A survey of solutions to the coverage problems in wireless sensor networks

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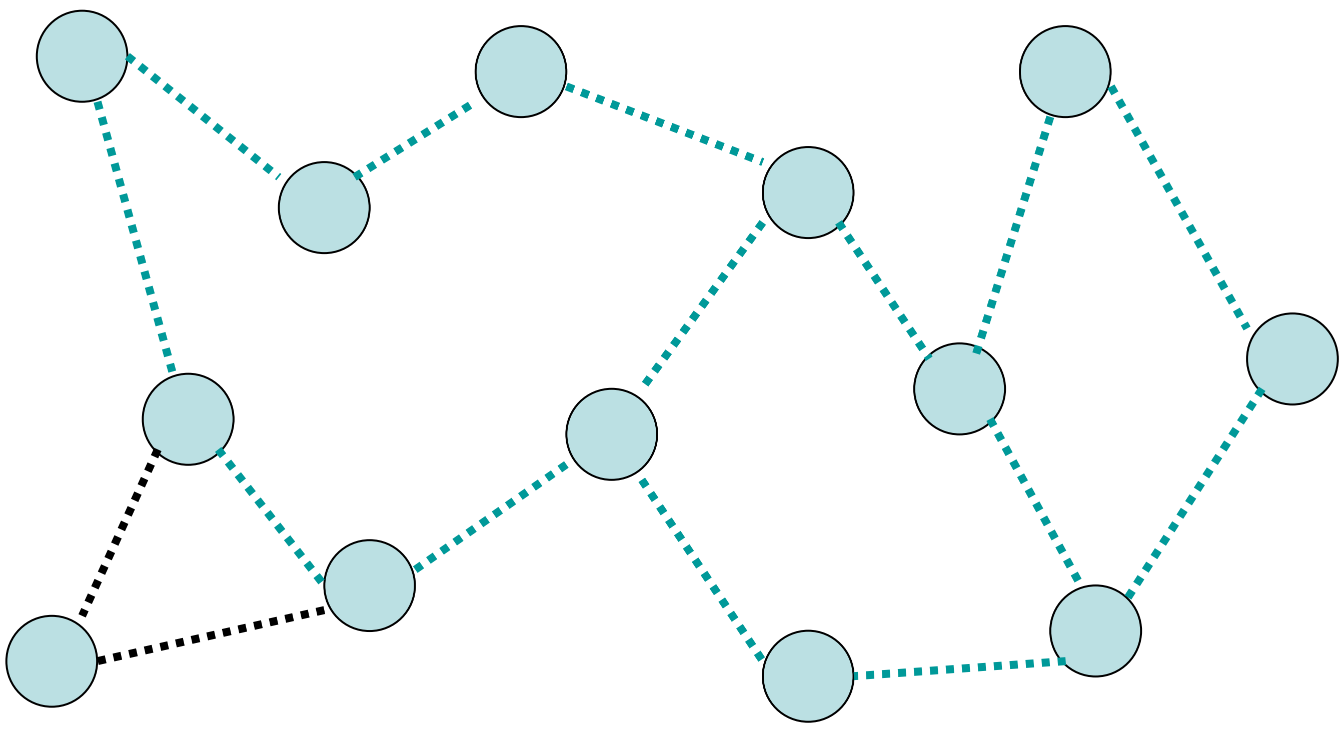
Outline

- Introduction
- Related Geometric Problems
- Surveillance and Exposure part-1
- Discussion
- *Coverage and Connectivity part-2*

Introduction

- Sensor networks



Introduction

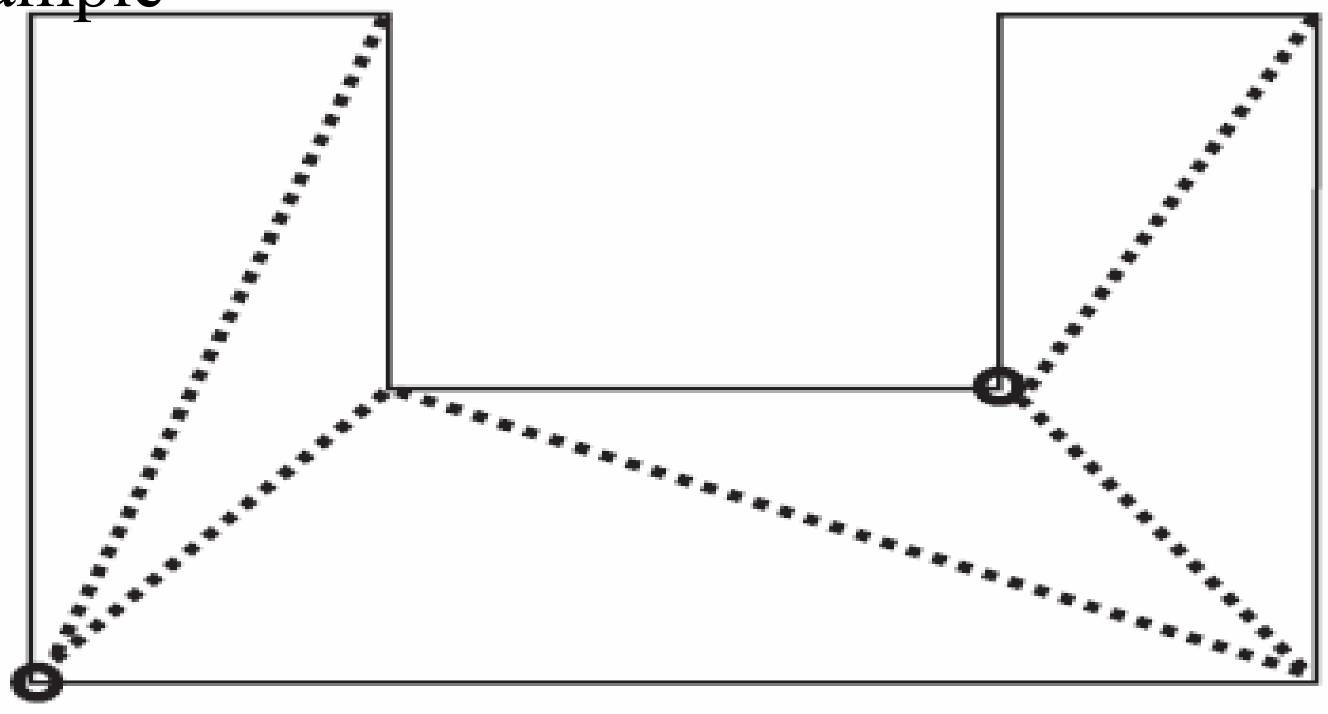
- Design issues
  - PHY and MAC Layers
  - Routing and Transport Protocols
  - Localization and Positioning applications
  - Coverage and Connectivity Problems

Related Geometric Problems

- Art Gallery Problem
  - How many cameras are needed
  - Where these cameras should be deployed
- The galley is usually modeled as a simple polygon on 2D plane
- Simple solution
  - Triangulating the polygon
  - Number of cameras = n/3

Art Gallery Problem

Example

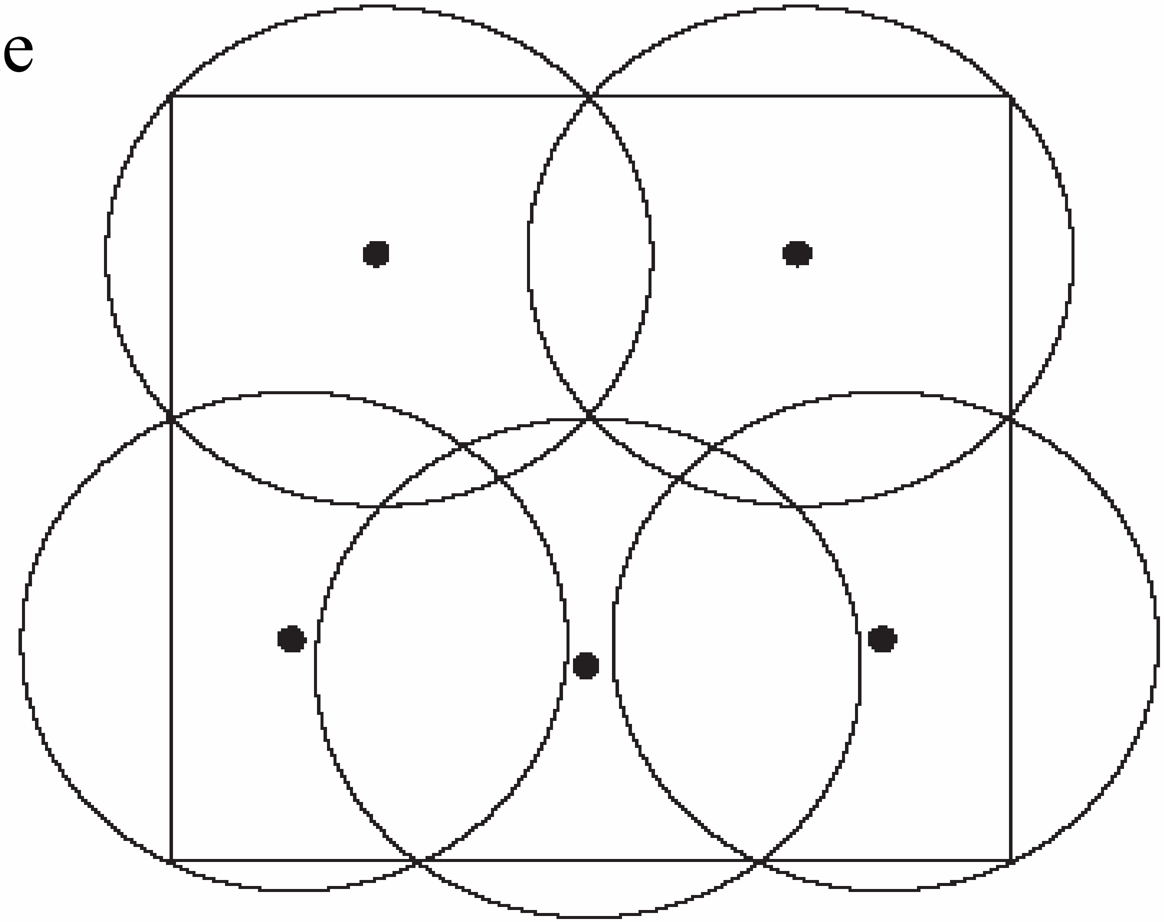


Related Geometric Problems

- Circle Covering Problem
  - To arrange identical circles on a plane that can fully cover the plane
  - Given a fixed number of circles, the goal is to minimize the radius of circles

Circle Covering Problem

Example



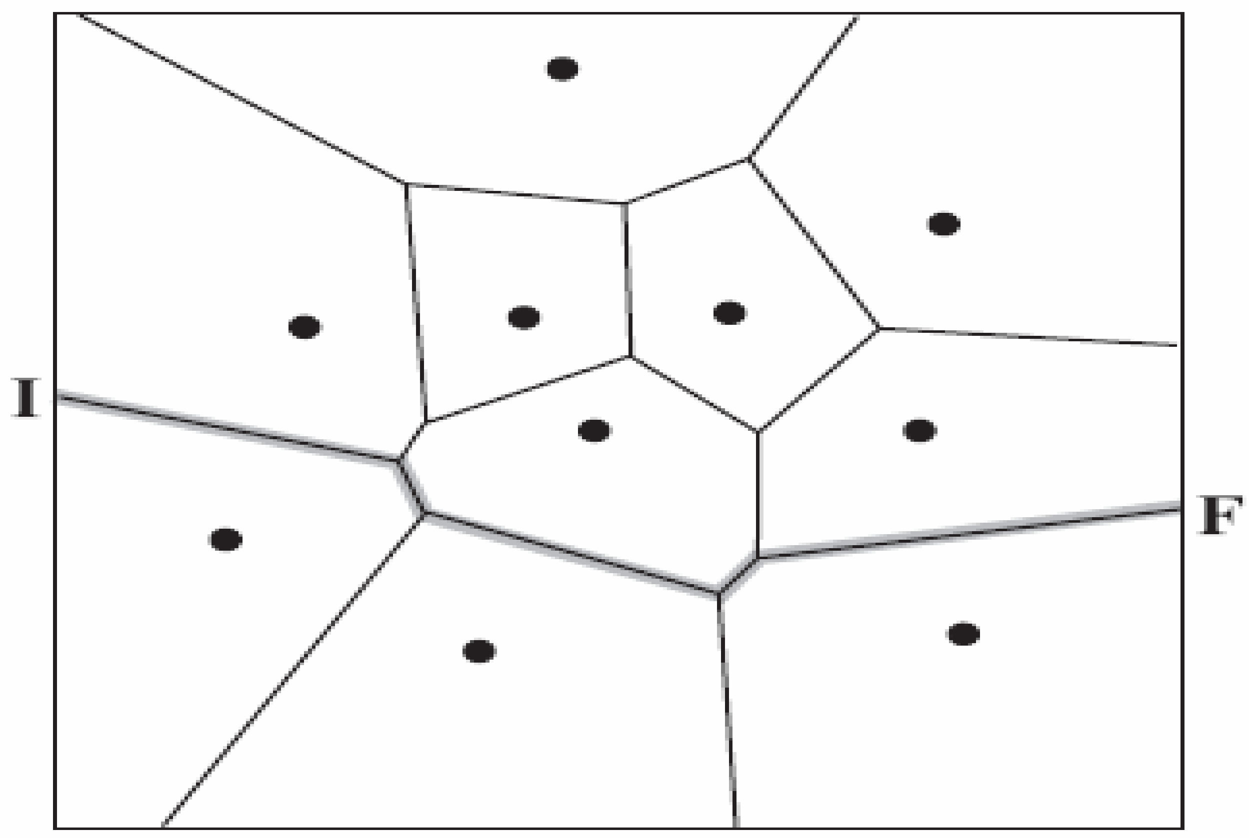
Surveillance and Exposure

- To find a path connecting these two points which is best and worst monitored by sensors
- Maximal branch path [1][5]
  - The distance form any point to the closest sensor is maximized
- Maximal support path [1][5]
  - The distance form any point to the closest sensor is minimized

Surveillance and Exposure

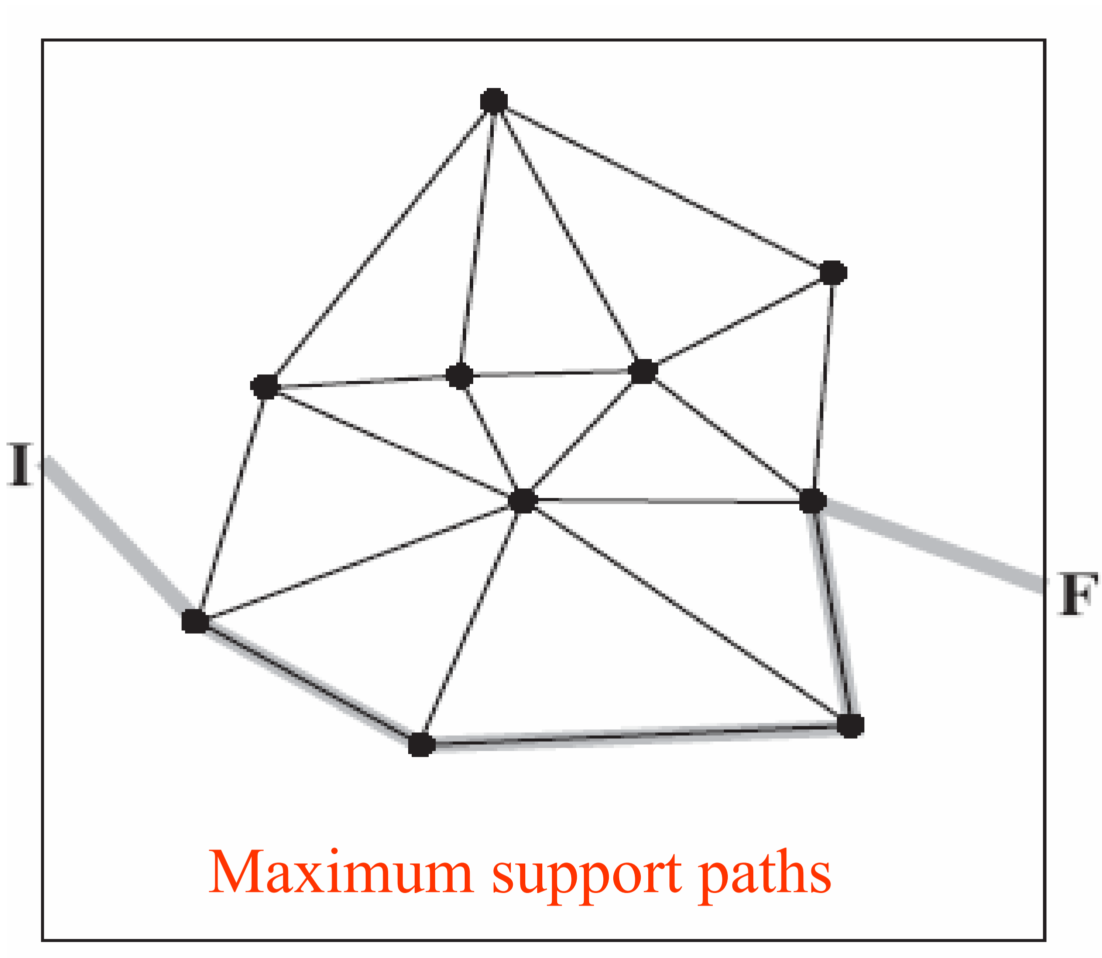
- How to fine these paths?
  - Voronoi diagram
    - Maximum branch paths
  - Delaunay triangulation
    - Maximum support paths

Voronoi diagram



Maximum branch paths

Delaunay triangulation



Maximal branch path (P_B)

Step 1: Generate Voronoi diagram for sensor S in field A

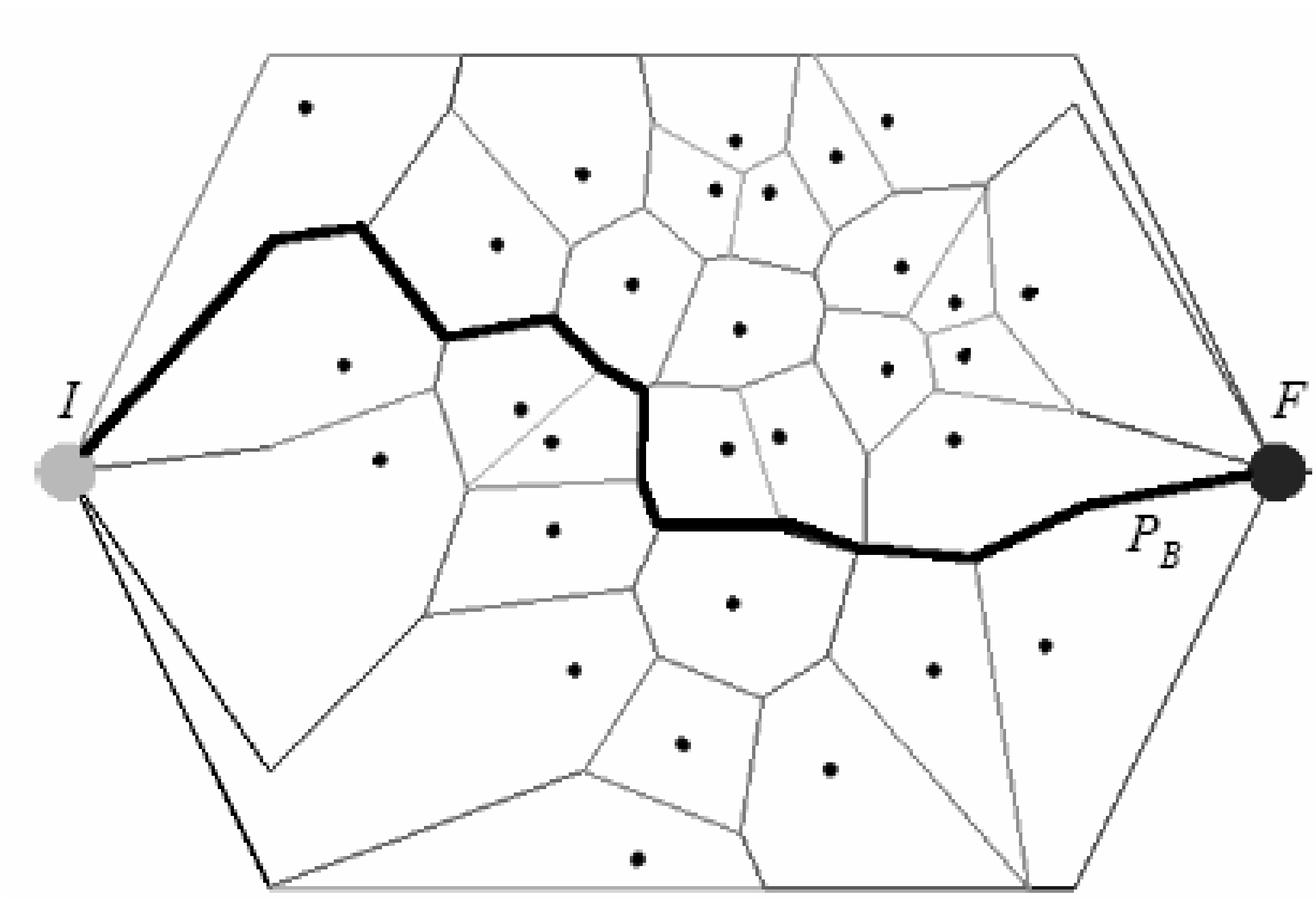
Step 2: Apply graph theory abstraction

Step 3: Find P_B using Binary-Search and Breadth First-Search

Maximal branch path (P_B)

- *Generate Bounded Voronoi diagram for S with vertex set U and*
- *line segment set L.*
- *Initialize weighted undirected graph G(V,E)*
- **FOR** each vertex $ui \in U$
- *Create duplicate vertex vi in V*
- **FOR** each $li(uj,uk) \in L$
- Create edge *ei*(*vj*,*vk*) *in E*
- *Weight(ei)=min distance from sensor* $si \in S$ for $1 \leq I \leq |S|$
- *min_weight = min edge weight in G*
- *max_weight = max edge weight in G*
- *range* = (*max_weight – min_weight*) / *2*
- *breach_weight = min_weight + range*
- **WHILE** (*range > binary_search_tolerance*)
- *Initialize graph G'*(*V'*,*E'*)
- **FOR** each $vi \in V$
- Create vertex *vi'* in *G'*
- **FOR** each $ei \in E$
- **IF** *Weight(ei)* $\geq$ *breach_weight*
- *Insert edge ei' in G'*
- *range = range / 2*
- **IF** *BFS(G',I,F) is Successful*
- *breach_weight = breach_weight + range*
- **ELSE**
- *breach_weight = breach_weight – range*
- **END IF**

Maximal branch path (P_B)



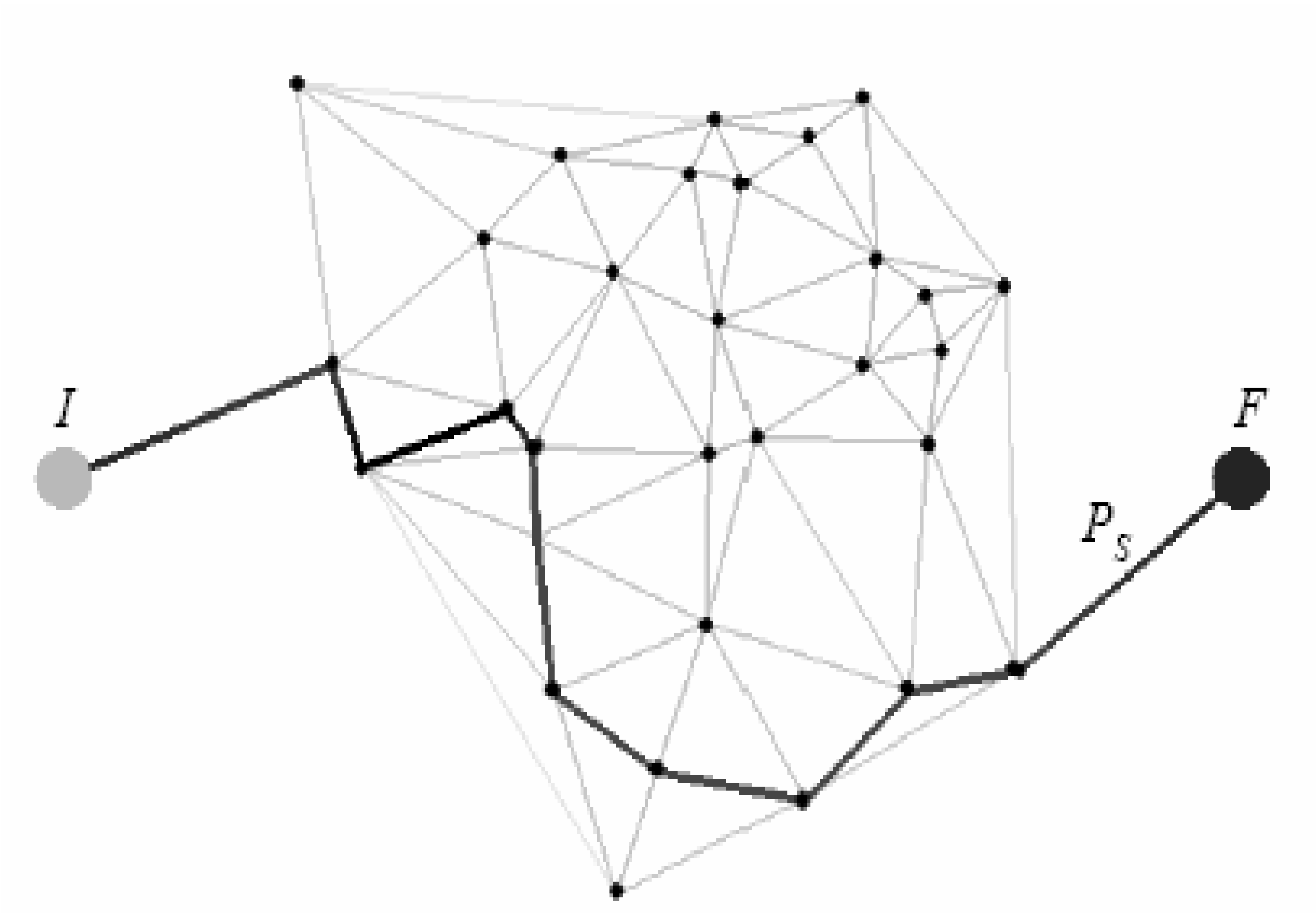
Maximal support path (P_s)

Step 1: The Voronoi diagram is replaced by the Delaunay triangulation as the underlying geometric structure

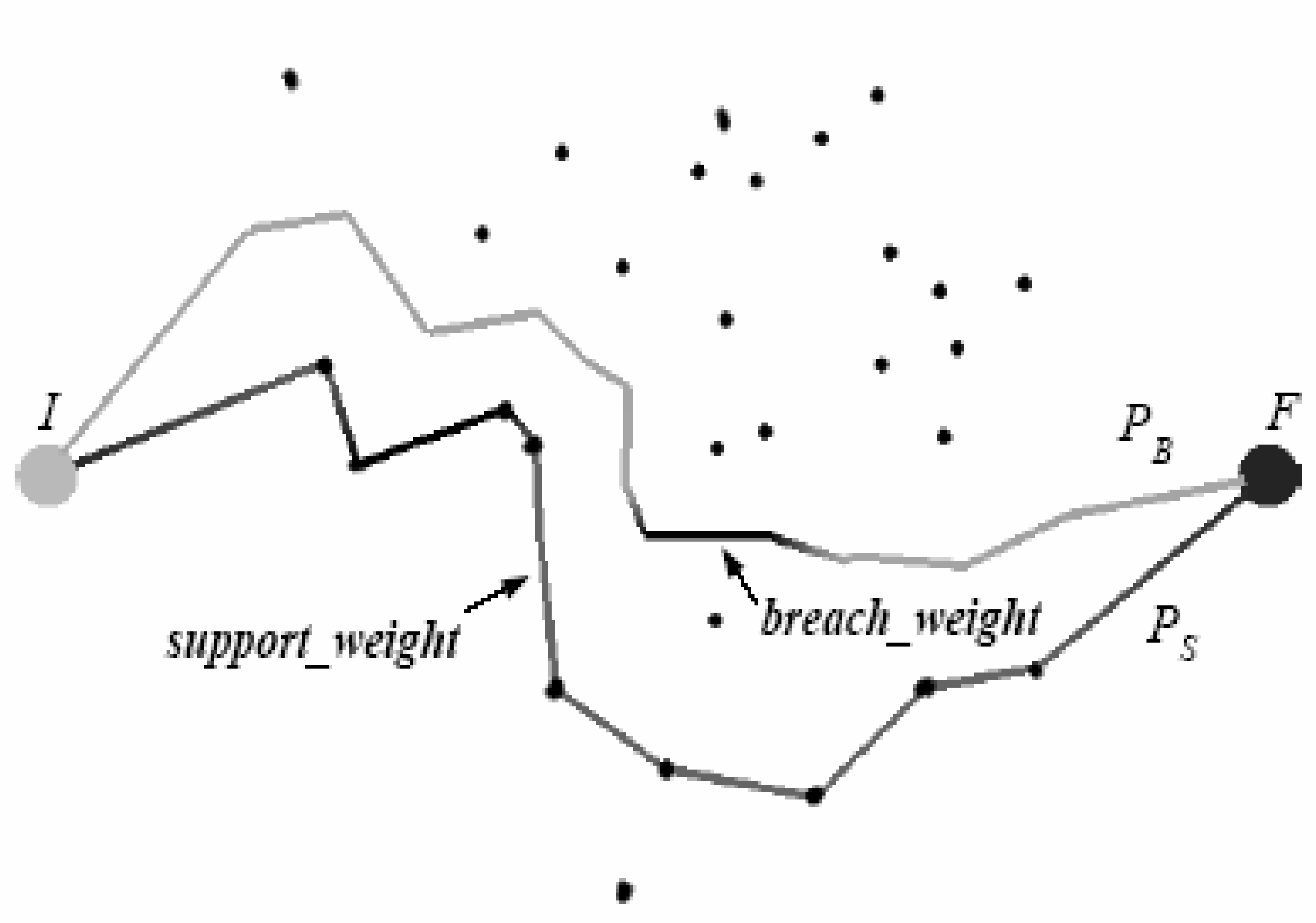
Step 2: The edges in graph *G* are assigned weights equal to the length of the corresponding line segments in the Delaunay triangulation

Step 3: The search parameter *breach_weight* is replaced by the new parameter *support_weight*.

Maximal support path (P_s)



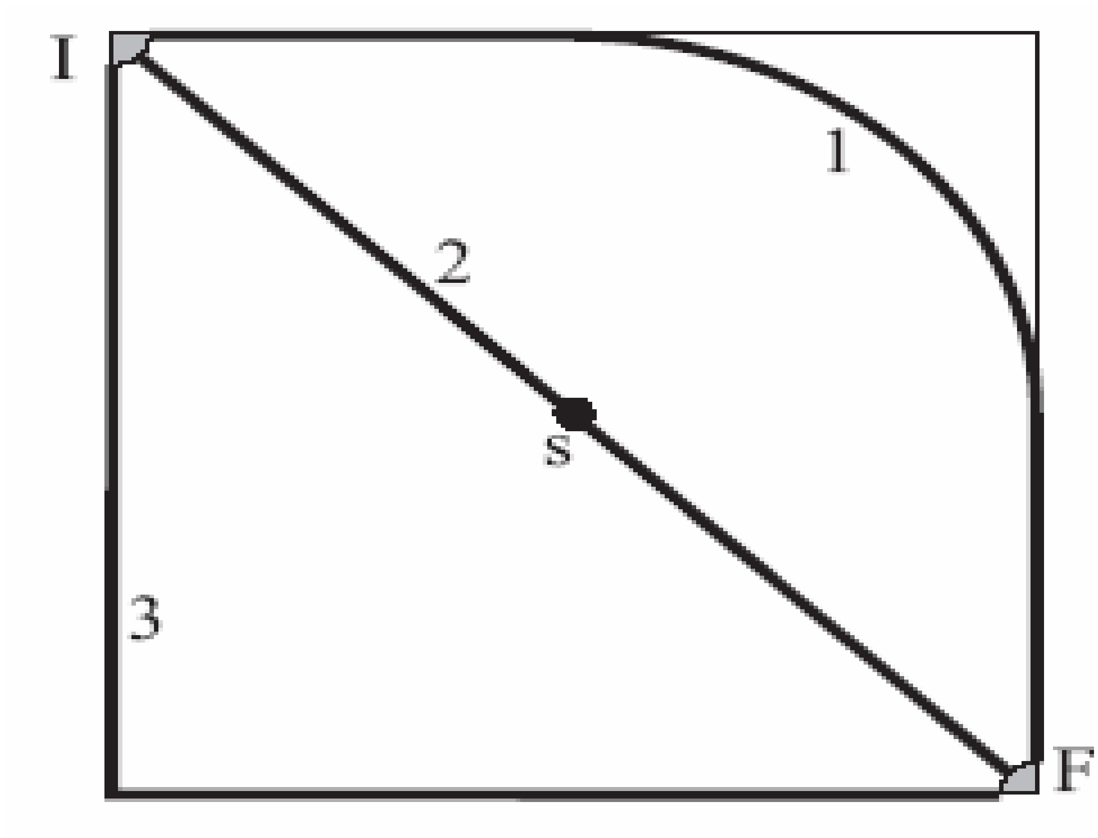
Surveillance and Exposure



Surveillance and Exposure

- Exposure: the sensing ability of sensors can be improved as the sensing time increases
  - Minimal exposure path [1][2][6][7]
    - Worst coverage of a sensor network
  - Maximal exposure path [1][3]
    - Best coverage of a sensor network
- They also use voronoi diagram and delaunay triangulation to partition the sensing filed

Example of exposure



Sensor models

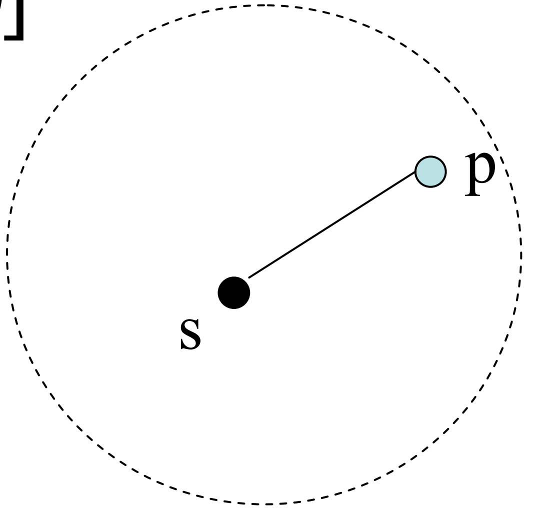
- For a sensor s, we express the general sensibility model S at an arbitrary p as

$$S(s, p) = \frac{\lambda}{[d(s, p)]^k}$$

d(s, p): the distance between s and p

λ : positive constants

k ： 2 ~ 4



Sensor field intensity

- Depending on the application and the type of sensor models, the sensor field intensity can be defined in several ways
- Two used models
  - All-Sensor Field Intensity: I_A
  - Closest-Sensor Field Intensity: I_C

Sensor field intensity

- All-Sensor Field Intensity
  - Assume there are n active sensors, s_1, s_2, s_3,…s_n

$$I_A(F, p) = \sum_{1}^{n} S(s_i, p)$$

- Closest-Sensor Field Intensity

$$s_{\min} = s_m \in S \,|\, d(s_m, p) \leq d(s, p) \forall s \in S$$

$$I_C(F, p) = S(s_{\min}, P)$$

Minimal Exposure

- The exposure for an object O in the sensor field during the time interval $[t_1, t_2]$ along the path p(t) is defined as

$$E\left(p(t), t_1, t_2\right) = \int_{t_1}^{t_2} I(F, p(t)) \left| \frac{dp(t)}{dt} \right| dt$$

- If p(t) = (x(t), y(t))

$$\left| \frac{dp(t)}{dt} \right| = \sqrt{\left(\frac{dx(t)}{d(t)} \right)^2 + \left(\frac{dy(t)}{d(t)} \right)^2}$$

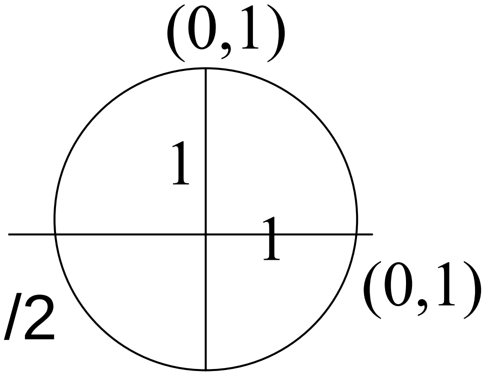
Minimal Exposure

- Example of exposure
  - How to travel from p(1, 0) to q(X, Y) with minimum exposure?

$$E = \int_0^1 \frac{1}{\sqrt{x(t)^2 + y(t)^2}} \sqrt{\left(\frac{dx(t)}{dt}\right)^2 + \left(\frac{dy(t)}{dt}\right)^2}\, dt$$

  - When q=(0, 1), the minimum exposure path is

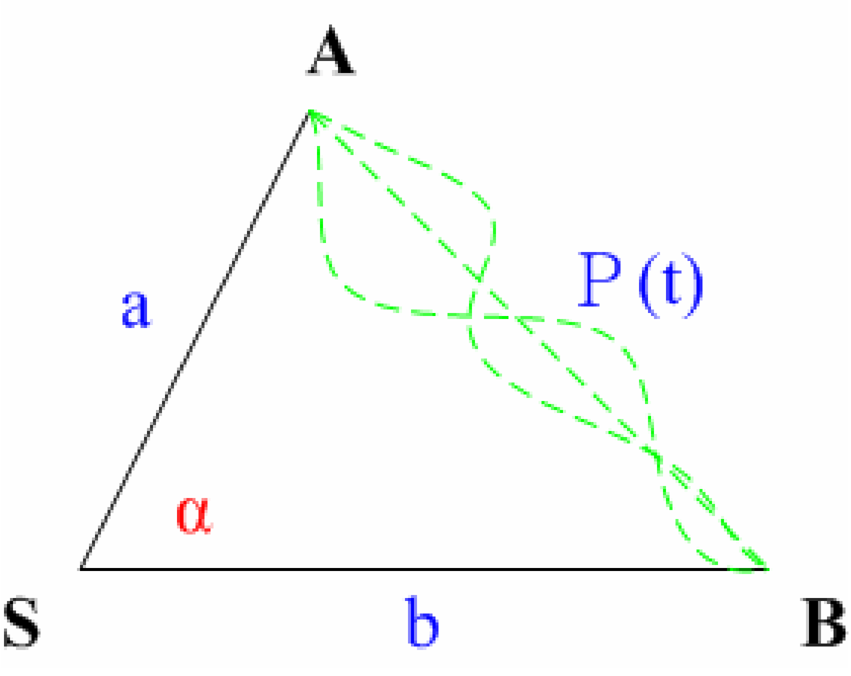
$$\left(\cos\frac{\pi}{2}t, \sin\frac{\pi}{2}t\right)$$



  - The exposure along the path is E = π /2

Minimal Exposure -part 2

- Variational calculus [2]
  - Using Polar Coordinates (ρ , θ)



Minimal Exposure -part 2

$$E(x(t), y(t), t_1, t_2) = \int_{t_1}^{t_2} I\big(x(t), y(t)\big)\sqrt{\left(\frac{dx(t)}{dt}\right)^2 + \left(\frac{dy(t)}{dt}\right)^2}\, dt$$

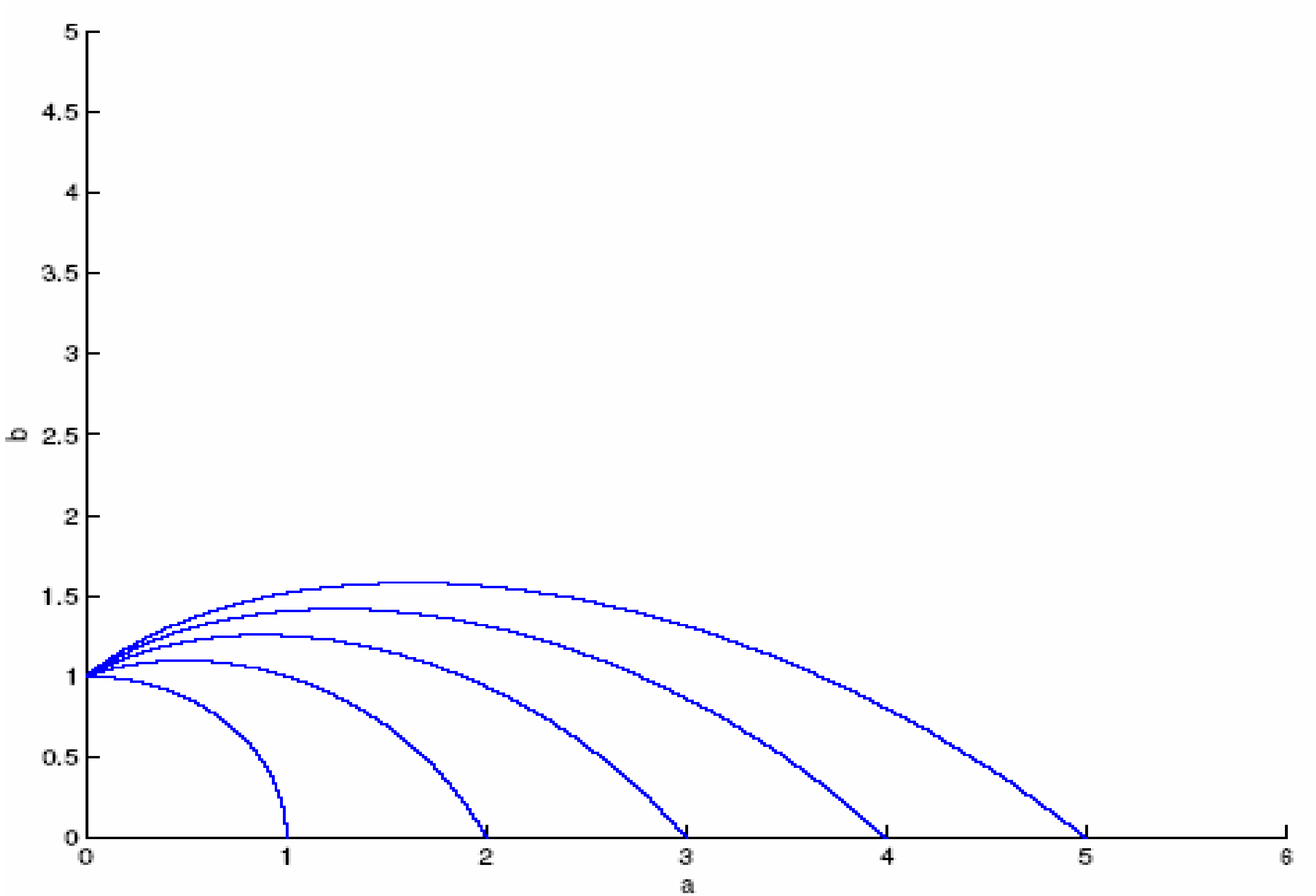
$$x(t) = \rho(t)\cos\theta(t)$$

$$y(t) = \rho(t)\sin\theta(t)$$

$$E(\rho(t), \theta(t), t_1, t_2) = \int_{t_1}^{t_2} I\big(\rho(t), \theta(t)\big)\sqrt{\left(\rho\frac{d\theta(t)}{dt}\right)^2 + \left(\frac{d\rho(t)}{dt}\right)^2}\, dt$$

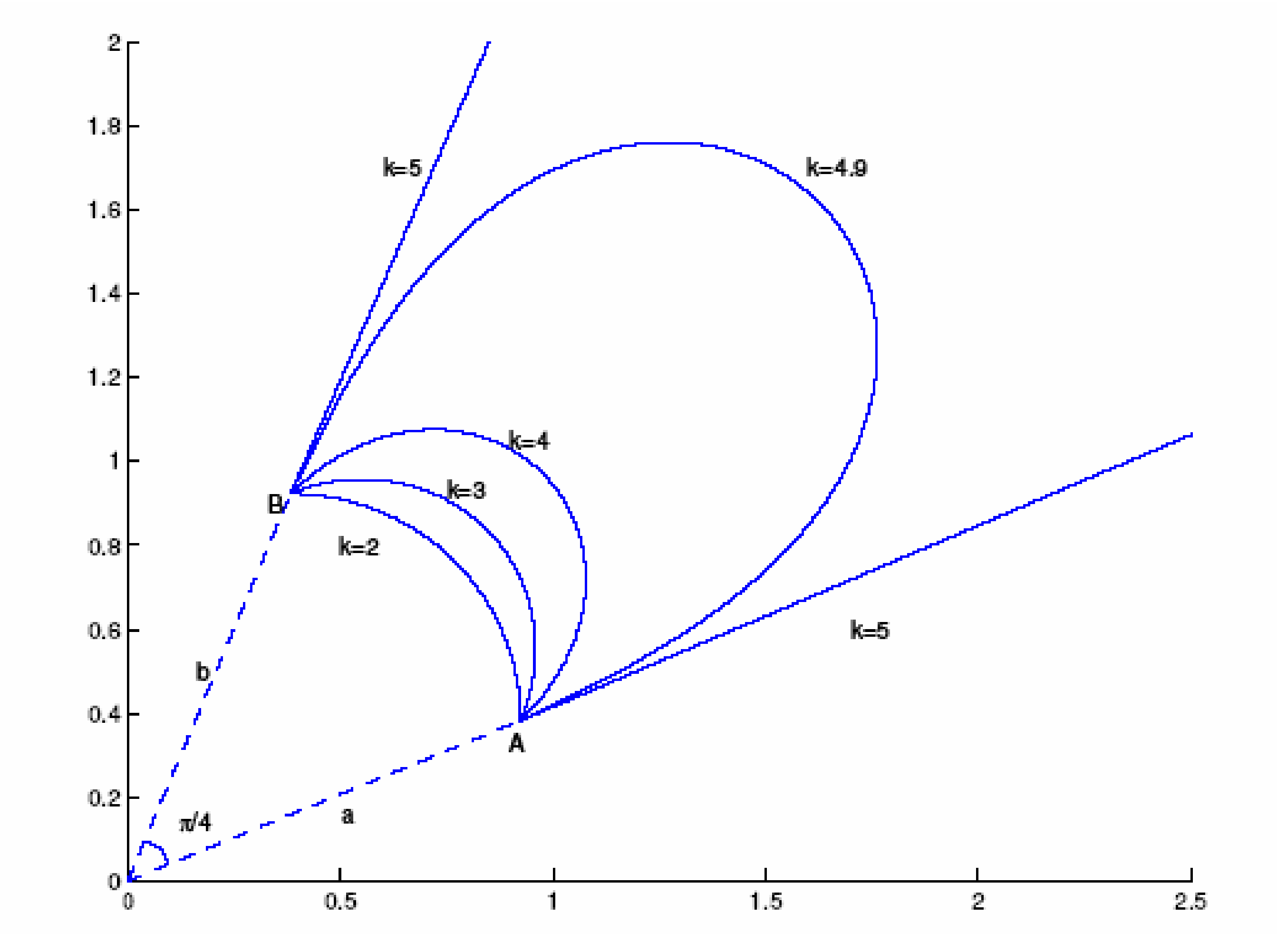
$$E(\rho(t), \theta(t), t_1, t_2) = \int_{\theta(t_1)}^{\theta(t_2)} I\big(\rho(t), \theta(t)\big)\sqrt{\big(\rho(t)\big)^2 + \left(\frac{d\rho(t)}{d\theta(t)}\right)^2}\, d\theta(t)$$

Minimal Exposure -part 2



Minimal Exposure -part 2

- General case：k>1



Minimal Exposure -part 2

- Critical angle for $1/r^k$

$$\alpha_c(k) = \frac{\pi}{k-1}$$

- If the angle $\alpha > \alpha_c$, the minimal exposure path always extends infinity

Maximal Exposure

- Maximal exposure path [3][5][6][7]

  → Best coverage problem

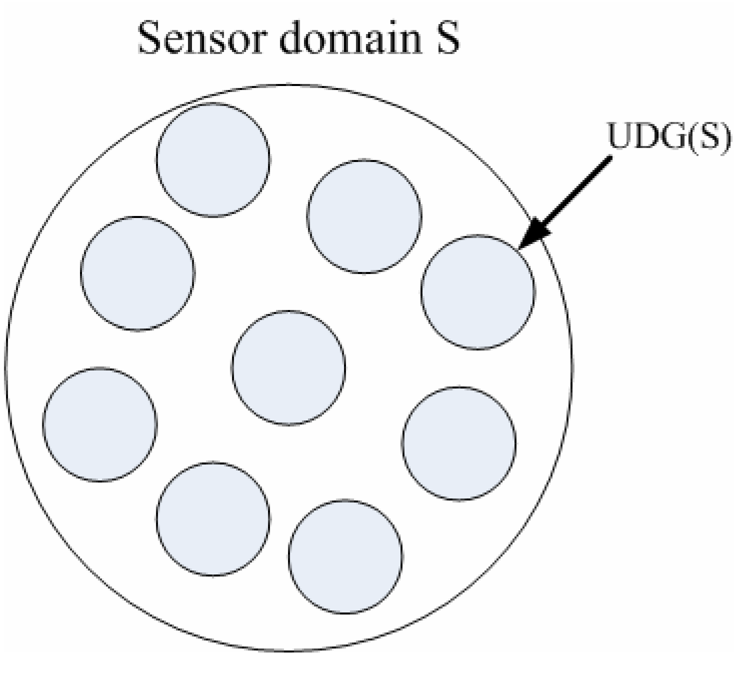
  – To find a path connecting two points (s, t) which maximize the smallest obserability of all points on the path.

Maximal Exposure

- Centralized algorithm [5][6][7]
  - Voronoi diagram
  - Delaunary triangulation
- Distributed algorithm [3]
  - Localized Delaunary Triangulation
    - Gabriel Graph (GG)
    - Relative Neighborhood Graph (RNG)

Maximal Exposure

- All wireless nodes S together define a unit disk graph UDG(S)
  - $N_k(u)$: k-local nodes of u.   K=1 or 2



Maximal Exposure

- Unit Delaunay trangulation

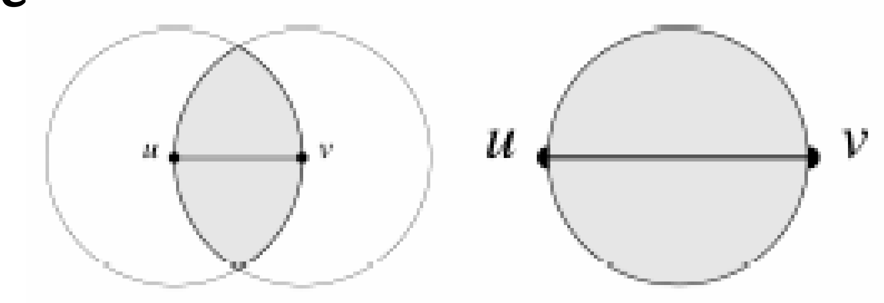
$$UDel(S) = Del(S) \cap UDG(S)$$

$$then$$

$$UDel(S) = GG(S) : Gabriel \quad Graph$$

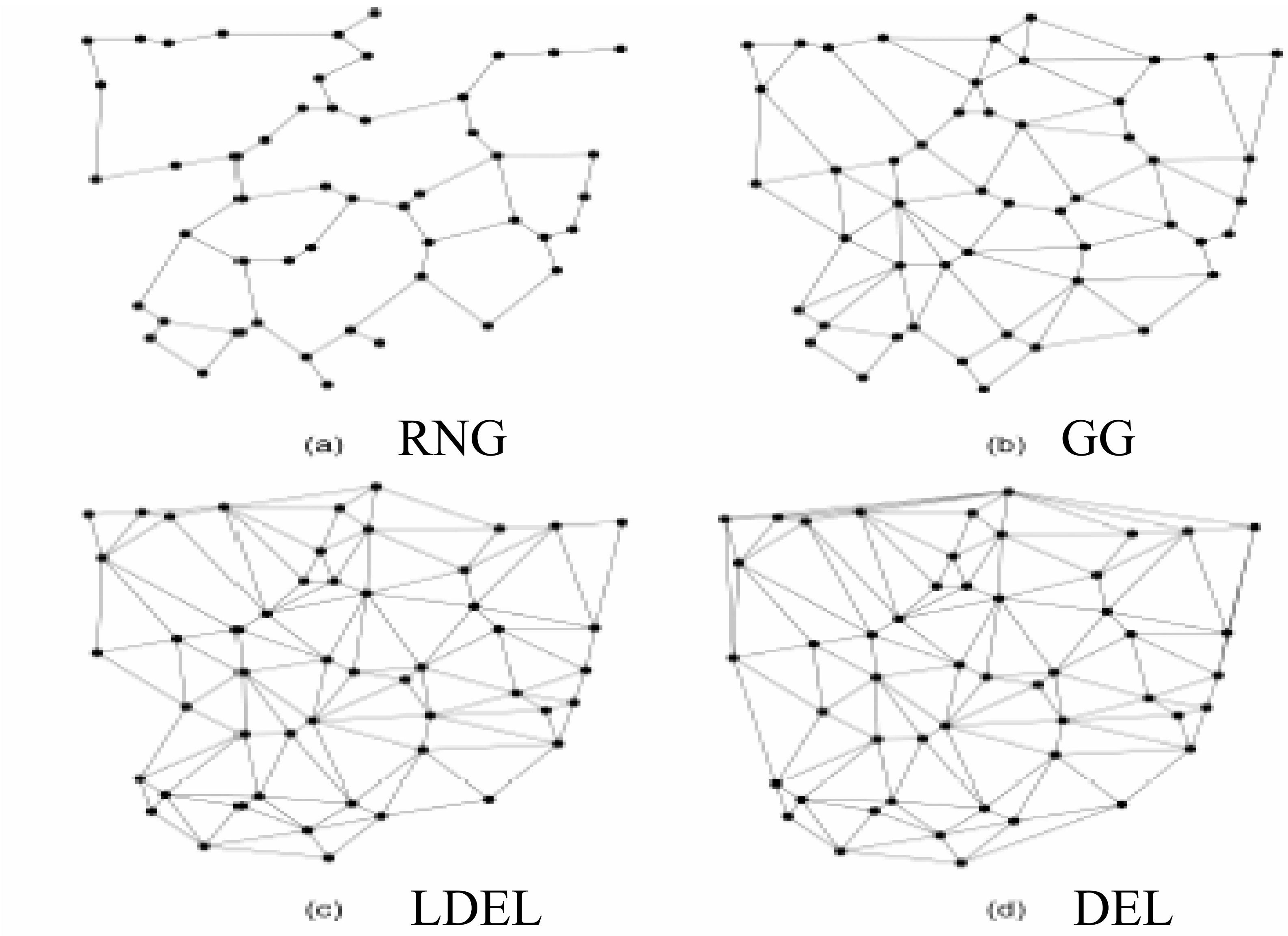
- Localized Delaunay triangulation contains UDel(S) as a sub-graph
- RNG(S): a sub-graph of GG(S)

RNG



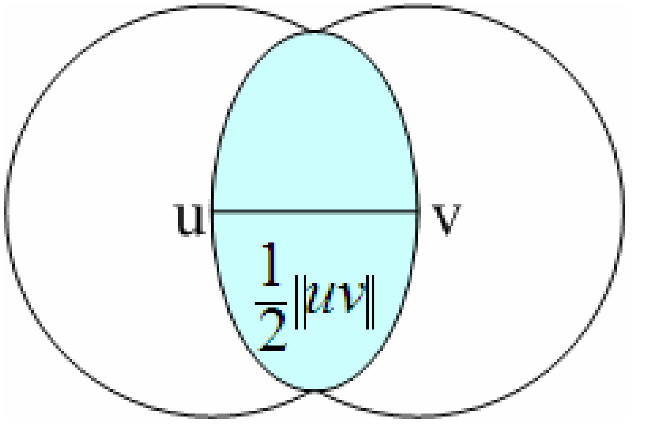
GG

Maximal Exposure



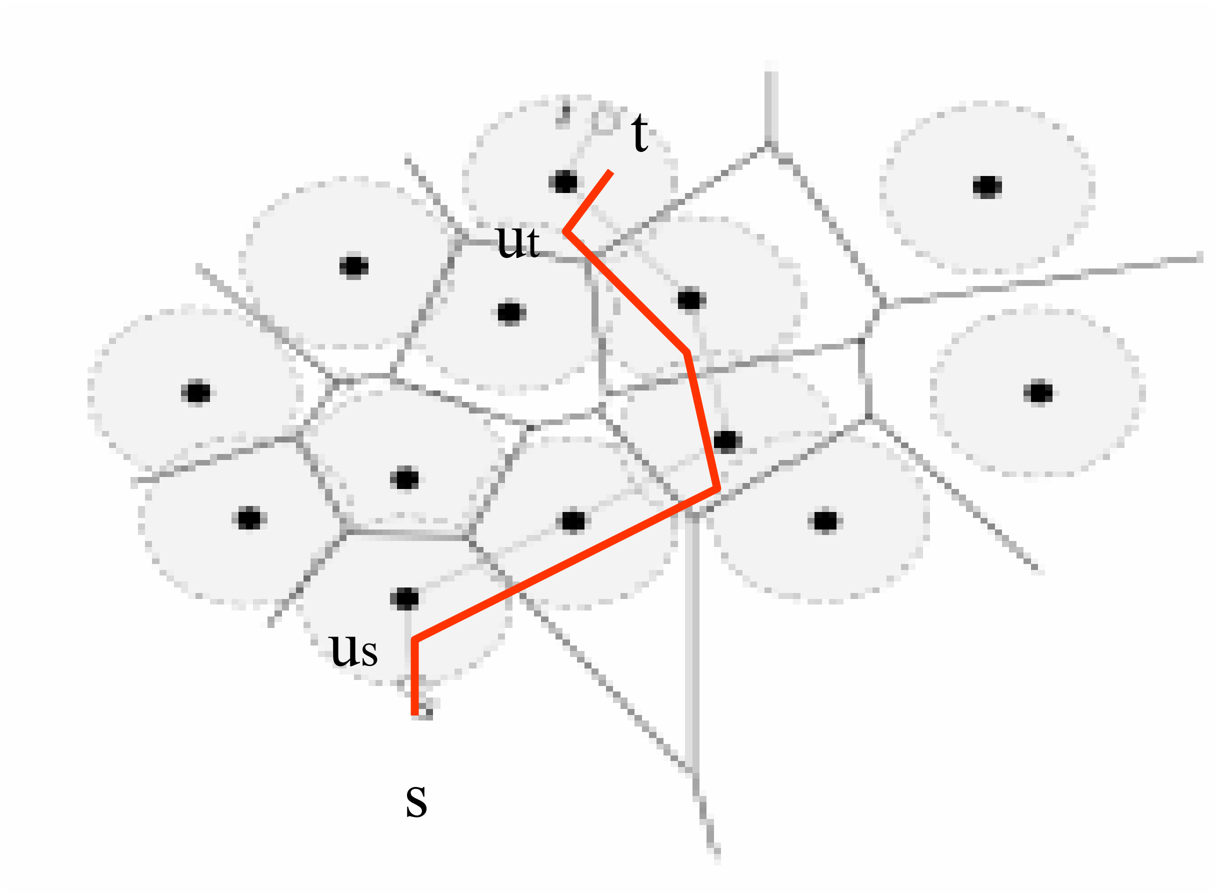
Maximal Exposure

- Starting point s, Ending point t
  - Closest sensor u_s, u_t
- Construct RNG using 1-hop local information



- Assign each edge uv weight = $\frac{1}{2}\|uv\|$
- The maximal exposure path has the minimum weight amoung all path connecting u_s and u_t

Maximal Exposure



Summary

- Surveillance (QoS)
  - It is a far-and-near problem
- Exposure
  - How well an object, moving on an arbitrary path, can be observed by the sensor network over a period of time
- Sensing model
  - The sensing ability will decrease with distance
  - Communication range = sensing range

Discussion

- Worst coverage problem (minimal exposure path) with distribution method?
- Probability based sensing model
  - A node is sensed with a probability P.
- Is sensing region always a circle?
- Coverage preserving and Energy conserving
  - Critical density [1]
  - Coverage and connectivity [8][9]
- Sensing range vs. Communication range

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