Understanding Node Localizability of Wireless Ad-hoc Networks

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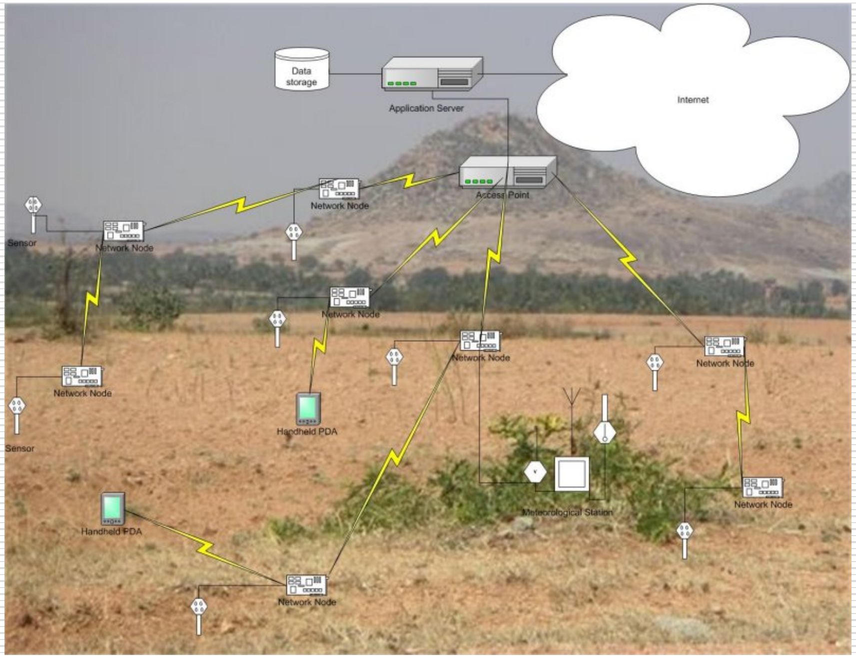
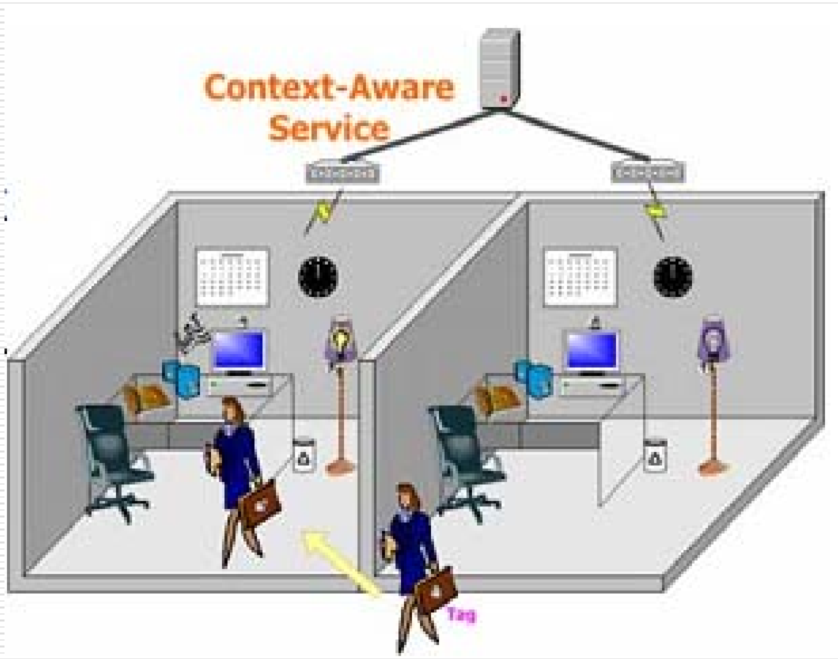
Outline

- Introduction
- Network Localizability
- Node Localizability
- Conditions for Node Localizability
- Performance Evaluation
- Conclusions and Future Work

Localization

- Determine the locations of wireless devices in a network



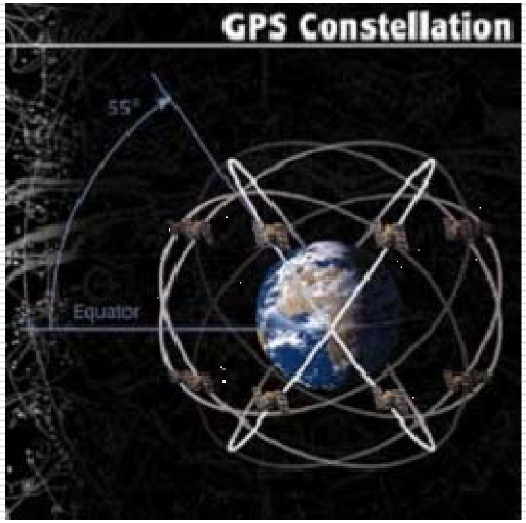


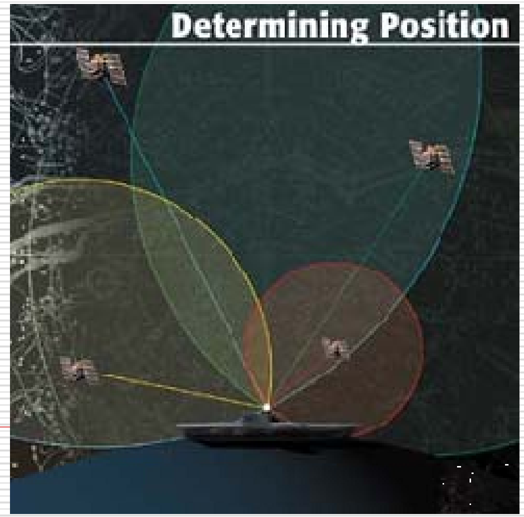
Why locations are important?

- Location-aware computing
  - Wireless sensor networks
    - Environmental monitoring, object tracking, …
    - *“Sensing data without knowing the sensor location is meaningless.”* [IEEE Computer, Vol. 33, 2000]
  - Mobile computing
    - Mobile p2p streaming
  - Pervasive computing
    - Smart space

Why is Localization a Non-Trivial Problem?

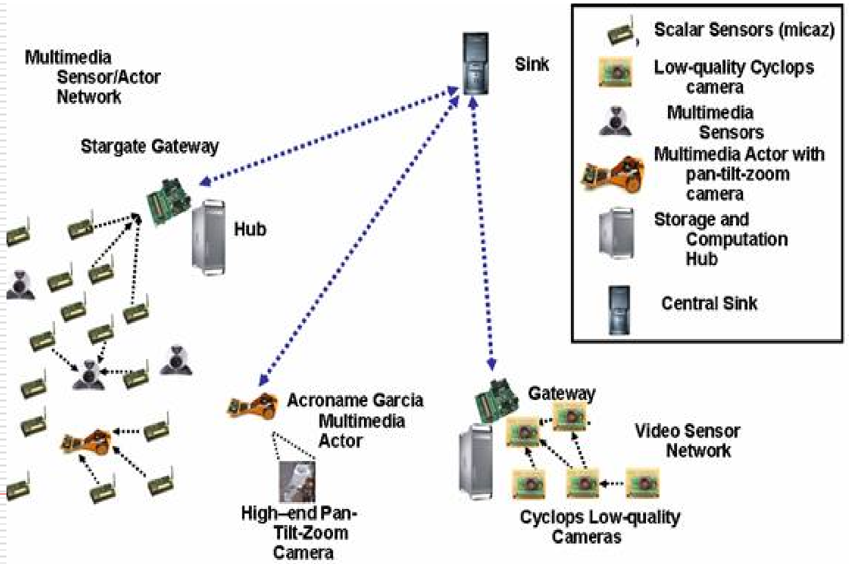
- Manual configuration
  - Unscalable and sometimes impossible
- Why not use GPS?
  - Hardware requirements
  - Obstructions to GPS satellites
    - Indoor
    - Underground
  - GPS accuracy (10-20 feet) poor for short range sensors





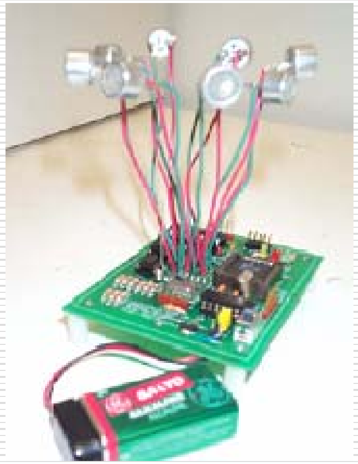
Network Localization

- Network Localization
  - Beacons
    - special nodes at known locations
  - Non-beacon nodes
    - Distance ranging

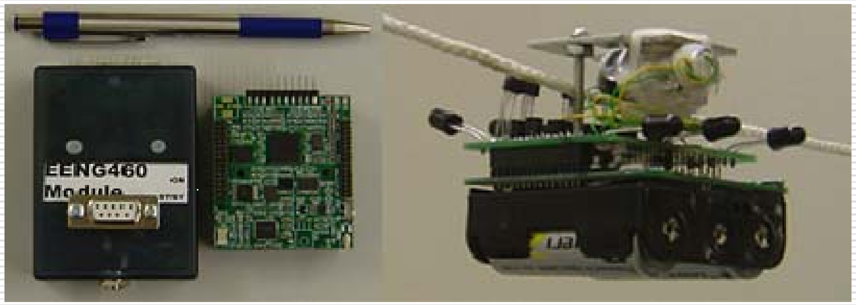


Distance Measuring

- Ranging techniques
  - Radio Signal Strength (RSS)
  - Time Difference of Arrival (TDoA)
- Ranging systems



UCLA medusa mote



Yale XYZ mote

MIT Cricket mote

Distance Graph Model

- Distance graph G_N of a wireless network N
  - Vertices: wireless devices (e.g., laptops, PDAs, or sensor nodes)
  - Edges: an edge connecting two vertices (i and j) if the distance $d(i,j)$ between corresponding nodes can be measured

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Network Realization

Definition

A *realization* of a graph *G* is a function *p* that maps the vertices of *G* to points in a Euclidean space.

Generally, realizations are referred to the *feasible* ones that respect the pairwise distance constraints

Localizability

Definition

A network is *localizable*

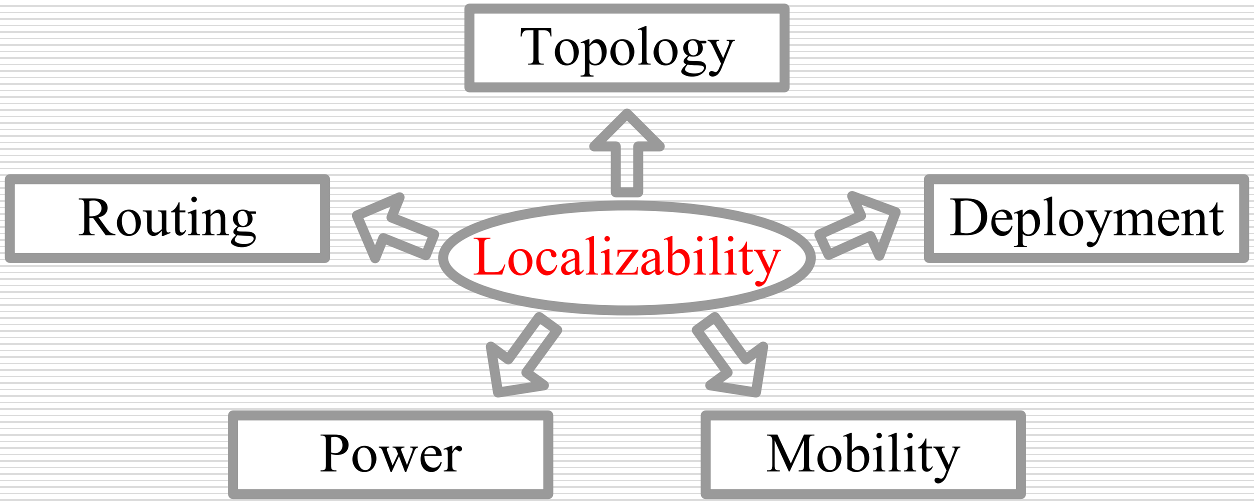
if it has a unique realization in some metric space.

Localizability

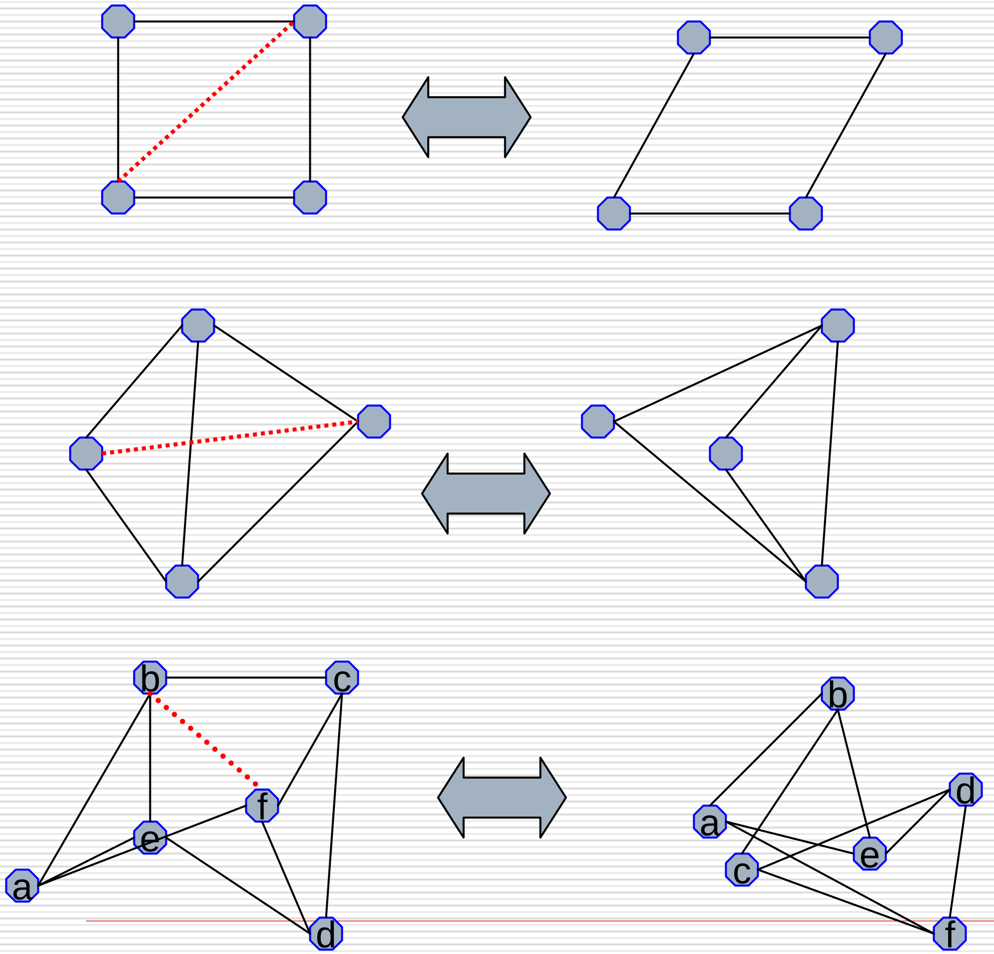
- **Localizability** V.S **Localization**
  - If a network is **NOT** localizable, by no means it can be localized.
  - If a network is localizable, it can be localized in theory (but may be computationally infeasible).

Why Localizability is Important?

- Being aware of localizability helps:



Localizability and Graph Rigidity



Solution:

G must be *rigid.*

G must be 3-connected.

G must be *redundantly rigid:*
It must remain rigid upon
removal of any single edge.

Localizability and Graph Rigidity

Global rigidity (by Jackson and Jordan, 2003)

A graph is generically globally rigid in 2D plane iff. it is 3-connected and redundantly rigid.

The necessary and sufficient condition for localizability.

Network localizability (Eren, 2004)

A network is uniquely localizable iff. its distance graph is globally rigid and it contains at least three beacons.

Localizability Test Algorithm

- Network localizability can be tested
  - Polynomial time to the graph size
    - Rigidity: $O(n^2)$ by the pebble game algorithm by Jacobs and Hendrickson (1997)
    - Redundant rigidity: $O(n^2)$ algorithm by Hendrickson (1991)
    - 3-connectivity: $O(n)$ algorithm by Tarjan (1972)
- So far, it seems …

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Node Localizability

Observations

Almost **all the time** the network is **NOT** entirely localizable.

A large portion, on average nearly **80%**, of nodes are actually localizable.

Node Localizability

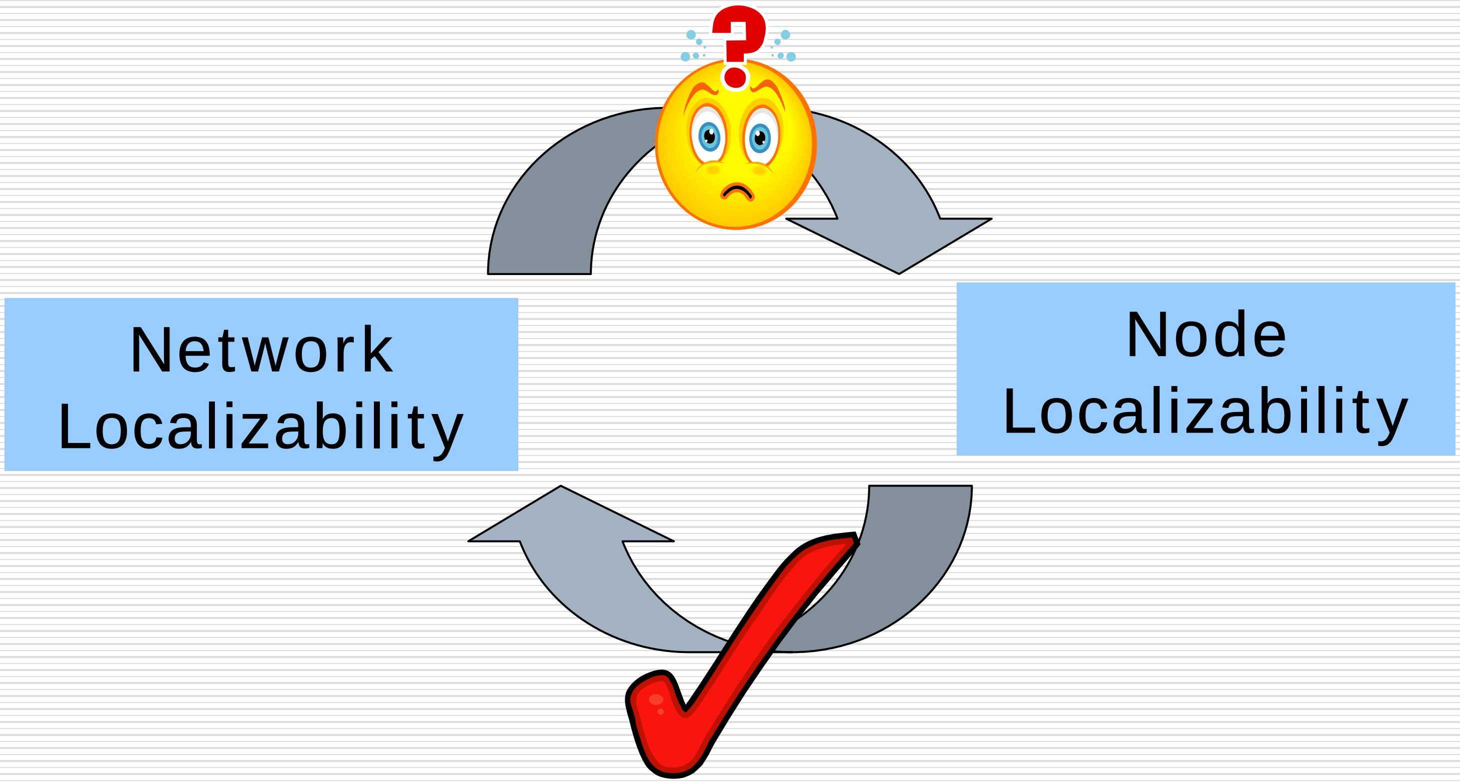
- Node localizability
  - To answer the question that *whether a particular node has a unique location*.
  - Single node V.S entire network

Why Node Localizability is Important?

- Partially localizable networks
  - They are not localizable.
  - A portion of nodes have unique locations while others do not.
- Application
  - A portion of nodes draw remarkable attentions

Node Localizability

- Which one is harder?

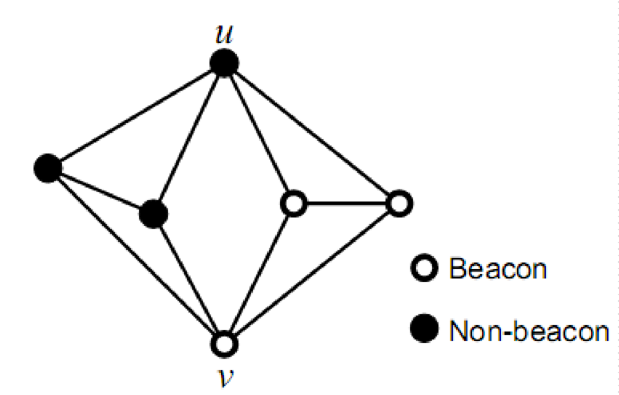


Why Node Localizability Is Difficult?

- A straight-forward solution
  - Find a sub-network that is localizable
  - Identify all nodes in the sub-network localizable
- Correct? YES, BUT…

Why Node Localizability Is Difficult?

- Missing localizable nodes
  - *G* is not 3-connected
  - *u* is localizable



Some conditions *essential* to network localizability are *no longer necessary* for node localizability.

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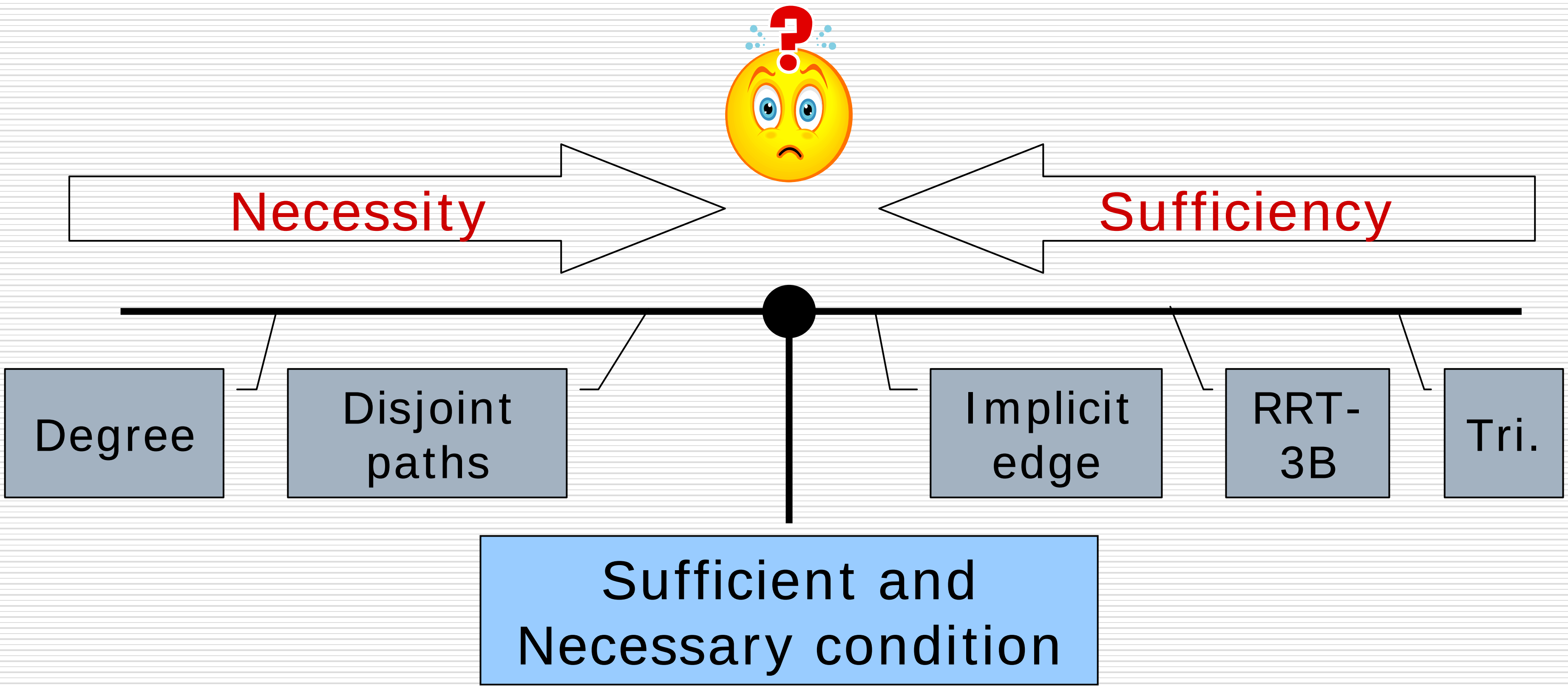
Conditions for Node Localizability

- Necessity
  - Degree = 3
  - 3 vertex-disjoint paths to 3 distinct beacons [Goldenberg, 2005]
- Sufficiency
  - Trilateration
  - Localizable sub-network [Goldenberg, 2005] .
  - Implicit edge [Eren, 2005]

Previous work



Necessary Conditions

- 3 vertex-disjoint paths (3P)
  - Goldenberg, 2005
- Redundant Rigidity (RR)
  - In this study, 2009
  - If a vertex is localizable, it is included in the redundantly rigid component of beacon nodes.

Necessary Conditions

- Necessity
  - The combination of 2 necessary conditions is also a necessary condition

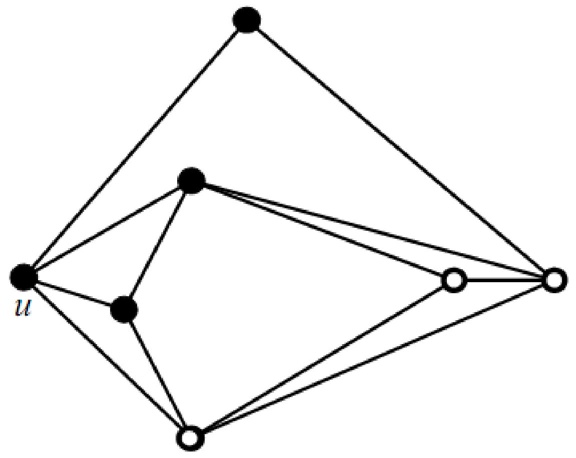
RR-3P

Theorem

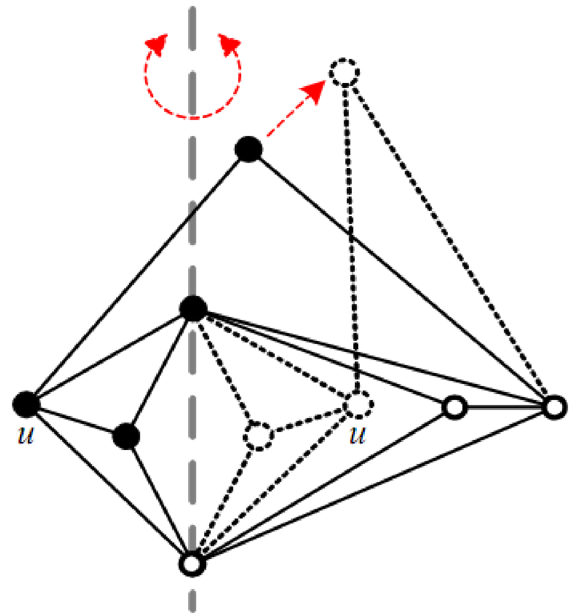
In a distance graph $G = (V, E)$ with a set $B \subset V$ of $k \geq 3$ vertices at known locations, if a vertex is localizable, it is included in the **redundantly rigid** component that contains B and has **3 vertex-disjoint paths** to 3 distinct vertices in B.

Necessary Conditions

- RR-3P is **NOT** sufficient



(a) The vertex u satisfies RR-3P.



(b) u suffers a discontinuous flexing.

Sufficient Conditions

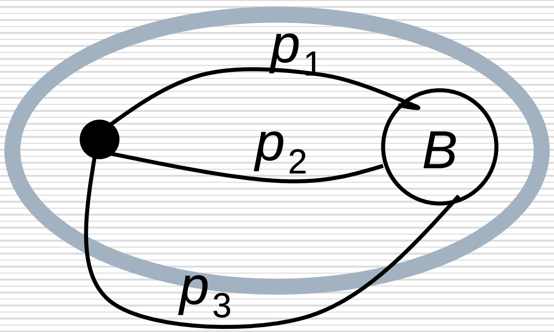
- RR3P condition

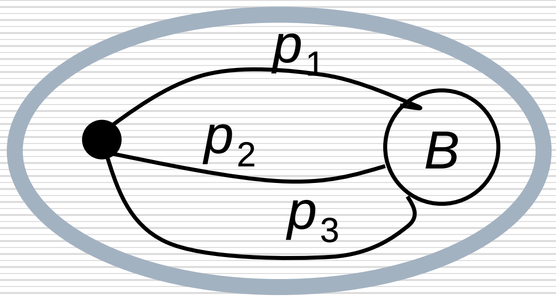
Theorem

In a distance graph $G = (V, E)$ with a set $B \subset V$ of $k \geq 3$ vertices at known locations, a vertex is localizable if it belongs to the redundantly rigid component of B in which it has 3 vertex-disjoint paths to 3 distinct vertices in B.

Summary (1)

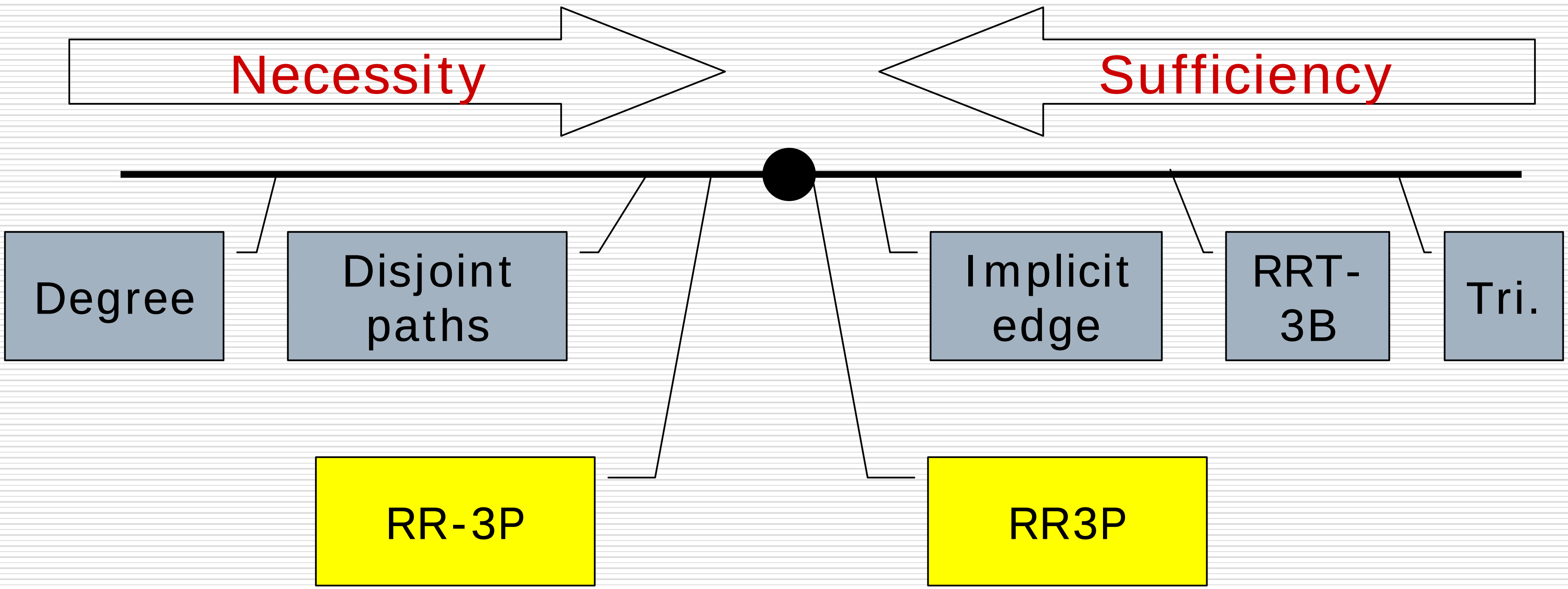
Necessity	Sufficiency
RR-3P	RR3P





All paths are strictly included

Summary (2)


Necessity
Sufficiency
Degree
Disjoint paths
Implicit edge
RRT-3B
Tri.
RR-3P
RR3P

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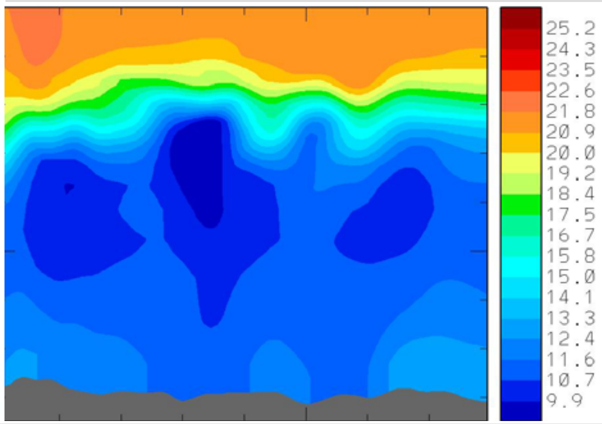
System Description

- Sea monitoring WSN
  - 100 wireless sensors
  - Environmental Data
    - temperature, humidity, illumination…
  - Localization: Trilateration

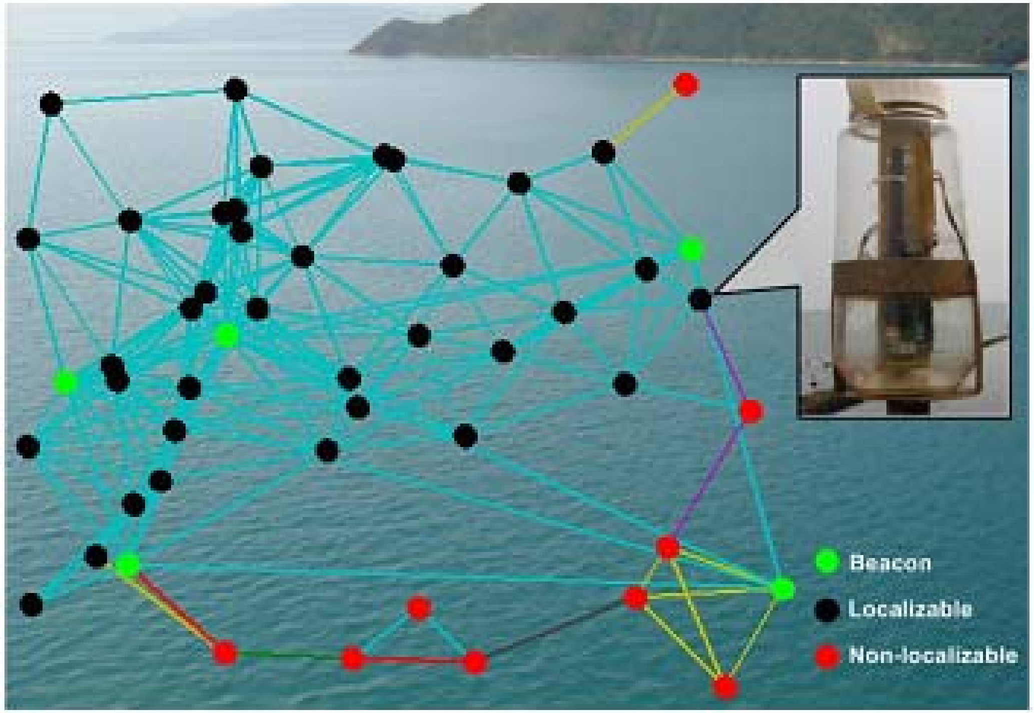


Observation (1)

- Observations
  - Almost all the time the network is **NOT** entirely localizable.
  - A large portion, on average nearly **80%**, of nodes are actually localizable
  - Specifically, **90%** of network topologies have at least **60%** of nodes localizable

- The importance of node localizability.

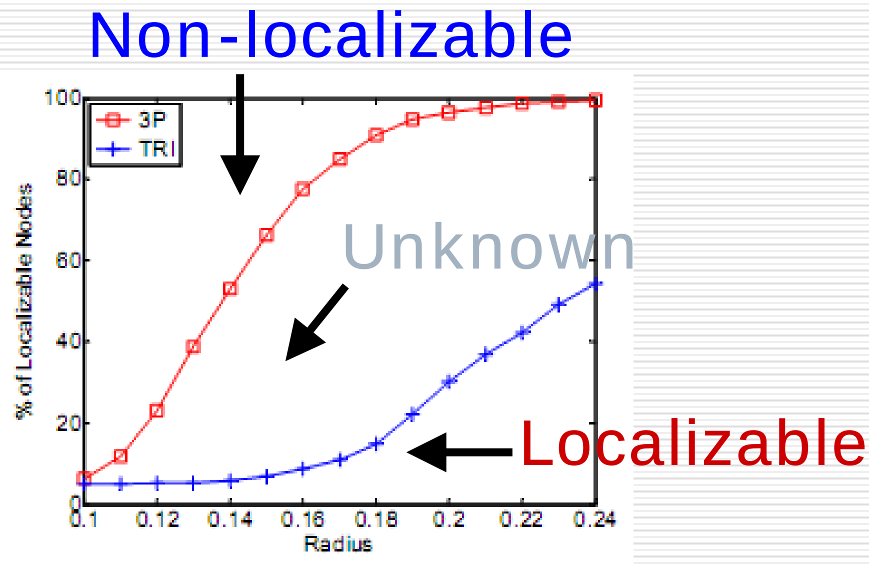
Observation (2)



Simulations

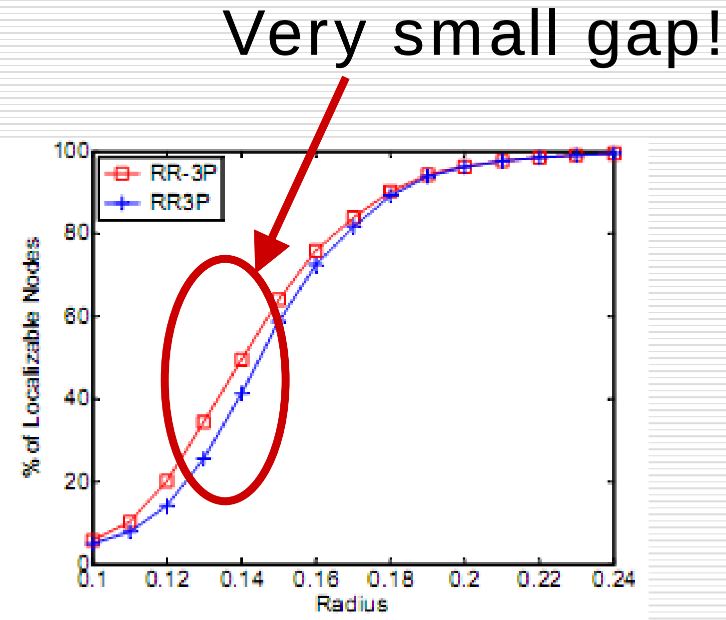
- Metrics
  - the number of nodes that can be identified
- Comparison
  - Necessary conditions
    - **3P** V.S. **RR-3P**
  - Sufficient conditions
    - **TRI** V.S. **RR3P**

Results(1)



(a) The capability of 3P and TRI.

3P and TRI

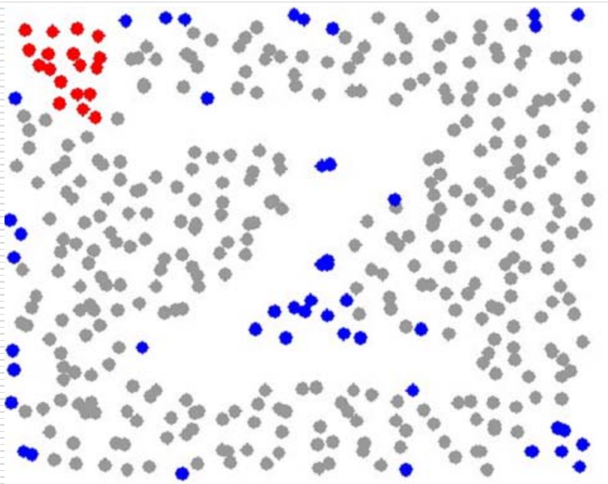


(b) The capability of RR-3P and RR3P.

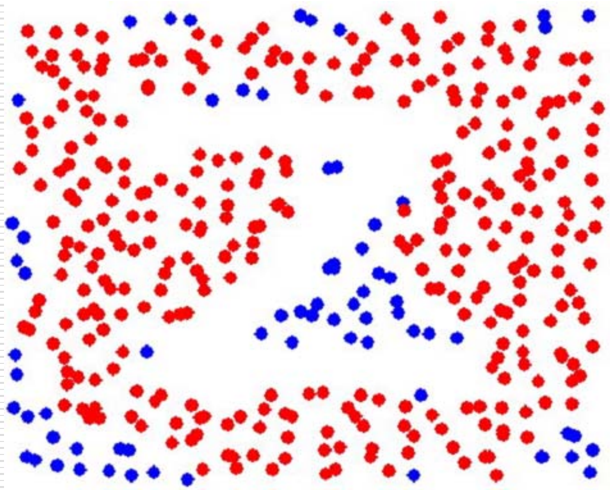
RR-3P and RR3P

Results(2)

- network with a "Z" hole
  - **Blue**: non-localizable
  - **Red**: localizable
  - **Grey**: unknown

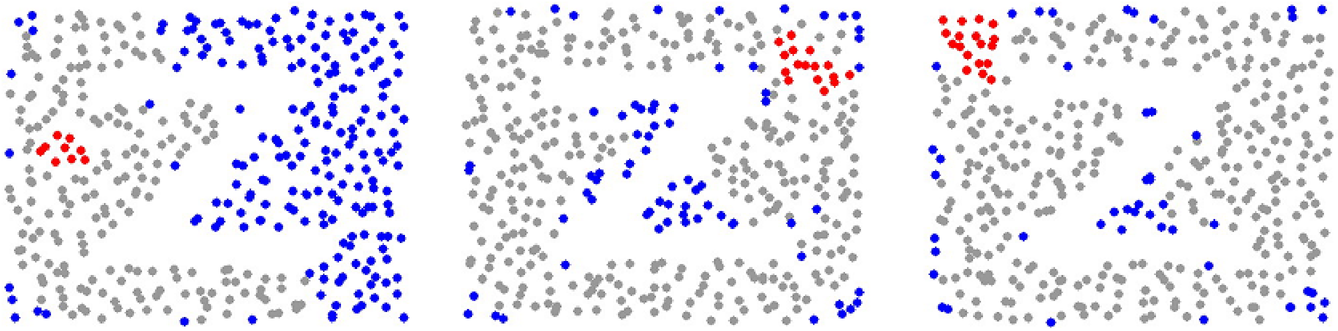


3P and TRI



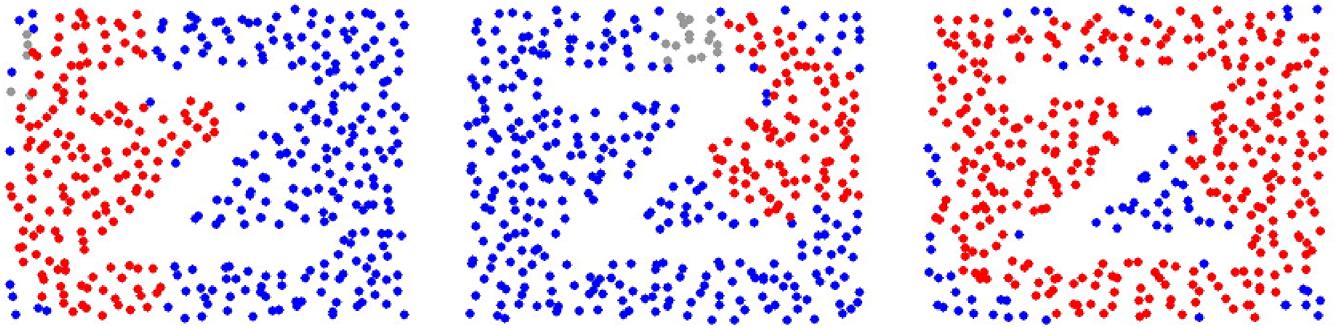
RR-3P and RR3P

Results(3)



(a) Case 1 (b) Case 2 (c) Case 3

Figure 15: Testing 3P and TRI on network instances with “Z” holes.



(a) Case 1 (b) Case 2 (c) Case 3

Figure 16: Testing RR-3P and RR3P on network instances with “Z” holes.

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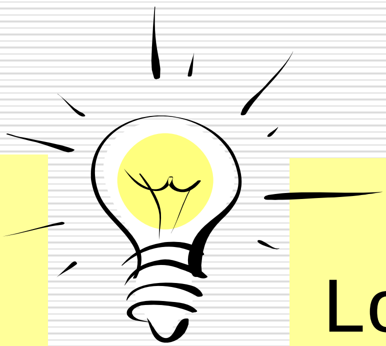
Conclusion

- Limitations of network localizability
- Node localizability
- Necessary and sufficient conditions

Graph Rigidity

Theory

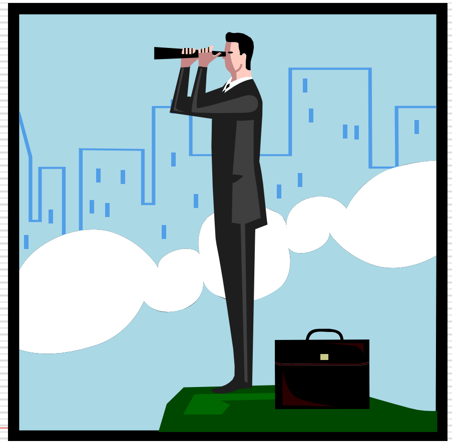


Node Localizability

Application

Future Work

- Localizability under noisy ranging
  - Localizable ???
    - perfect ranging
    - noisy ranging
  - Robustness of localizability testing



Thanks.

Any questions?