Wireless Sensor Networks COE 499
Deployment of Sensor Networks I

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Outline

- Structured vs Randomization deployment
- Over deployment vs incremental deployment
- Network topology
- Connectivity in geometric random graphs
- Connectivity using power control
  - COMPOW
  - CBTC
- Coverage metrics
  - K-coverage

Structured vs Randomized deployment

- The randomized deployment approach is appealing for futuristic applications of a large scale
  - nodes are dropped from aircraft or mixed into concrete before being embedded in a smart structure
- Many small-medium-scale WSNs are likely to be deployed in a structured manner via careful hand placement of network nodes
- In both cases, the cost and availability of equipment will often be a significant constraint

Structured vs Randomized deployment..

Methodology of Structured Deployment:

1. Place sink/gateway device at a location that provides the desired wired network and power connectivity
2. Place sensor nodes in a prioritized manner at locations of the operational area where sensor measurements are needed
3. If necessary, add additional nodes to provide requisite network connectivity

- Step 2 can be challenging if it is not clear exactly where sensor measurements are needed, in which case a uniform or grid-like placement could be a suitable choice

Structured vs Randomized deployment..

- Adding nodes to ensure wireless connectivity is a challenging issue, particularly when there are location constraints in a given environment that dictate where nodes can or cannot be placed
- If the number of available nodes is small with respect to the size of the operational area and required coverage, a balance between sensing and routing nodes has to be optimized

Structured vs Randomized deployment..

- Randomized sensor deployment can be even more challenging in some respects, since there is no way to configure a priori the exact location of each device
- Additional post-deployment self-configuration mechanisms are required to obtain the desired coverage and connectivity
- In case of a uniform random deployment, the only parameters that can be controlled a priori are the numbers of nodes and some related settings on these nodes, such as their transmission range.

Network Topology

Single-hop star:

- The simplest WSN topology is the single-hop star
- Every node in this topology communicates its measurements directly to the gateway
- The networking concerns are reduced to a minimum
- The limitation of this topology is its poor scalability and robustness properties
  - In larger areas, nodes that are distant from the gateway will have poor-quality wireless links

Network Topology..

Multi-hop mesh and grid:

- For larger areas and networks, multi-hop routing is necessary.
- Depending on how they are placed, the nodes could form an arbitrary mesh graph or they could form a more structured communication graph such as the 2D grid structure

Network Topology..

Two-tier hierarchical cluster:

- Multiple nodes within each local region report to different clusterheads
- There are a number of ways in which such a hierarchical architecture can be deployed
- An attractive approach in heterogeneous settings when the cluster-head nodes are more powerful in terms of computation/communication
- Decomposes a large network into separate zones within which data processing and aggregation can be performed locally

Network Topology..

Two-tier hierarchical cluster (cont'd)

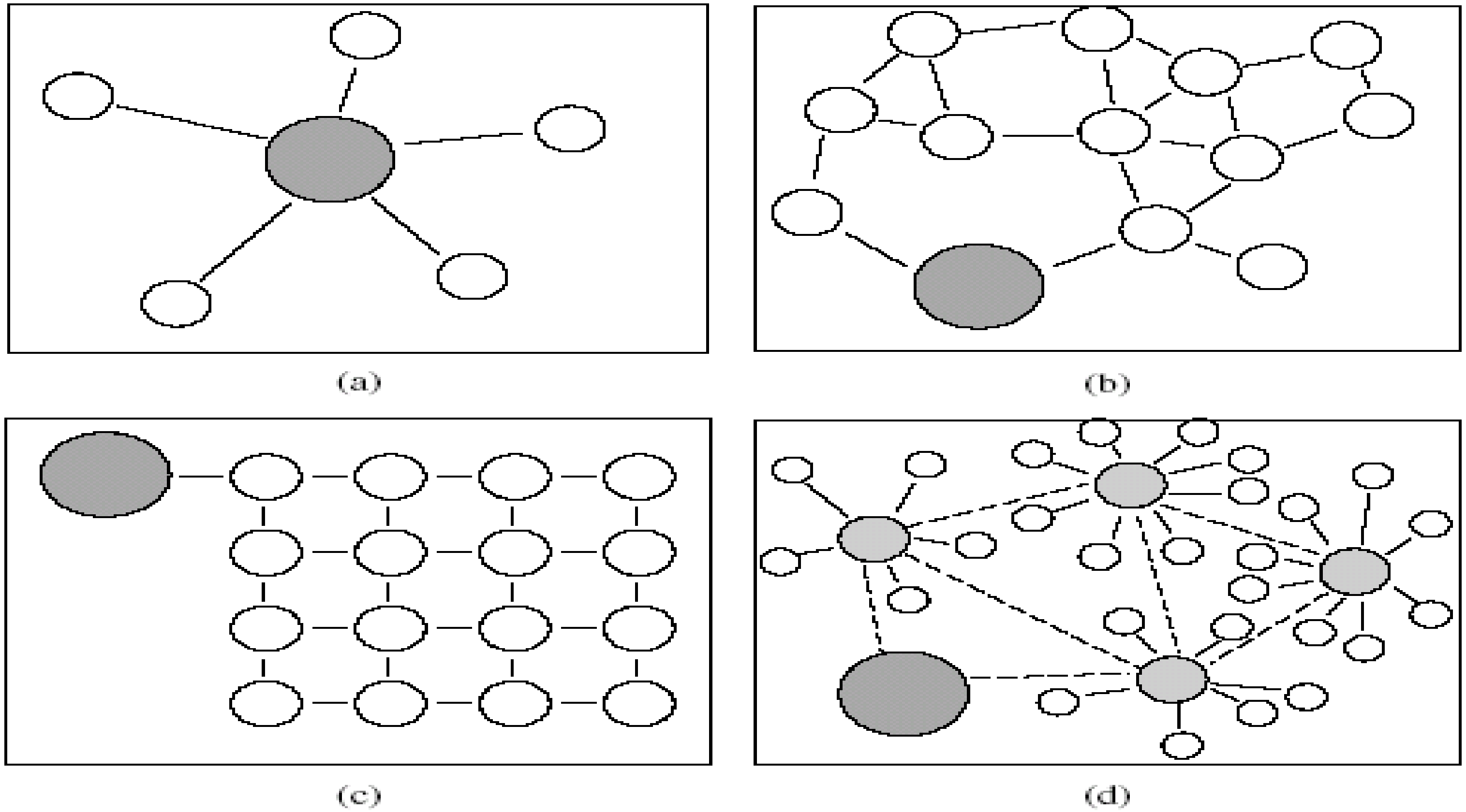
- Within each cluster there could be either single-hop or multi-hop communication
- Once data reach a cluster-head they would then be routed through the second tier network formed by cluster-heads to another cluster-head or a gateway
- The second-tier network may utilize a higher bandwidth radio or it could even be a wired network if the second-tier nodes can all be connected to the wired infrastructure

Network Topology..

Two-tier hierarchical cluster (cont'd)

- Having a wired network for the second tier is relatively easy in building-like environments, but not for random deployments in remote locations
- In random deployments there may be no designated cluster-heads
  - A self-election scheme should be used

Network Topology..

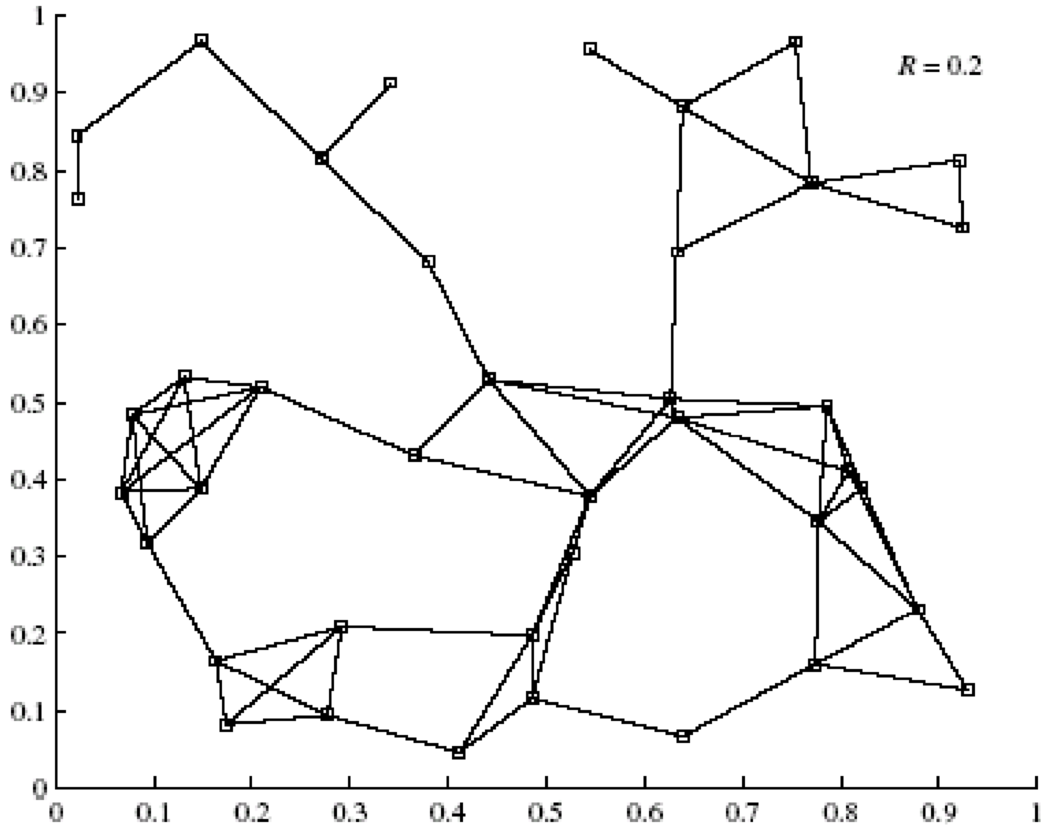


Different deployment topologies: (a) a star-connected single-hop topology, (b) flat multi-hop mesh, (c) structured grid, and (d) two-tier hierarchical cluster topology

Connectivity in Geometric Random Graphs

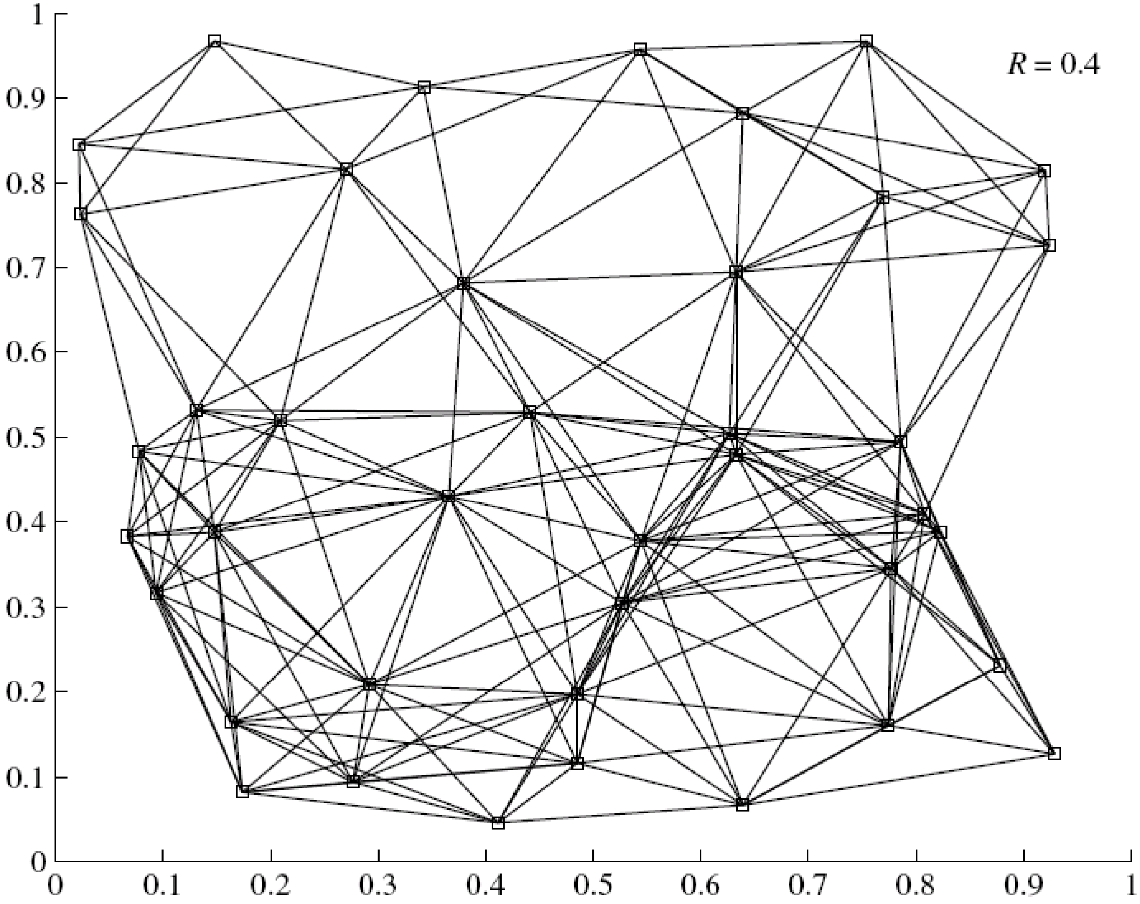
- The Bernoulli random graphs G(n, p) are formed by taking n vertices and placing random edges between each pair of vertices independently with probability p
- A random graph model represents wireless multi-hop networks is the geometric random graph G(n, R)
- In a G(n, R) geometric random graph, n nodes are placed at random with uniform distribution in a square area of unit size
- There is an edge (u, v) between any pair of nodes u and v, if the Euclidean distance between them is less than R
- Geometric random graphs do not show independence between edges. For instance, the probability that edge (u, v) exists is not independent of the probability that edge (u, w) and edge (v, w) exist

Connectivity in Geometric Random Graphs..



(a)

Connectivity in Geometric Random Graphs..



(b)

Connectivity in Geometric Random Graphs..

Connectivity in G(n, R)

- Figure 2.3 shows how the probability of network connectivity varies as the radius parameter R of a geometric random graph is varied
- Depending on the number of nodes n, there exist different critical radii beyond which the graph is connected with high probability
- These transitions become sharper (shifting to lower radii) as the number of nodes increases.
- Figure 2.4 shows the probability that the network is connected with respect to the total number of nodes for different values of fixed transmission range in a fixed area for all nodes

Connectivity in Geometric Random Graphs..

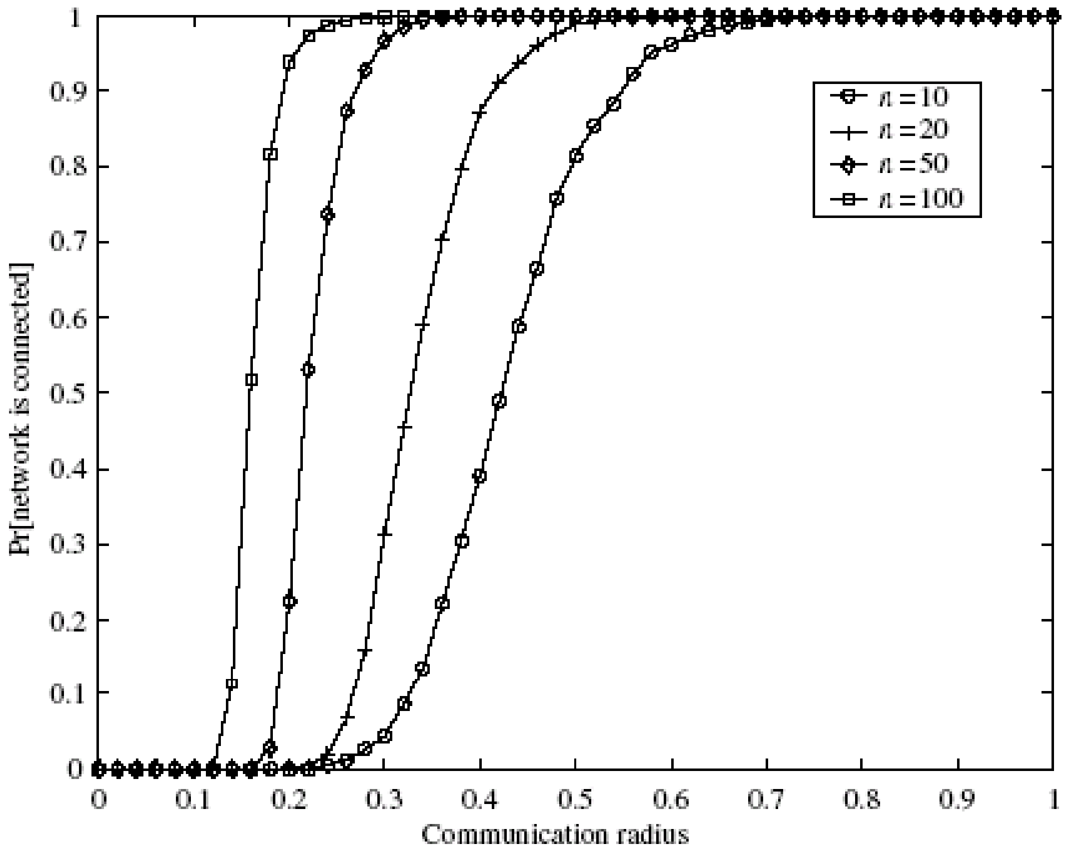


Figure 2.3 Probability of connectivity for a geometric random graph with respect to transmission radius

Connectivity in Geometric Random Graphs..

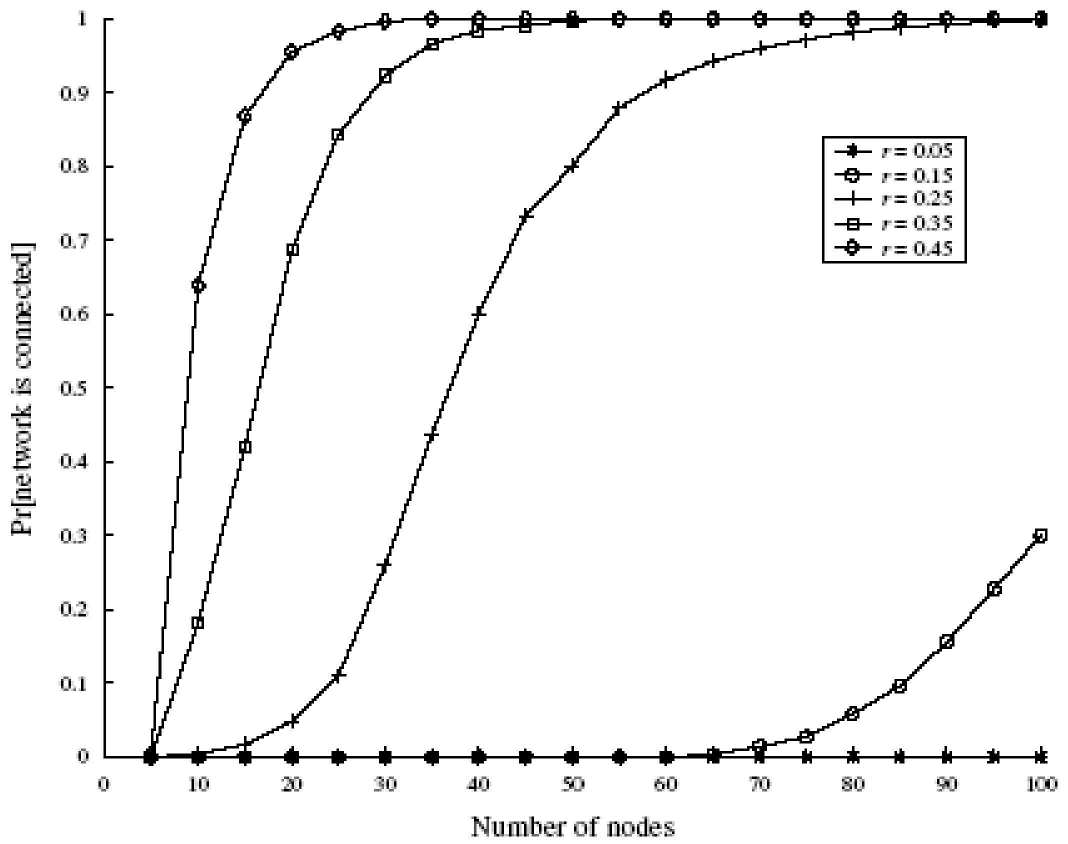


Figure 2.4 Probability of connectivity for a geometric random graph with respect to number of nodes in a unit area

Connectivity in Geometric Random Graphs..

onnectivity in G(n, R)

Gupta and Kumar have shown the following result:

Theorem 1

If $\pi R^2 = \frac{\log n + c(n)}{n}$, *the network is asymptotically connected almost surely if* $\lim_{n \to \infty} c(n) = \infty$ *and is disconnected asymptotically almost surely if* $\lim_{n \to \infty} c(n) = -\infty$.

It means, the critical transmission range for connectivity is $O\left(\sqrt{\left(\frac{\log n}{n}\right)}\right)$

A geometric random graph G(n, R) attains the property that all nodes have at least K neighbors is asymptotically equal to the critical radius at which the graph attains the property of K-connectivity

Connectivity in Geometric Random Graphs..

Monotone properties in G(n, R)

- A monotonically increasing property is any graph property that continues to hold if additional edges are added to a graph that already has the property
- Nearly all graph properties of interest from a networking perspective are monotone
- A key theoretical result pertaining to G(n, R) geometric random graphs is that all monotone properties show critical phase transitions
- All monotone properties are satisfied with high probability within a

Connectivity in Geometric Random Graphs..

Connectivity in G(n, K)

- In G(n, K) geometric random graph model, n nodes are placed at random in a unit area, and each node connects to its K nearest neighbors
- It allows different nodes in the network to use different powers
- It is known that K must be higher than 0.074*log n and lower than 2.72*log n, in order to ensure asymptotically almost sure connectivity

Connectivity in Geometric Random Graphs..

Connectivity and coverage in $G_{grid}(n, p, R)$

In the unreliable sensor grid model, n nodes are placed on a square grid within a unit area, p is the probability that a node is active (not failed), and R is the transmission range of each node

For this unreliable sensor grid model, the following properties have been determined:

For the active nodes to form a connected topology, as well as to cover the unit square region, p*R^2 must be $O(\frac{\log n}{n})$

The maximum number of hops required to travel from any active node to another is $O\left(\sqrt{(\frac{n}{\log n})}\right)$

There exists a range of p values sufficiently small such that the

Connectivity using Power Control

Once the nodes are in place, transmission power settings can be used to adjust the connectivity properties of the deployed network

- It can extend the communication range, increasing the number of communicating neighboring nodes and improving connectivity in the form of availability of end-to-end paths.
- For existing neighbors, it can improve link quality (in the absence of other interfering traffic
- It can induce additional interference that reduces capacity and introduces congestion

Some of these distributed algorithms aim to develop topologies that minimize total power consumption over routing paths, while others

Common Power Protocol

The authors claim that the protocol ensures that the lowest common power level that ensures maximum network connectivity

otocol Description

First multiple shortest path algorithms are performed, one at each possible power level

Each node then examines the routing tables generated by the algorithm and picks the lowest power level such that the number of reachable nodes is the same as the number of nodes reachable with the maximum power level

awbacks

- It is not very scalable
- By strictly enforcing common powers, it is possible that a single

Cone-Based Topology Control Protocol

The authors claim that the protocol provides a minimal direction-based distributed rule to ensure that the whole network topology is connected, while keeping the power usage of each node as small as possible.

otocol Description

Each node keeps increasing its transmit power until it has at least one neighboring node in every α cone or it reaches its maximum transmission power limit

It is assumed here that the communication range increases monotonically with transmit power

CBTC showed that $\alpha \leq 2\pi/3$ suffices to ensure that the network is connected

Cone-Based Topology Control Protocol

he left an intermediate power
 for a node at which there exists
: cone in which the node does not
e a neighbor. Therefore, as seen on
right, the node must increase its
er until at least one neighbor is
ent in every .

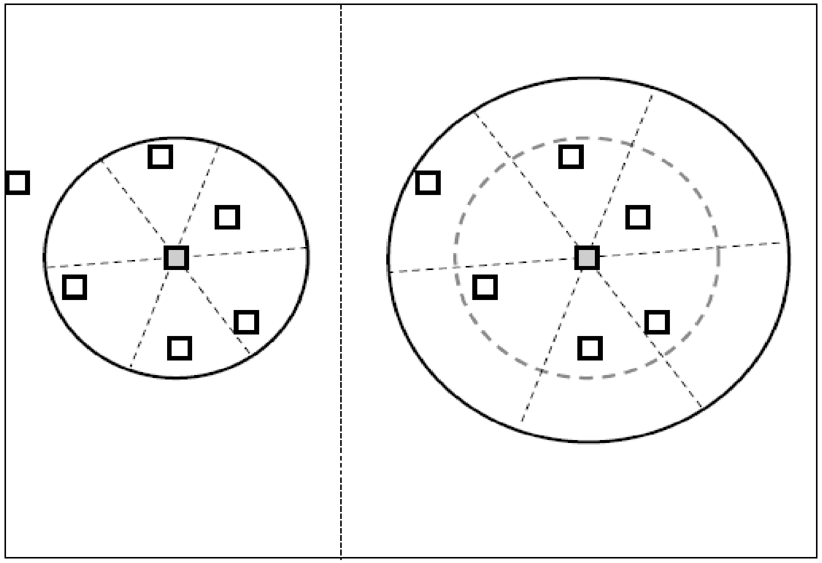


Illustration of the cone-based topology control (CBTC) construction

Coverage Metrics

- The choice of coverage metric is highly dependent on the application
- In most networks the objective is simply to ensure that there exists a path between every pair of nodes
  - If robustness is a concern, the K-connectivity metric may be used

K-Coverage

- A field is said to be K-covered if every point in the field is within the overlapping coverage region of at least K sensors. Only 2D coverage is considered in our course

Definition 1

Consider an operating region A with n sensor nodes, with each node i providing coverage to a node region $A_i \in A$ (the node regions can overlap). The region A is said to be K-covered if every point $p \in A$ is also in at least K node regions.

- In an s ×s unit area, with a grid of resolution ϵ unit distance, there will be $(\frac{s}{\epsilon})^2$ such points to examine, which can be computationally intensive

K-Coverage..

- A slightly more sophisticated approach would attempt to enumerate all subregions resulting from the intersection of different sensor node-regions and verify if each of these is K-covered
- In the worst case there can be $O(n^2)$ such regions and they are not straightforward to compute

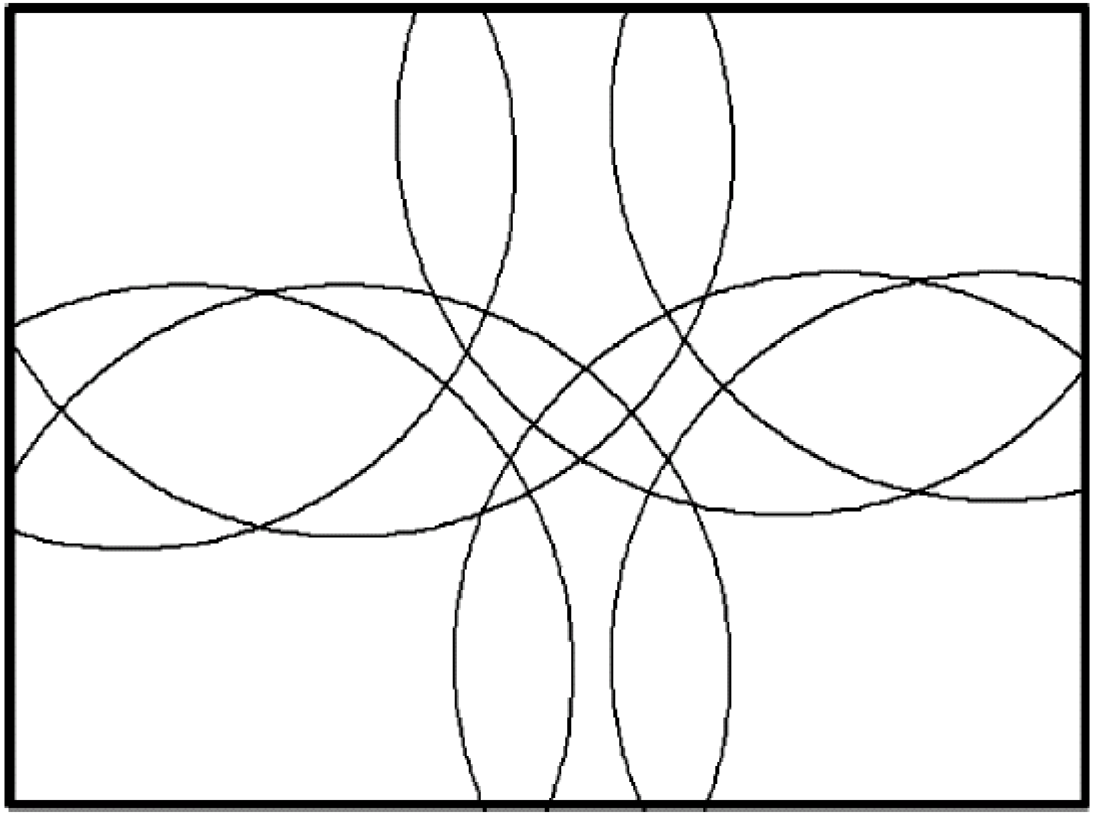
Definition 2

A sensor is said to be K-perimeter-covered if all points on the perimeter circle of its region are within the perimeters of at least K other sensors.

Theorem 3

The entire region is K-covered if and only if all n sensors are k-perimeter-covered.

K-Coverage..



An area with 2-coverage (note that all intersection points are 2-covered)

K-Coverage..

Theorem 4

The entire region is K-covered if and only if all intersection points between the perimeters of the n sensors (and between the perimeter of sensors and the region boundary) are covered by at least K sensors.

Theorem 5

If a convex region A is K-covered by n sensors with sensing range R_s and communication range R_c, their communication graph is a K-connected network graph so long as $R_c \geq 2R_s$.