Algorithmic and Foundational Aspects of Sensor Systems

WAC 2005

Invited talk

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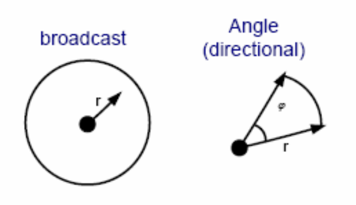
- Sensors:
  - Fully autonomous
  - small (projected 1 mmm^2)
  - can sense temperature

  perfume, radiation
  - low power
  - can execute simple programs
  - can communicate (wireless)

  (Radio, optical less common)
  - cheap
  - may fail easily

  GPS antennae : expensive technology

  Communication at a maximum distance r, power dependent



Sensors Networks:

– a vast number of sensors deployed in an area (2D or 3D)

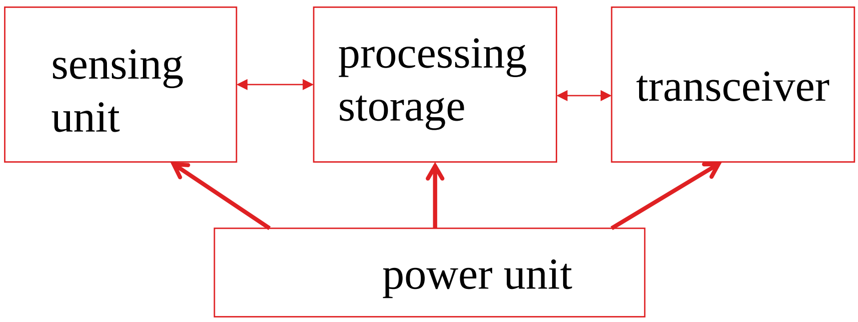
– purpose is to cooperate and accomplish a global task

Ultra small Sensors: Abstracted to points (particles)

– smart dust
– smart dust cloud

– The net may have (one or more) powerful base stations (to collect sensor info and relay to external systems)

Sensor node



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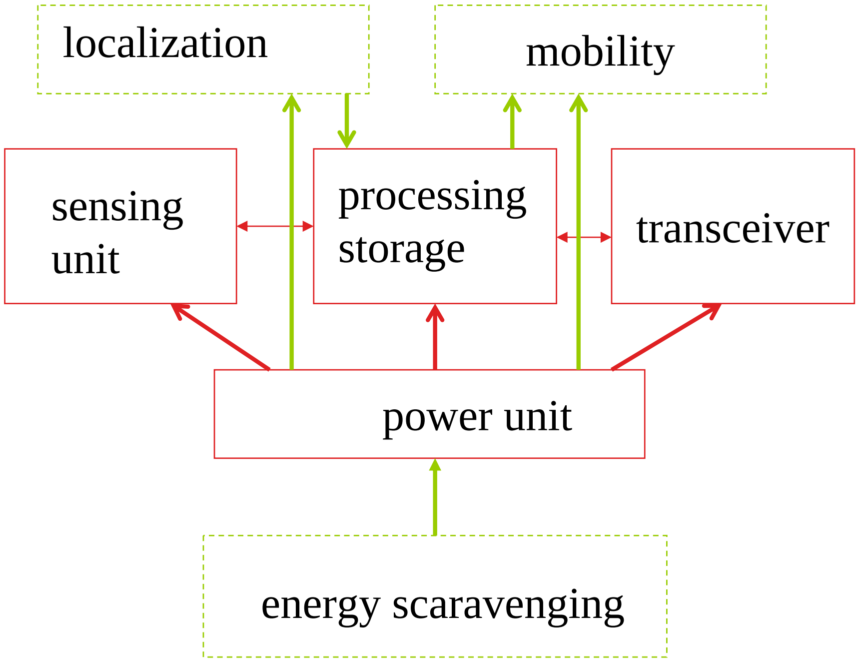


Sensor characterictics:

- consume low power
- autonomous
- operate in high volumetric densities
- adaptive to environment
- cheap

Transceiver unit

- Radio Frequency (RF)
- Optical laser beam (smart dust)

Transceiver unit

- Radio Frequency (RF)

  more expensive and larger. Interference

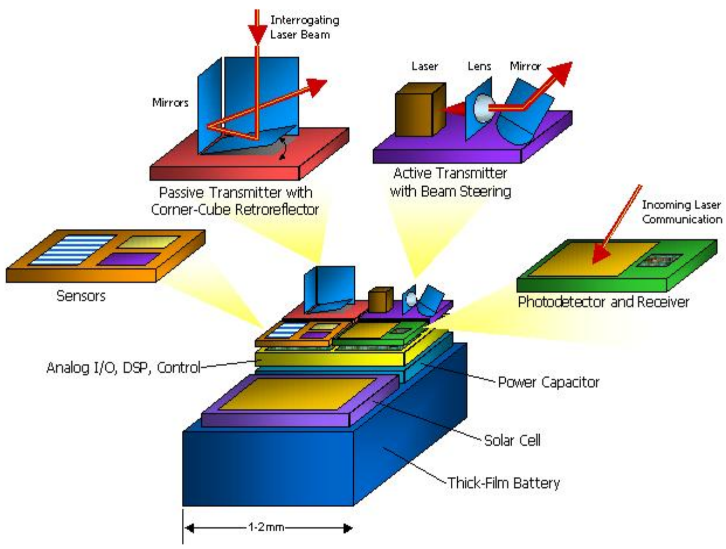
  omnidirectional antenna

  directional antenna
- Optical laser beam (smart dust)

Transceiver unit

- Radio Frequency (RF)
  more expensive and larger. Interference
    omnidirectional antenna
    directional antenna
- Optical laser beam (smart dust)
  need line of sight for communication
  no interference

Ex. Smart Dust:



- Sensor network particles are assumed to take ad-hoc positions in the deployment area.
(particles cannot move, may “drift”)

- The area of deployment may have sub-areas where no sensor can be found (obstacles, lakes)
(e.g. due to massive failures)

- Sensor nets differ from general ad-hoc nets since local resources of each particle are seriously constrained

- What can a sensor net do (or not do) globally ?

- yet another challenge in modern algorithmic thought

- models exist but are partial, premature

- maybe a new algorithmic subfield, results can be basic prerequisite for pragmatic issues

Graph Models for static networks

- Omnidirectional RF
- Directional RF, smart dust

Random Geometric Graphs (RGG)

E.N. Gilbert: Random Plane Networks
J. Soc. Ind. Appl. Math. 9 (4) 533-543, 1961.

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… To construct a random plane network, pick points from the plane by a Poisson process with density D points per unit area. Next joint each each pair of points by a line if they are at distance less that r. …

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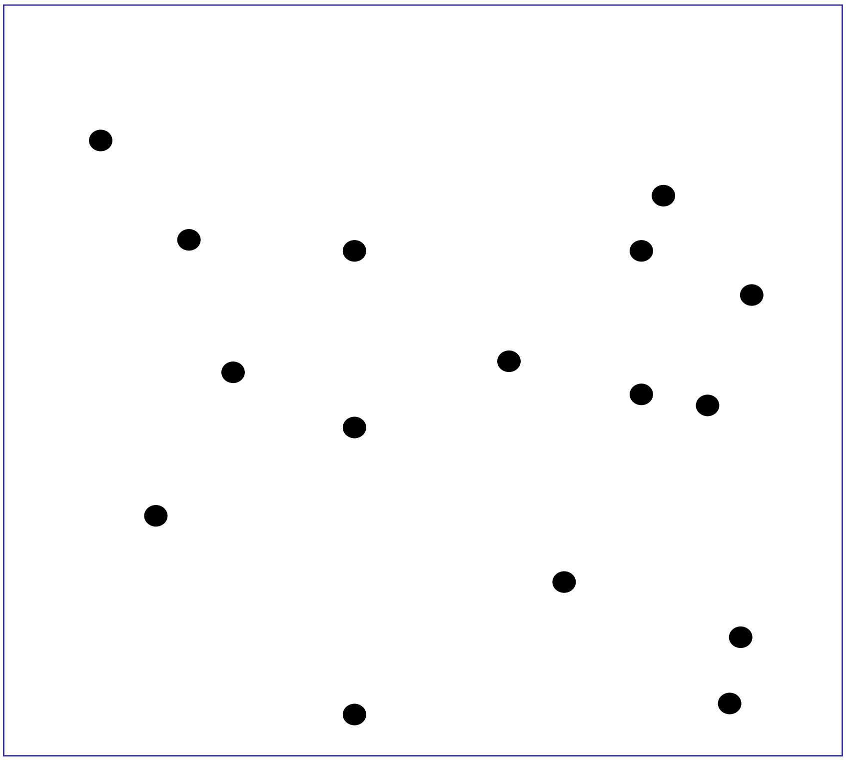
- Given a communication radius r, two points are connected if they are at distance $\leq r$.

RGG



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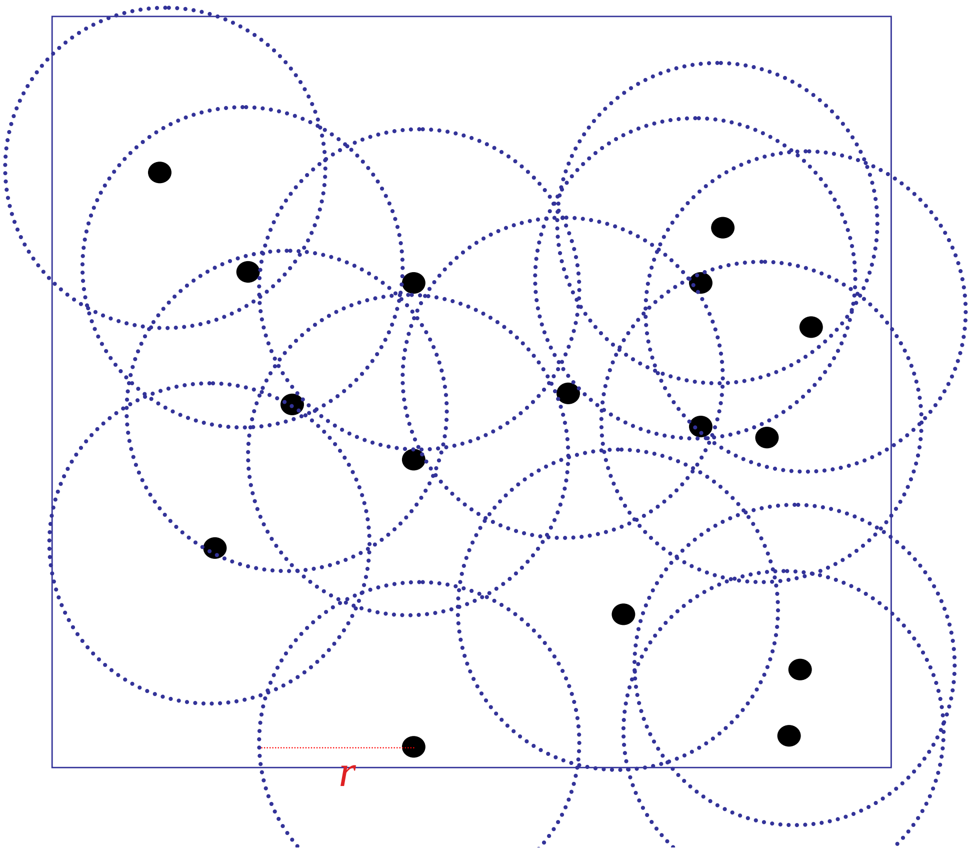

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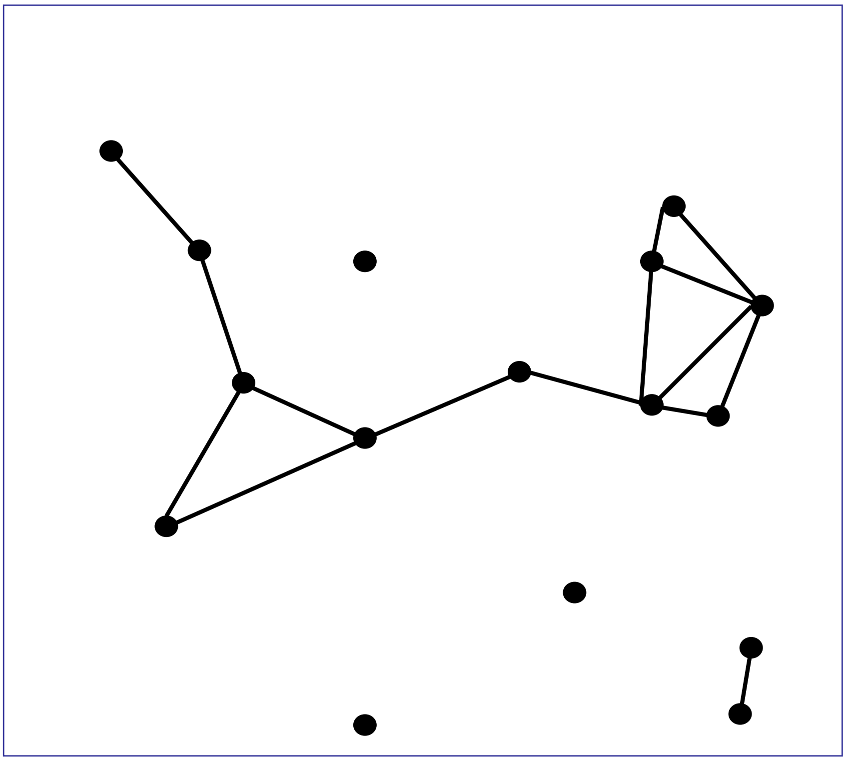

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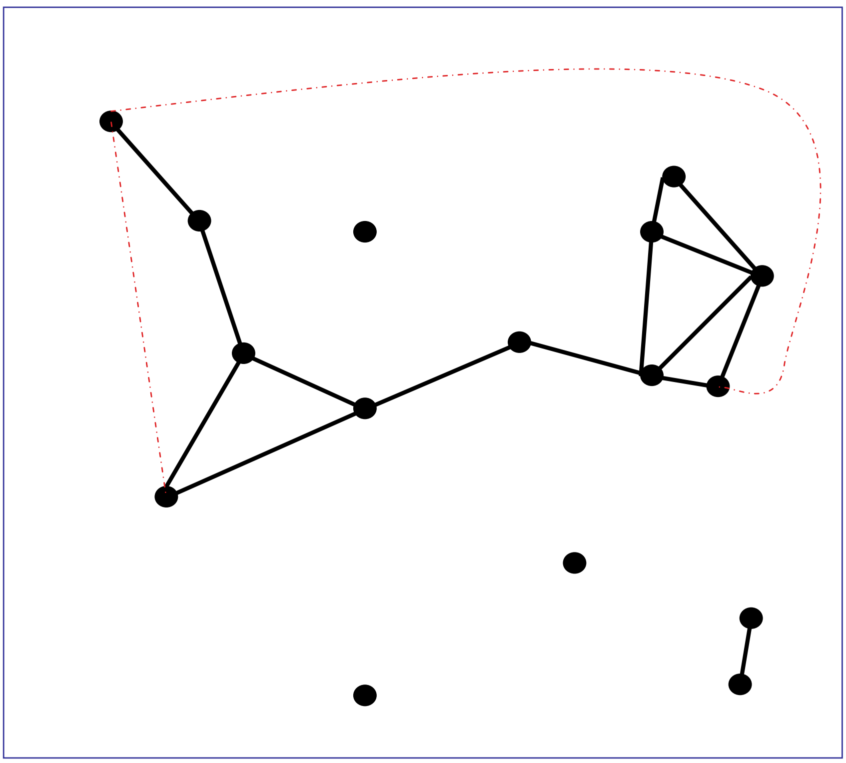

G(n,r) Asymptotic Results:

- Threshold: Given *G(n,r)*, *r(n)* and property *Q*, wish to find smallest $r_Q(n)$ s.t. *Q* holds w.h.p.

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- Thm (Goel, Rai, Krishnamachari-04). Any monotone *Q* of *G(n,r)*, has a threshold.

G(n,r) Asymptotic Results:

- Connectivity(Penrose-97, Gupta-Kumar-98):

Let $r_c^2 = \frac{\log n + \gamma_n}{\pi n}$ then

$$Pr[G(n, r_c) \text{ connected}] = 1 \text{ if } \gamma_c \to +\infty$$

$$Pr[G(n, r_c) \text{ connected}] = 0 \text{ if } \gamma_c \to -\infty$$

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- $r_c = \sqrt{\frac{\log n}{n}}$ is a sharp a threshold for connectivity.

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  If $r < r_c$ (sparse case) $\chi / \omega \longrightarrow$ *1 in prob.*

  If $r \geq r_c$ (dense case) $\chi / \omega \longrightarrow$ *1.103 a.s.*

  C. McDiarmird RSA-2003

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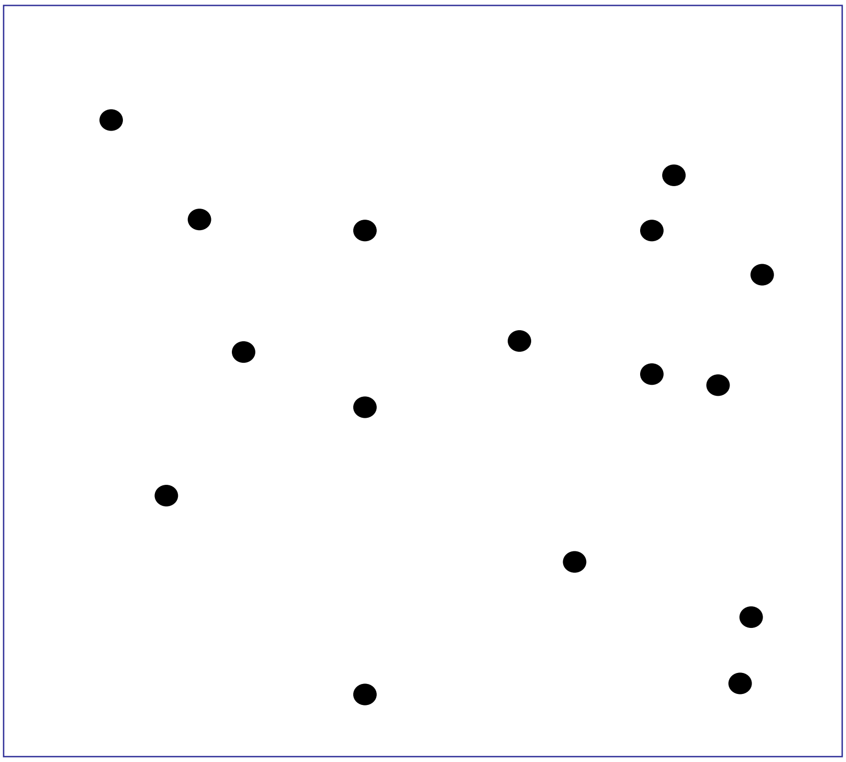
  I.e. in $G(n, r_c)$ each ball contains $\Theta(\log n)$ nodes.

Proximity graph $G(n,\varphi(n))$

- Scale down to $I=[0,1]^2$
- Springle n vertices u.a.r on I
- Connect each vertex v with the $f(n)$ nearest neighbors (euclidian distance)

A measure of the number of nodes needed to connect a network

Example *G(n,3)*



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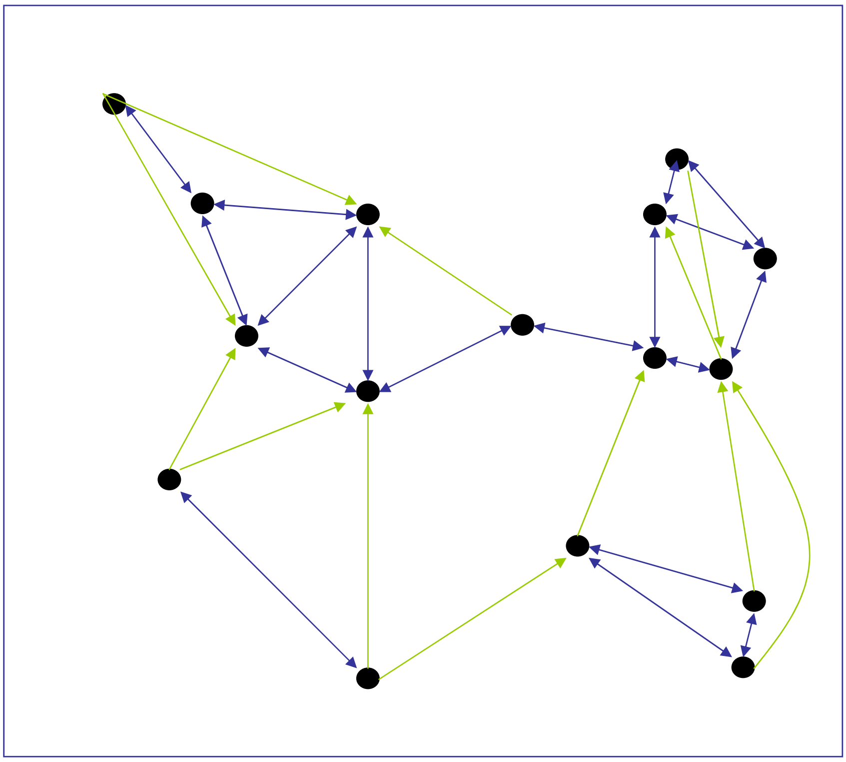

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- (Fan-Xue, Kumar-03) Let *n* = min number of neighbors of any node. If *n* ≤0.0074 log *n*, then whp the graph is disconnected. If *n*≥5.117log *n*, then whp the graph is strongly connected.

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- Open problem: Any monotone property has a sharp threshold property?

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- Fix angle *a*. Let $X_n=\{x_1,..,x_n\}$ i.u.d. points in I, let $B_n=\{\beta_1,..\beta_n\}$ a sequence of i.u.d. angles, let $\{r_i\}$ a sequence in $[0,1]$. $G_a(X_n,B_n,r_n)$ is a random sector graph, where (x,y) is an arc iff y in S_x.

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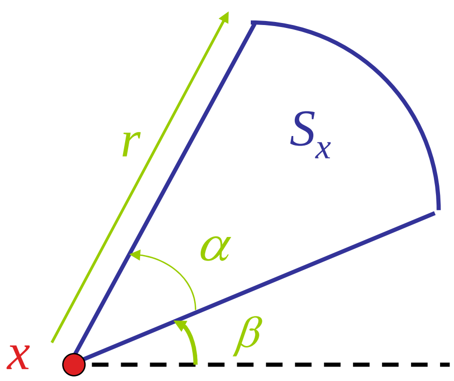
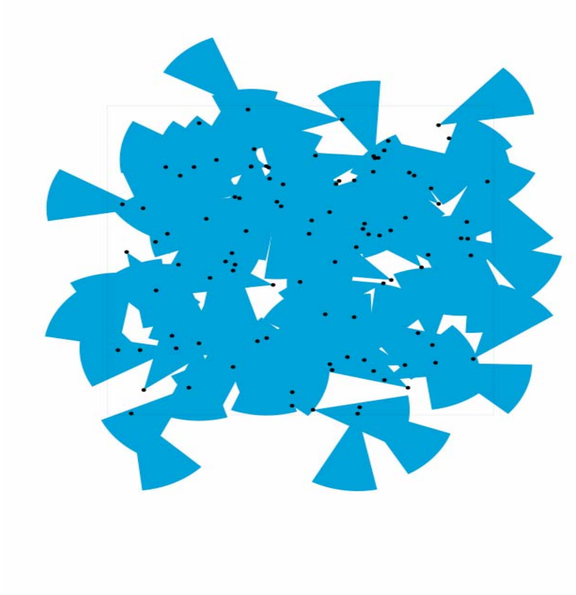
  D.,Petit,Serna IEEE Trans. MobiComp 2004

Model for RSG

Each sensor *x* covers a sector S_x, defined by *r* and *a* (parameters of the system)





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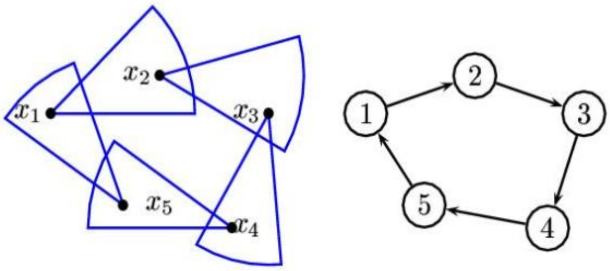
- If x_5 is not in S_{x1}, to communicate from x_1 to x_5:



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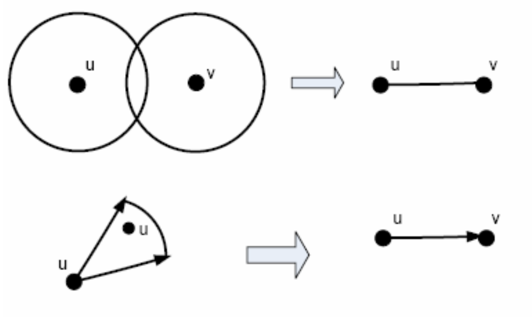
- Undirected chromatic number: Fix r_c

  If $a < \pi$ then $\chi(G) = \Theta(\ln n / \ln\ln n)$ whp

  If $a > \pi$ then $\chi(G) = \Theta(\ln n)$ whp

  [Diaz, Serna, Spirakis 05, TCS]

- New combinatorial objects inspired by sensor nets
  e.g. Random Geometric Networks [Diaz, Penrose] (RGN)



Also Random Intersection Graphs

– Each $u \in V$ has $S_u \subseteq \{1, 2, \ldots, m\}$

– S_u formed by a random experiment

$\{u, v\} \in E$ iff $S_u \cap S_v \neq 0$

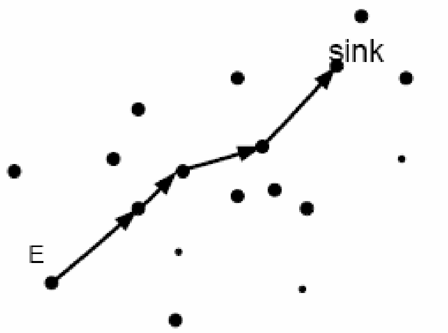
[Karonski, Fill]

[Nikoletseas, Raptopoulos, Spirakis ICALP 04]

1. Reporting a local event

- An (unusual) event, *E*, is sensed by a particle.
- Problems: How to propagate *info*(*E*) efficiently to a base station ?
- Event driven data delivery

- **Difficulties**
  - ad-hoc position of nodes
  - (usually) each particle has its own coordinate system
  - *info*(*E*) can be sent only to particles

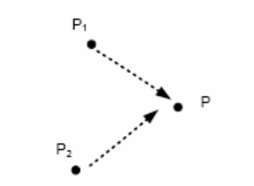


  - Sequence of “hops”

- **Case I** Particles are not aware of positions of other particles in the field (Graph unknown)
- **Solution:** Each sensor receiving *info*(*E*), runs a local propagation protocol *A*
- e.g. flooding the net (each activated sensor broadcasts to all "possible" neighbors)

Efficiency Measures

- Hops ratio $h(A) = \frac{l(A)}{l_{opt}}$
  where $l(A)$= hops done by protocol *A*
  l_{opt} = length of shortest path to a sink
- Shortest path notion may include energy availability
- issue of conflicts when two particles "broadcast" simultaneously to a receiver



Let

- n_A = # of particles activated by A
- n = # of particles activated in the net

  activated ratio $r_A = \frac{n_A}{n}$

  (captures energy spent by A)
- Competitive analysis
- May assume a known distribution of particles in the area
- Usually the direction towards a sink is assumed known by each particle
- Each activated particle must decide whether to forward *info*(E) or not

  Probabilistic Protocols

- [Chatzigiannakis, Dimitriou, Nikoletseas, Spirakis, 04] Probabilistic Forwarding
- [Chatzigiannakis, Nikoletseas, Spirakis, 02] Local Target Protocols
- [CDMSP 03, 04] Performance comparisons

- **Case II** Particles know their “neighbours” in the graph
- **Proposal:** Deliver *info*(E), to the closest to the sink neighbour (Greedy)
- Geometric Routing

but

- voids (particles with no neighbour closer to sink)
- cannot rely on precise geometric coordinates
- needs preprocessing of the net

- [Rao, Papadimitriou, Shenker, Stoika 03]
  Fictitious virtual coordinates

  Let $G(V,E)$, $|V| = n$ embedded in R^{κ}

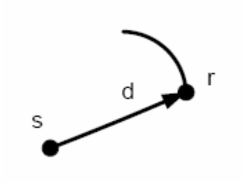
  Distance decreasing path

  $(v_0 = souce, v_1, \ldots, v_m = sink)$

  so that $d(v_i, v_m) < d(v_{i-1}, v_m)$

- What G have the property that there exists a distance decreasing path from s to $t \, \forall s, t$?
  [Papadimitriou, Patajczak 04]

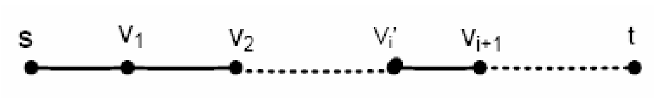
2. Energy Optimality Issues



- power $Pr = \frac{P_s}{d(s,r)^{\delta}}$
- $\delta \geq 2$ distance-power gradient [Lauer]
- A message can be decoded by r only if P_r is no less than some threshold γ
- s may not have enough energy left to broadcast to distance $d(s, r)$

A simple Energy/Time Tradeoff

- Assume $\gamma = 0$, available energy = ∞ in all nodes



l edges, each distance r

- Should v_i broadcast *info*(E) to v_{i+1} (and spend energy ε) or use a big radious (> $d(v_i, t)$) to save time?

    Say x hops and a long transmission

    Time $T = x + 1$ i.e. $x = T - 1$

    Energy $E = \varepsilon x + c(l - x)^{\delta}$. So,

$$E = \varepsilon(T - 1) + c(l + 1 - T)^{\delta}$$

(like VLSI area-time tradeoffs)

- **Note:** nodes around sink are not many
- Successive routings of event transfers depletes their energy
- Range Assignment Problems
  - off-line [Kirousis et al]
  - on-line

3. New Network Optimization Problems

- Smart Dust cloud = a uniform communication medium between any two nodes covered by the cloud

E.g. Superimpose a (wired) net *G*(*V*,*E*) with a cloud covering $V' \subseteq V$

The area of *V'* is covered by a vast number of particles

- **Max-Flow**
  We may think of a new graph $\hat{G}$ where a clique of edge-capacity *c* is superimposed in *V'*
- What is now the max flow?
- If |*V'*| = *k* and *V'* connected in *G* how to select it to maximize max-flow of $\hat{G}$? (NP-complete)
- Connectivity, Chromatic Number
- *V'* seen as an area that needs a net service but quickly, and is hard to upgrade carefully (hostile, densely populated, ...)

Topology Control

- Input: A smart dust cloud *C* and a protocol *A* for each particle $v \in C$ to determine its neighbours for communication
- Question: What are the global properties of the net constructed ?
  E.g.
  - Connectivity
  - expansion
  - max degree
  - small hop count (wrt Euclidean distance)
    hop distortion
  - ..
  - ..

e.g.

- **Bluetooth scheme**

Cloud = n nodes in $[0, 1]^2$

Each node connects just to c nodes

chosen randomly within distance r

Bluetooth Graph

[Panconesi, Radhakrishnam 04]

$c \geq 2 \Rightarrow$ net connected whp

$c \geq 10^7 \Rightarrow$ expander whp

e.g.

- **Nearest Neighbour Scheme**

Each particle communicates to the same number, k, of closest neighbours

[Xue, Kumar, 04]

$k = \Theta(\log n) \Leftrightarrow$ net connected whp

- Topology control issues also good for general ad-hoc nets
- Need an assumption about particles distribution
- Quite open field
- Requires sensors to be able to adapt radious and to broadcast at small angles (optical)

The problem of localization

Each sensor to know its possition

- Each sensor to have a GPS (expensive)
- To place bacons (and triangulate)
- A few sensors with GPS (anchor-based)
- Anchor-free + capability of computing distances between neighbors
- A cricket sensor with GPS (or BTS transmit coordinates)

The problem of localization

Many interesting solutions

Priyantha, Balakrishnan, Demaine, Teller: Anchor-free distributed localization. SenSys 2003.

Conclusions

- New algorithmic subfield
- Impossibility results?
  (a la PODC)
- Technology driven wrt models
- Meaningful questions