put forces to the nodes, nodes move, until stabilization.
- Force:  $F_{ij} = d_{ij} - r_{ij}$ , along the direction  $p_i p_j$ .
- Total force on  $n_i$ :  $F_i = \sum F_{ij}$ .
- Move the node  $n_i$  by a small distance (proportional to  $F_i$ ).



## Spring Embedder Discussion

- Problems:
  - may deadlock in local minimum
  - may never converge/stabilize (e.g. just two nodes)
- Solution: Need to start from a reasonably good initial estimation.



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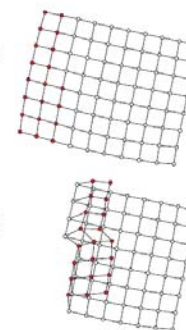
## Heuristics: Priyantha et al.

N.B. Priyantha, H. Balakrishnan, E. Demaine, S. Teller: **Anchor-Free Distributed Localization in Sensor Networks**, *SenSys*, 2003.

iterative process minimizes the layout energy

$$E(p) = \sum_{\{i,j\} \in E} (\|p_i - p_j\| - \ell_{ij})^2$$

- fact: layouts can have *foldovers* without violating the distance constraints
- problem: optimization can converge to such a local optimum
- solution: find a good initial layout *fold-free* → already close to the global optimum (=“real layout”)

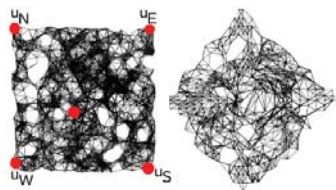


[Fleischer & Pich]

## Heuristics: Priyantha et al. (continued)

Phase 1: compute initial layout

- determine periphery nodes  $u_N, u_S, u_W, u_E$
- determine central node  $u_C$
- use polar coordinates



$$\rho_v = d(v, u_C) \quad \theta_v = \arctan \left( \frac{d(v, u_N) - d(v, u_S)}{d(v, u_W) - d(v, u_E)} \right)$$

as positions of node  $v$

Phase 2: Spring Embedder

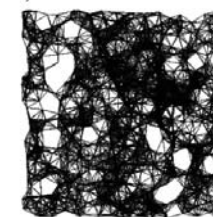
[Fleischer & Pich]

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## Heuristics: Gotsman et al.

C. Gotsman, Y. Koren [5]. **Distributed Graph Layout for Sensor Networks**, *GD*, 2004.

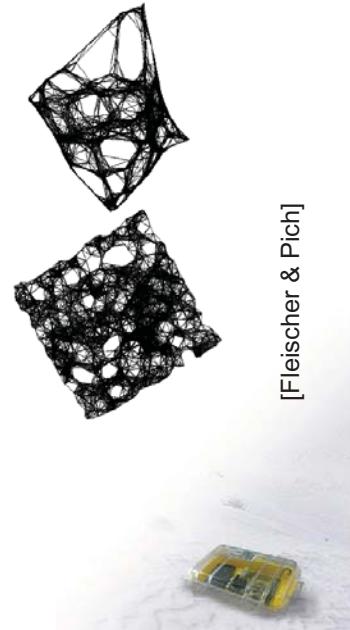
- initial placement: spread sensors  $\frac{\sum_{\{i,j\} \in E} \exp(-\ell_{ij}) \|p_i - p_j\|^2}{\sum_{i < j} \|p_i - p_j\|^2} \rightarrow \min$
- linear algebra: minimized by second highest eigenvector  $v_2$  of  $A$  where 
$$a_{ij} = -\frac{\exp(-\ell_{ij})}{\sum_{j: \{i,j\} \in E} \exp(-\ell_{ij})}$$
 
$$a_{ii} = 1$$
- $x, Ax, A^2x, A^3x, \dots$  converges to  $v_2$
- $x_i \leftarrow \frac{1}{2} \left( x_i + \frac{\sum_{j: \{i,j\} \in E} \exp(-\ell_{ij} x_j)}{\sum_{j: \{i,j\} \in E} \exp(-\ell_{ij})} \right)$
- compute third eigenvector  $v_3$ , use  $v_2, v_3$  as coordinates



[Fleischer & Pich]

## Heuristics: Gotsman et al. (continued)

- ▶ distributed optimization (spring model)
- ▶ alternative: *majorization*
- ▶ compute sequence of layouts  $p^{(0)}, p^{(1)}, p^{(2)}, \dots$  with  $E(p^{(0)}) \geq E(p^{(1)}) \geq E(p^{(2)}) \geq \dots$ 
  - ▶ solve linear equation  $L^{(t+1)}p^{(t+1)} = L^{(t)}p^{(t)}$  in distributed manner



[Fleischer & Pich]

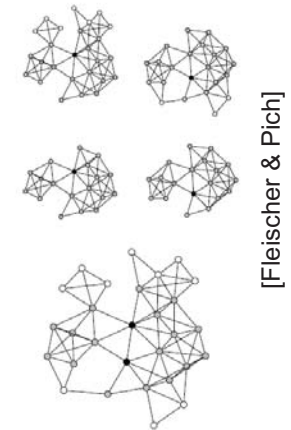
Ad Hoc and Sensor Networks – Roger Wattenhofer – 10/45

## Heuristics: Shang et al.

Y. Shang, W. Ruml [7].

**Improved MDS-based Localization**, *IEEE Infocom*, 2004.

- ▶ compute a local map for each node (local MDS of the 2-hop neighborhood)
- ▶ merge local map patches into a global map (use incremental or binary-tree strategy)
- ▶ apply distributed optimization to the result

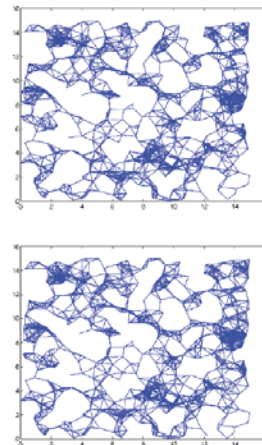


[Fleischer & Pich]

## Heuristics: Bruck et al.

J. Bruck, J. Gao, A. Jiang [8]. **Localization and Routing in Sensor Networks by Local Angle Information**, *Mobile Ad Hoc Networking & Computing*, 2005.

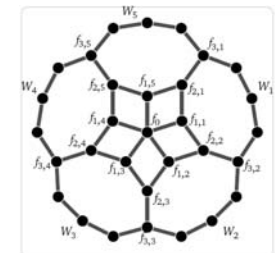
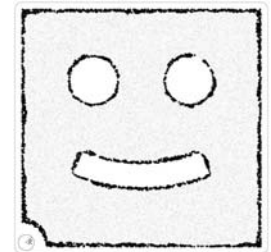
- ▶ Choose an edge  $e$  as  $x$ -axis to obtain absolute angles.
- ▶ Form an LP whose variables are the edge lengths  $\ell(e)$ .
- ▶ For all edges  $0 \leq \ell(e) \leq 1$ .
- ▶ For any cycle  $e_1, \dots, e_p$ :  $\sum_{i=1}^p \ell(e_i) \cos \theta_i = 0$  and  $\sum_{i=1}^p \ell(e_i) \sin \theta_i = 0$ .
- ▶ Non-adjacent node pair constraints.
- ▶ Crossing-edge constraints.



[Fleischer & Pich]

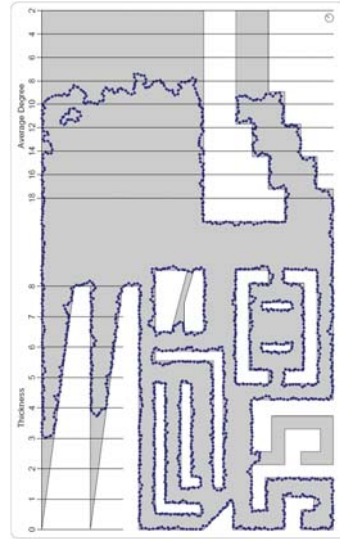
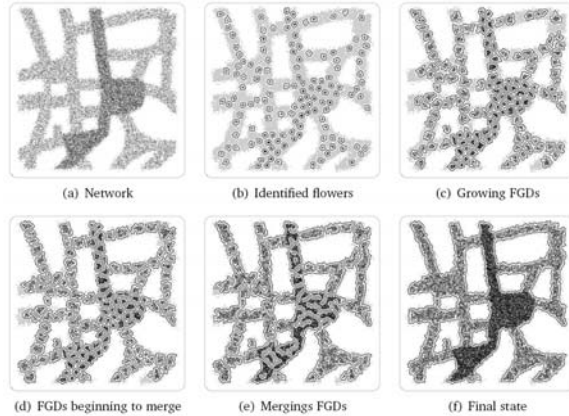
## Boundary recognition

- Related problem, given a connectivity graph, what is the boundary?
- So far heuristics only, one heuristic uses the idea of independent nodes; specifically, an interior (non-boundary) node sees enough (e.g. 5) independent neighbors which in turn have a ring around them; these are called “flowers”. Flowers can be grown and connected to compute the boundary.
- However, this is only a heuristic, and does not always work...





## Boundary recognition



## Open problem

- One tough open problem of this chapter obviously is the **UDG embedding** problem: Given the adjacency matrix of a unit disk graph, find positions for all nodes in the Euclidean plane such that the ratio between the maximum distance between any two adjacent nodes and the minimum distance between any two non-adjacent nodes is as small as possible.
- There is a large gap between the best known lower bound, which is a constant, and the polylogarithmic upper bound. It is a challenging task to either come up with a better approximation algorithm or prove a stronger (non-constant) lower bound. Once we understand this better, we can try networks with anchors, or with (approximate) distance/angle information.
- Generally, beyond GPS this area is in its infancy.

