A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots

Ad Hoc Networks - Seminar, WS 08/09

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Computer Networks and Telematics
University of Freiburg

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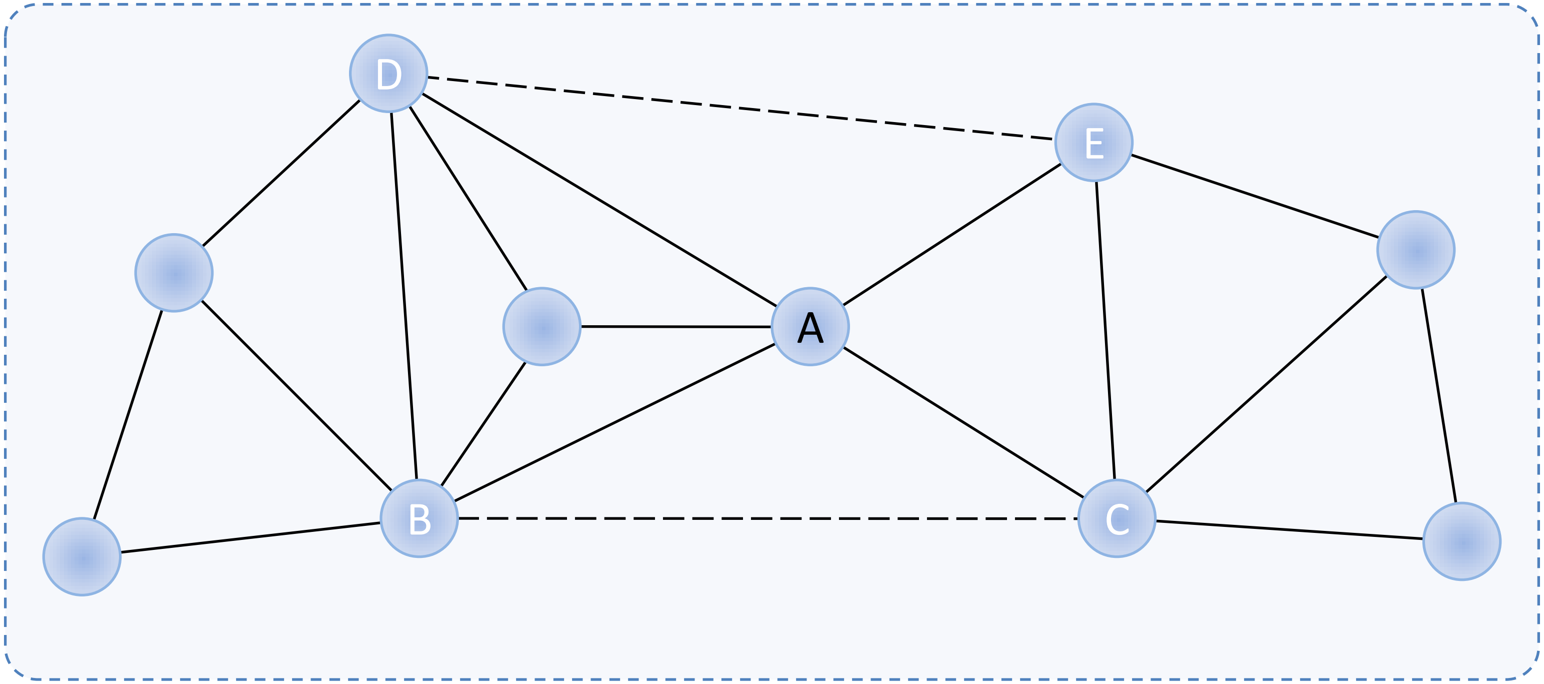
Introduction

- Multi-robot systems have become more and more attractrive in the past few years due to the significant advancements in robotics technology
- Generally wireless ad hoc networks are used for communication in such systems
- But most of the existing algorithms are only suitable for robots with verly low or even no failure rates!
- This is not very practical because robots are susceptible to failures!

Conclusion

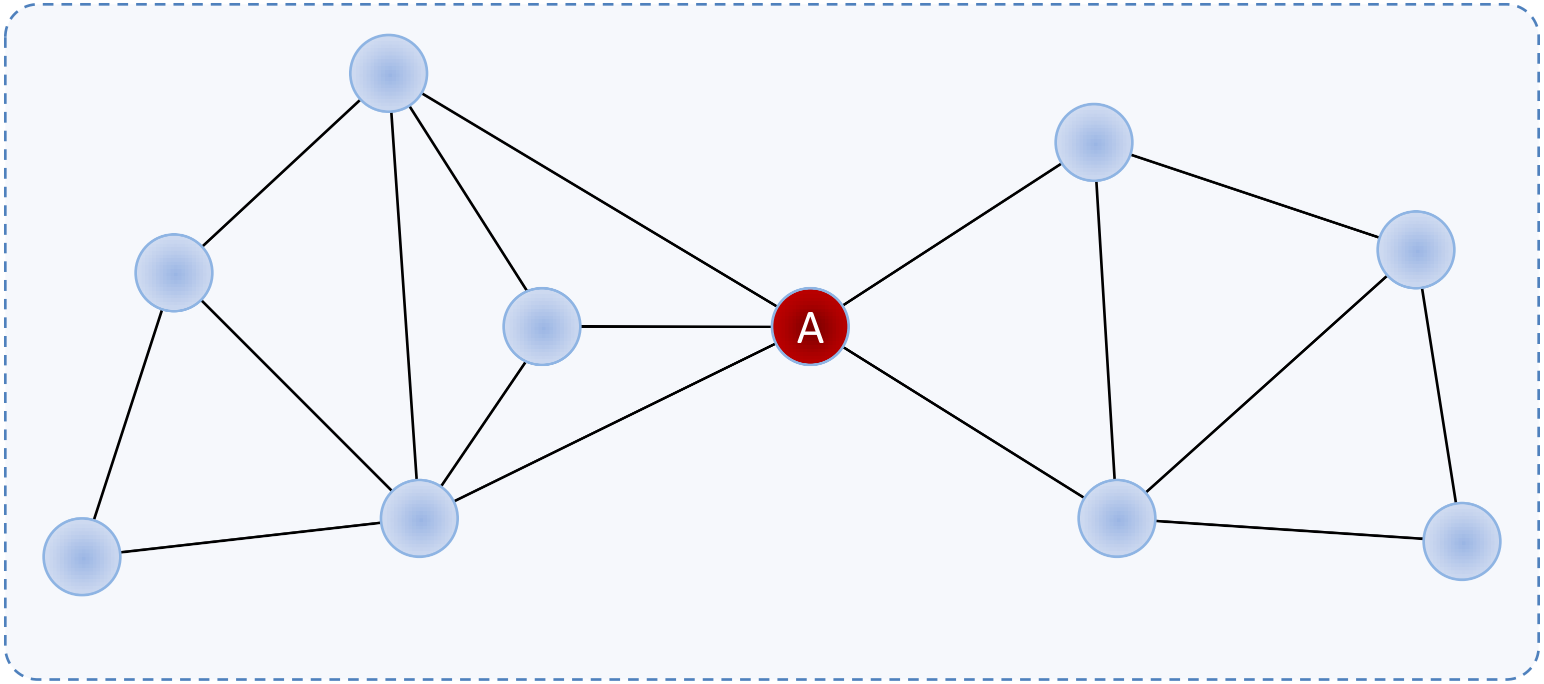
In a fault-tolerant network there should be at least two node-disjoint communication paths between each pair of robots in order to handle communication faults



Definition

A network is **bi-connected** if there exist two node-disjoint paths between any pair of nodes in the network

➡ **Conclusion:** Networks is still connected if one node fails!



Definition

A node is called a critical node if the network is disconnected without the node

Conclusion: There are no critical nodes in bi-connected networks!

Problem Definition

- Communication links in mobile Networks can easily fail!
  (e.g. hardware damage, energy depletion, harsh environments, malicious attacks)

➡ There should be at least two node-disjoint paths between any two nodes

➡ Network should be bi-connected

Task: Given a *connected* but not *bi-connected* network
move the robots such that the network becomes *bi-connected*

Objective: Minimize total movement of robots

Lokal vs. Global

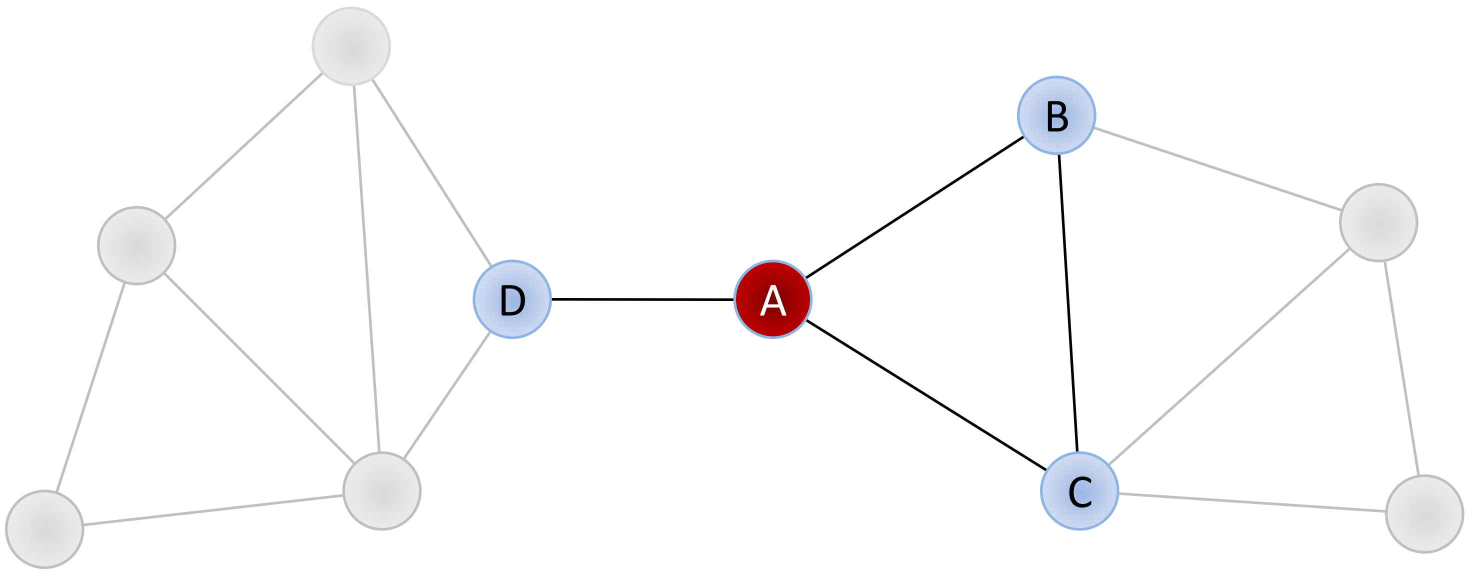
- so far only **globalized** Algorithm exists
- at least one node has to know the entire topology of the Network

➡ Applicable only for small size Networks

- **localized** Algorithm is executed on each node of the Network
- uses only *p-hop* neighbor information

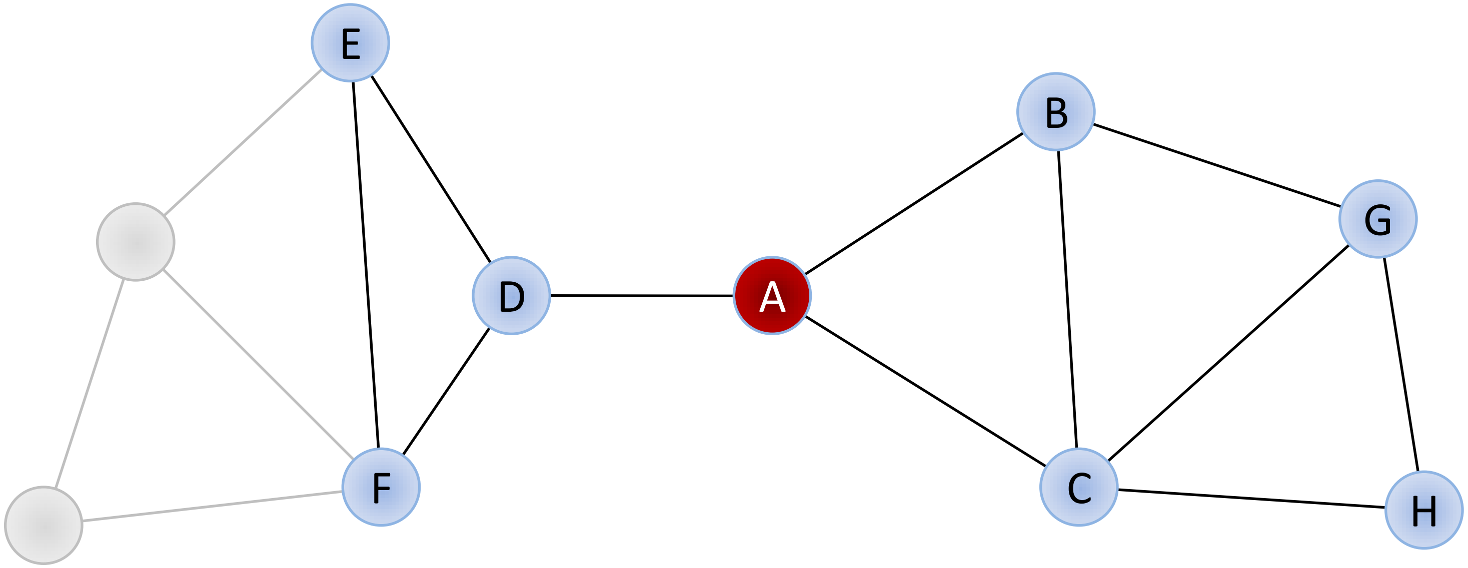
➡ more practical for large size Networks

p-Hop Neighborhood



p = 1

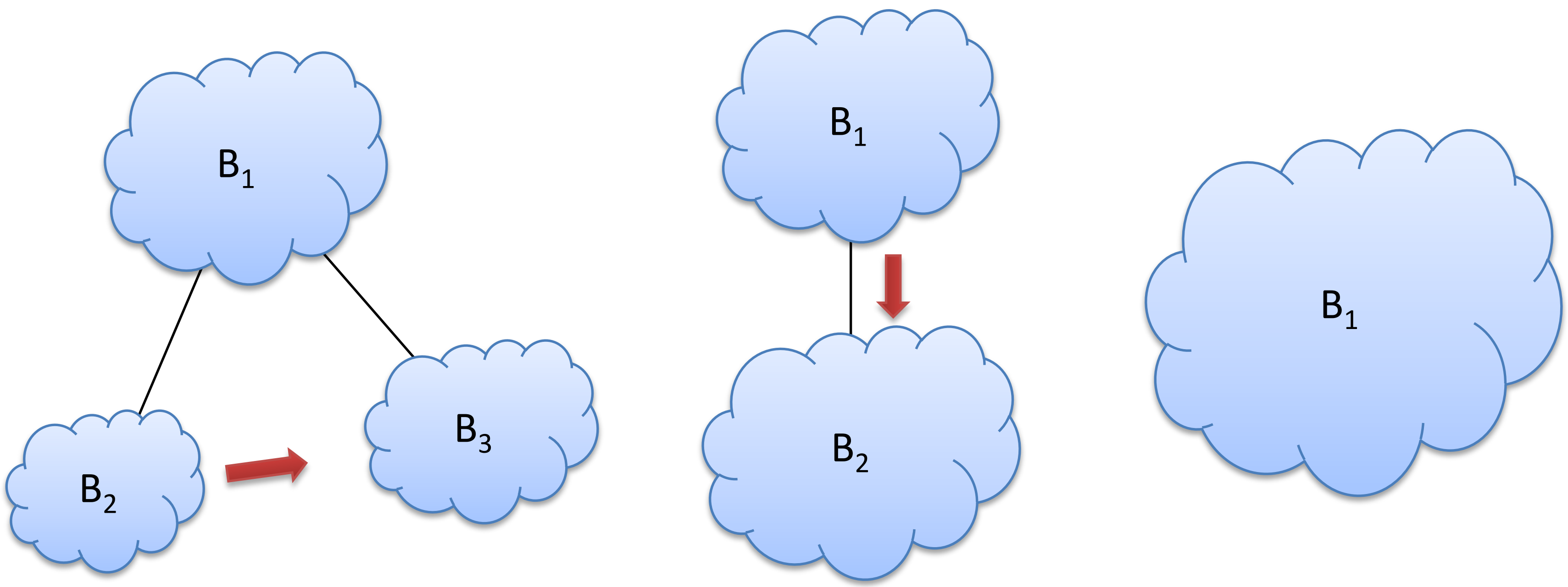
p-Hop Neighborhood



p = 2

Globalized Algorithm

- Divides the network into bi-connected blocks
- Every node knows the entire topology of the network
- Blocks are iteratively merged to form a single bi-connected block



Localized Movement Control Algorithm

- First localized movement control algorithm to achieve bi-connectivity
- Executed at each node iteratively (every iteration consits of two phases)
- Significant improvement when compared to the globalized algorithm

Assumptions:
- all nodes have a common communication range *r*
- each node knows its *p-hop* neighborhood (HELLO messages)
- network is *connected* but not *bi-connected*

Drawbacks:
- does not guarantee bi-connectivity
- may stop at connected but not bi-connected stage
- may even partition the network
- can cause coverage holes

Phase 1 - Initialization

- Each node checks whether it is a p-hop critical node

Definition

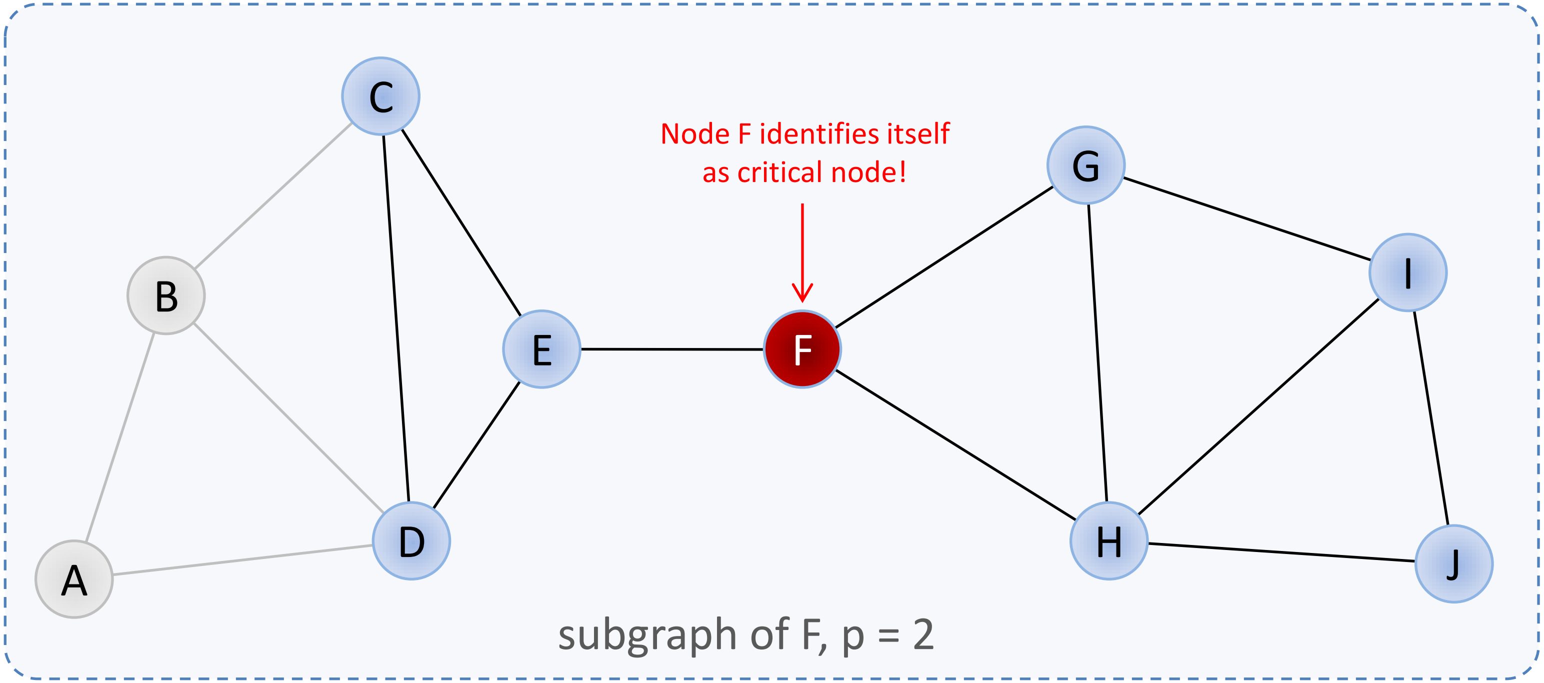
A node is called a p-hop critical node if and only if its *p-hop subgraph* is disconnected without the node

➡ Every *p-hop* critical node broadcasts a critical announcement packet to all its direct neighbors

Remarks:

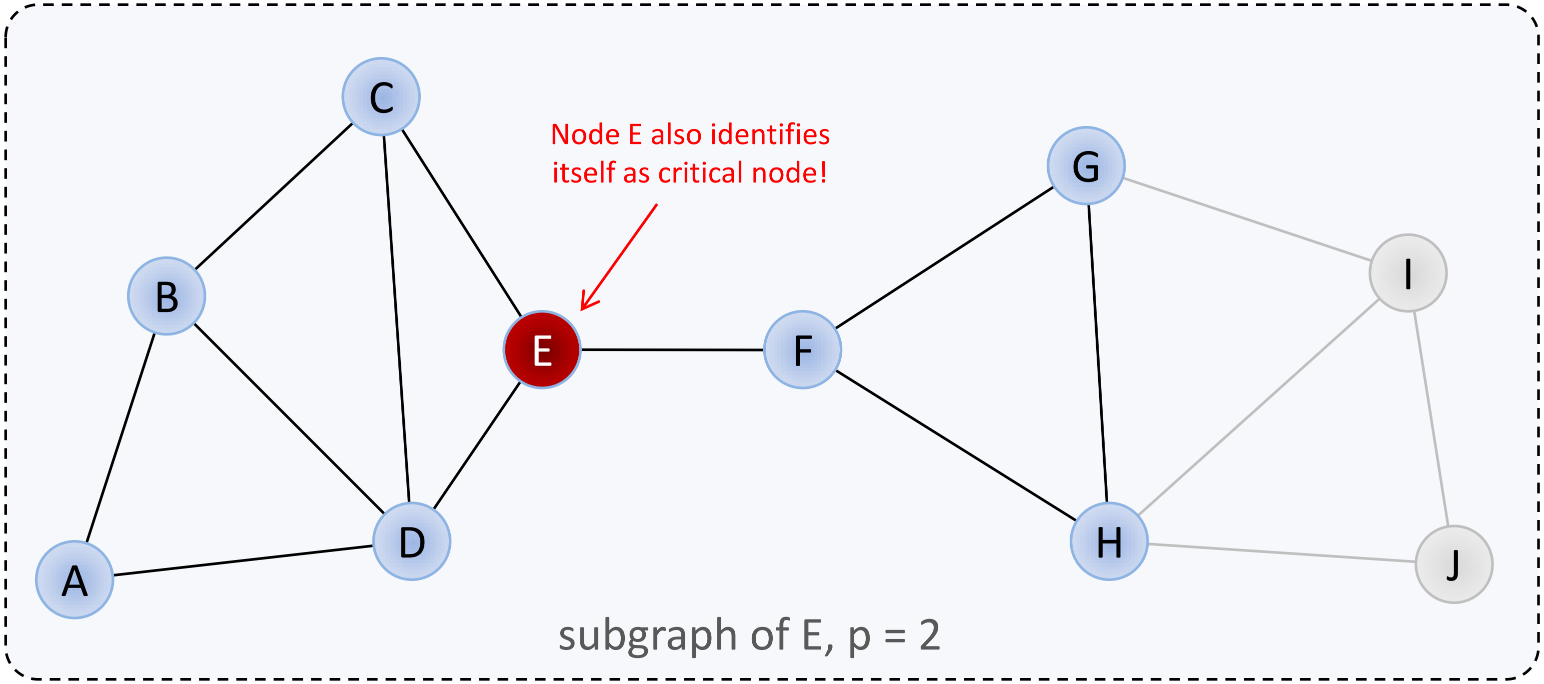
- A *p-hop* critical node is not necessarily globally critical but every globally critical node is a *p-hop* critical node for any *p*
- Experiments showed that over 80% of locally estimated critical nodes are indeed globally critical

Phase 1 - Initialization



- Critical nodes should not be moved because breaking some current links of a critical node can disconnect the network
- So the basic idea is to move only non-critical nodes such that critical nodes become non-critical

Phase 1 - Initialization



- Critical nodes should not be moved because breaking some current links of a critical node can disconnect the network
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Phase 2 – Node Movement

- After the initialization phase a *p-hop* critical node knows which of his neighbors are also *p-hop* critical nodes!
- Critical nodes try to make their neighborhood bi-connected by moving some of the nodes in their neighborhood which are non-critical

3 Cases

1. There are no critical neighbors
2. There exists exactly one critical neighbor
3. There exist two or more critical neighbors

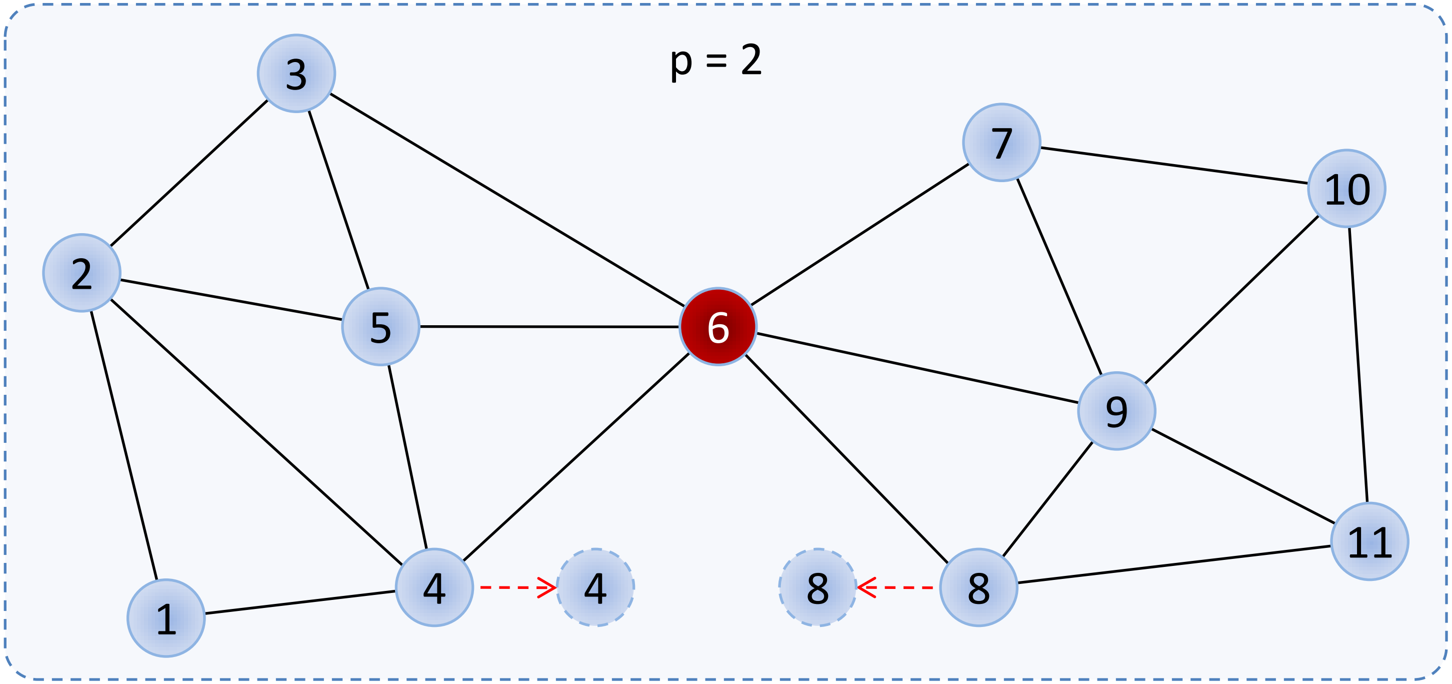
2.1 - No critical neighbor

- Select two neighbors from disjoint sets of the *p-hop subgraph* and move them towards each other until they become neighbors
- Every node should move *(d-r)/2* when *d* is the distance between them
- To minimize the movement choose the pair of nodes with minimal distance

➡ After movement any node that loses a neighbor or finds a new neighbor broadcasts a *topology update packet*

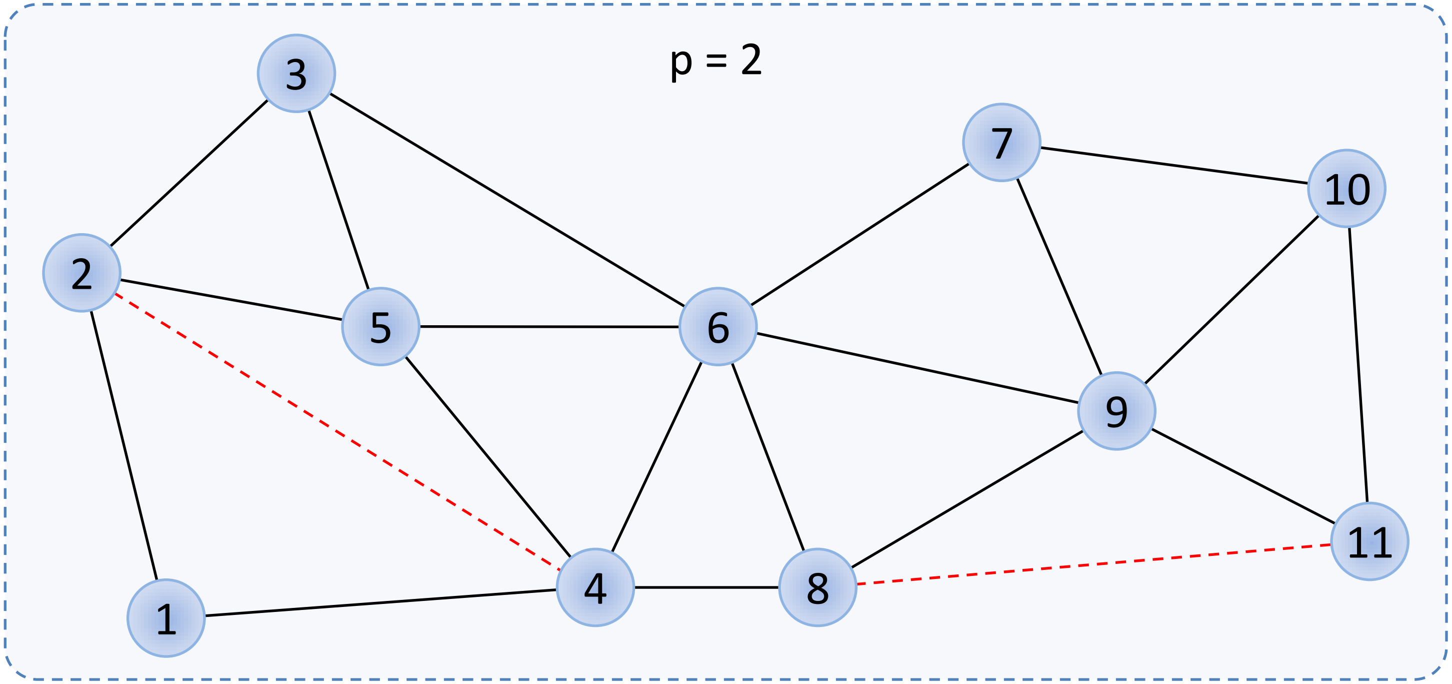
➡ A node which receives a *topology update packet* updates its *p-hop subgraph* for the next iteration of the algorithm

2.1 - No critical neighbor (Example)



- Nodes 4 and 8 have minimal distance

2.1 - No critical neighbor (Example)



- some connections may get lost
- perhaps new critical nodes are created

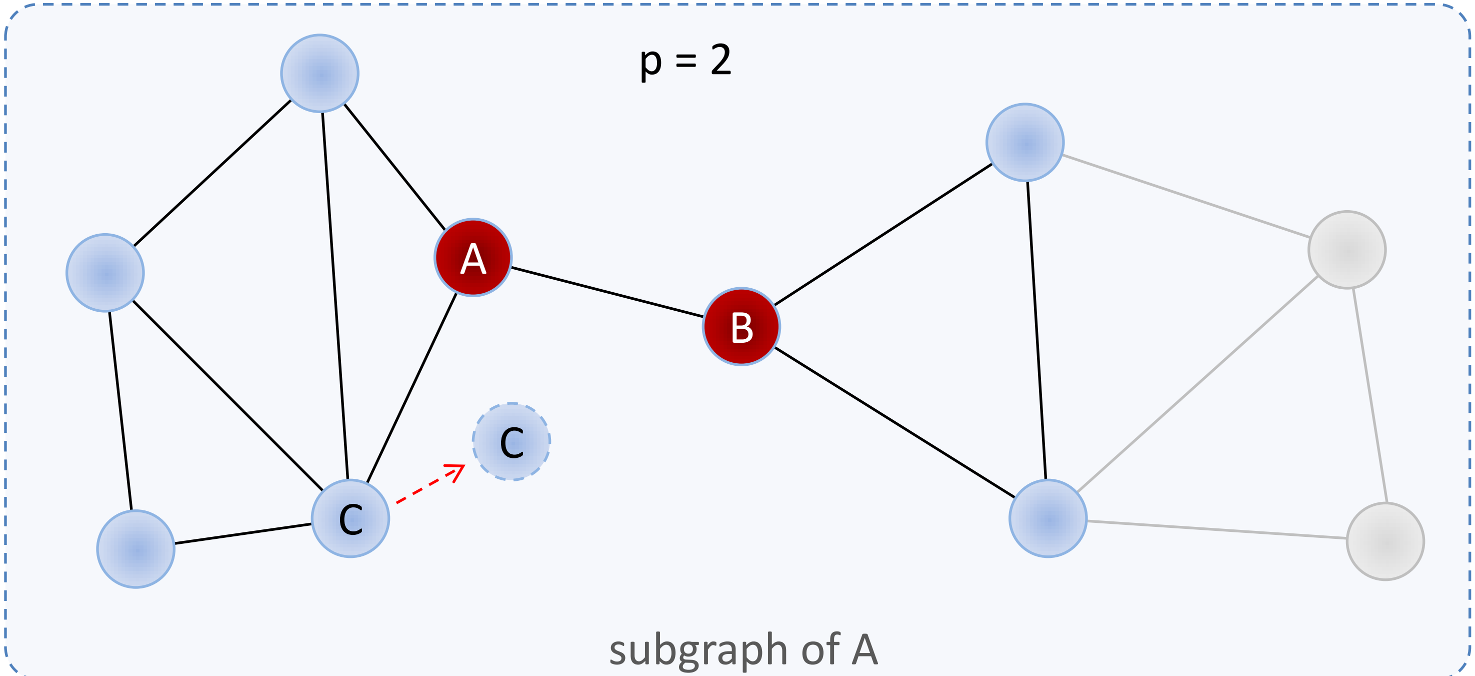
2.2 – Exactly one critical neighbor

- Two adjacent critical nodes (suppose A and B)
- Node with larger ID leads the movement control (suppose A)
  -> Node IDs are used to assign priorities
- A selects a non-critical neighbor with minimal distance to B and let it move towards B (from the disjoint set not including B)
- Selected neighbor should move *d-r* when *d* is the distance between them

➡ After movement any node that loses a neighbor or finds a new neighbor broadcasts a *topology update packet*

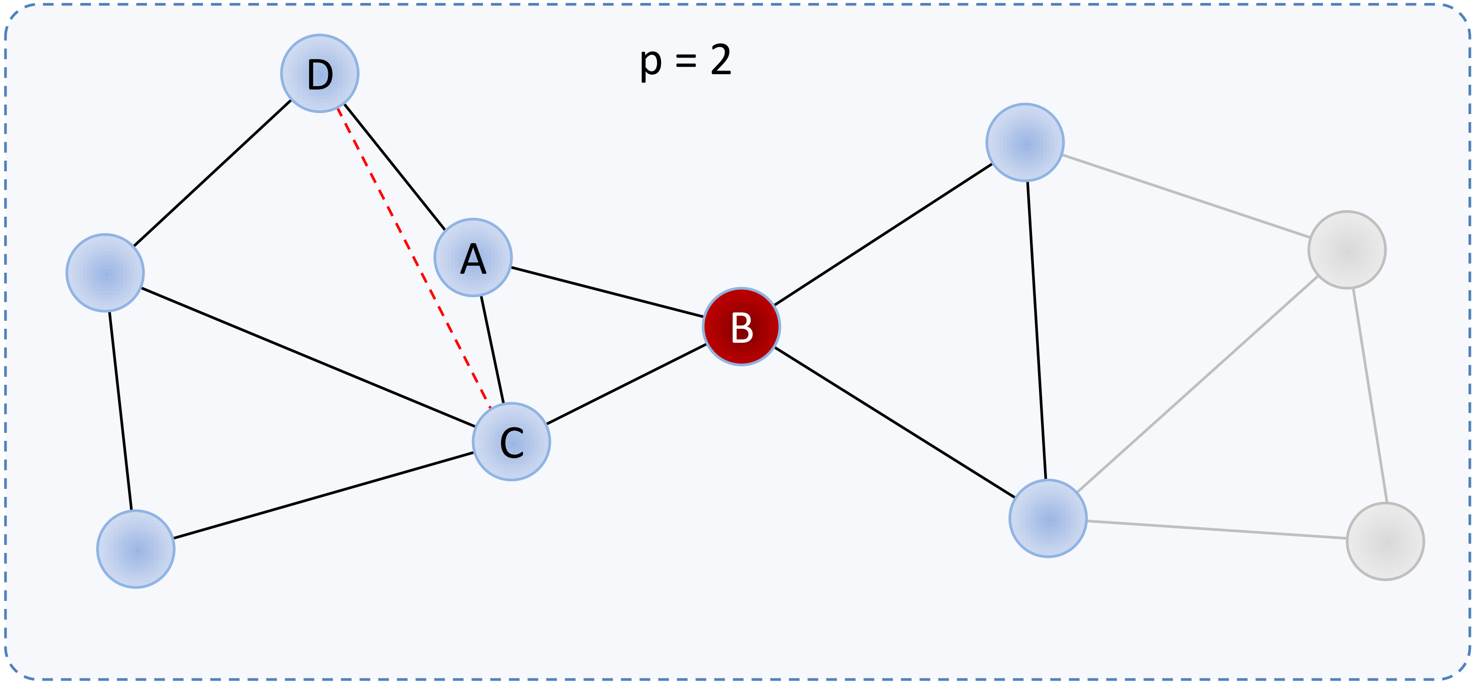
➡ A node which receives a *topology update packet* updates its *p-hop subgraph* for the next iteration of the algorithm

2.2 – Exactly one critical neighbor (Example)



- suppose node A has larger ID than node B

2.2 – Exactly one critical neighbor (Example)



- some connections may get lost
- perhaps new critical nodes are created

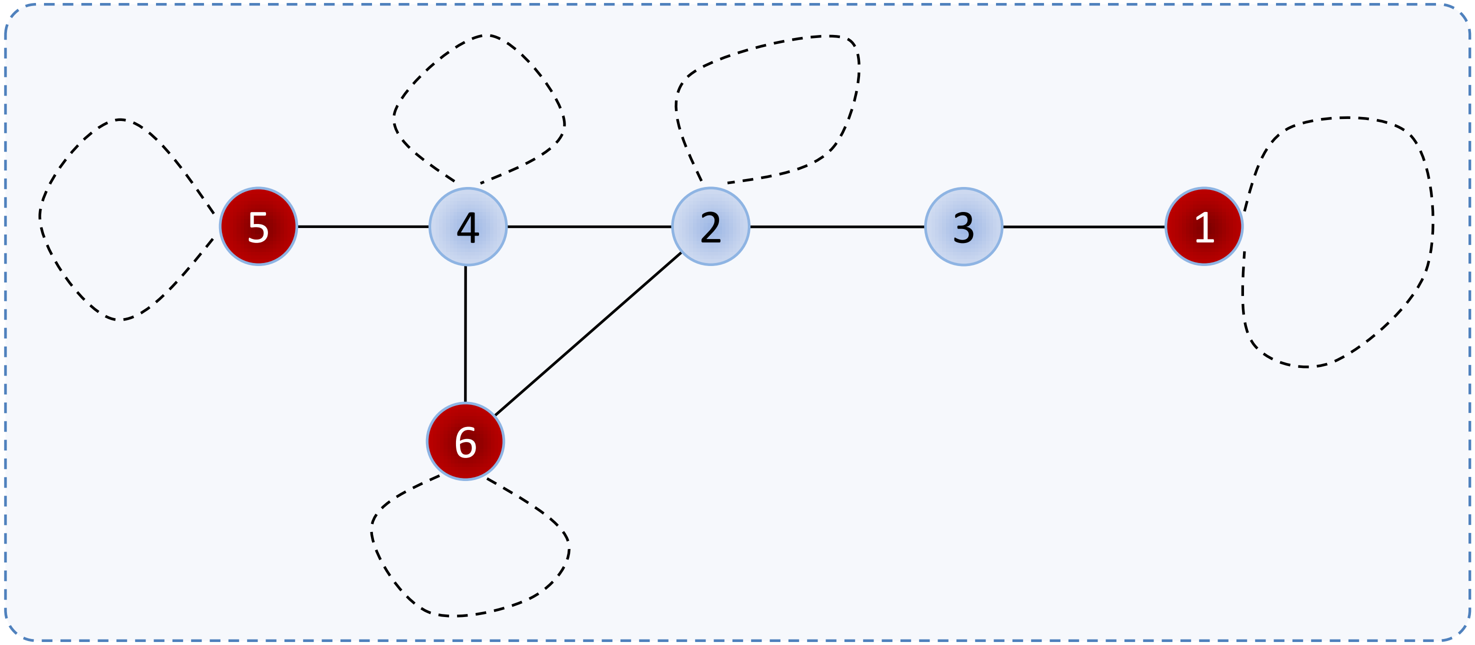
2.3 – Two ore more critical neighbors

Definitions

- A critical node is available if it has *non-critical neighbors* and non-available otherwise
- A critical node is a critical head if and only if
  - It is *available* and its ID is larger than the ID of any *available critical neighbor*
  - Or it has no *available critical neighbors*

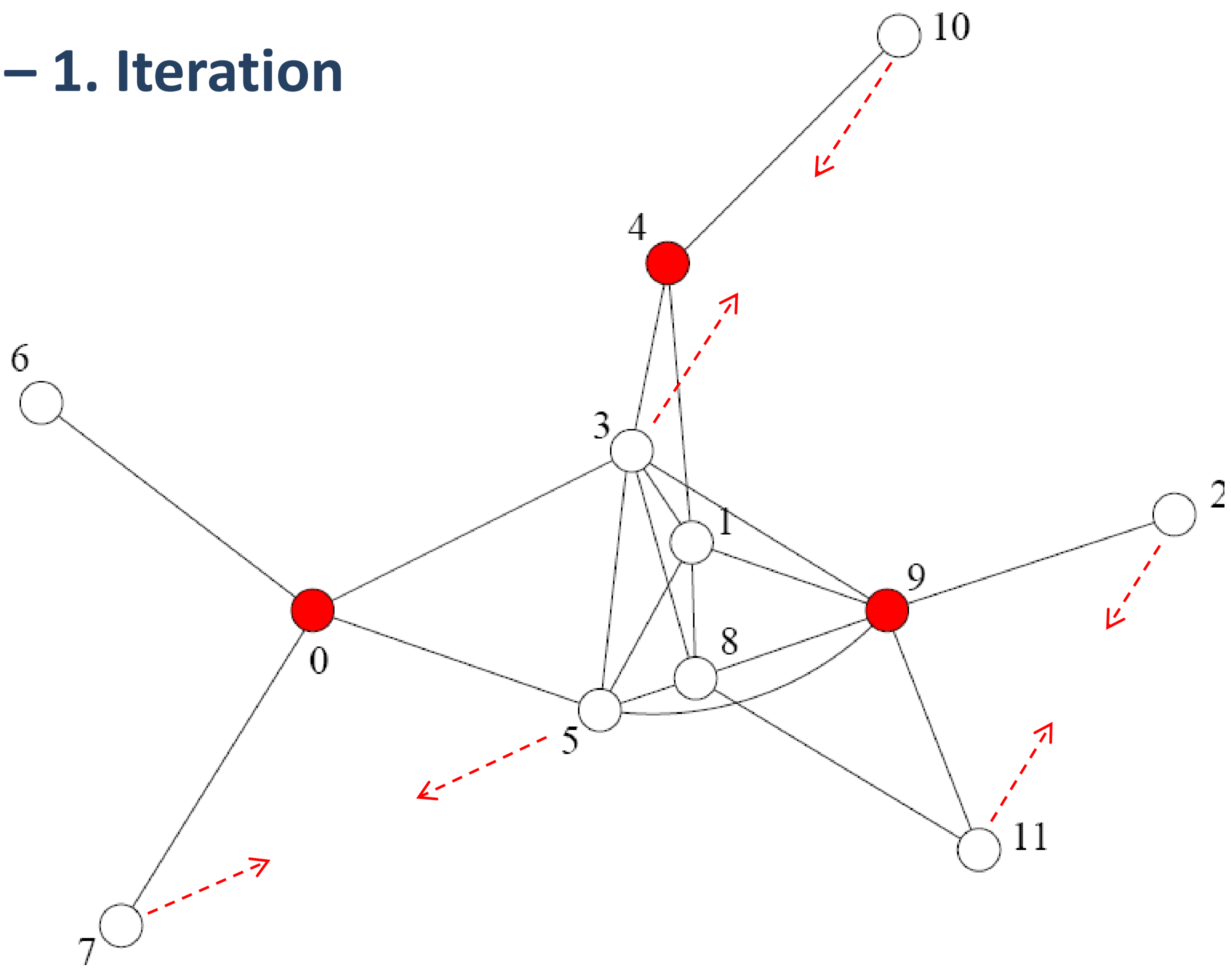
- Basic idea is to use a pair wise merging strategy
- Each critical head selects the available critical neighbor with largest ID it to pair with (or non-available if there is no available critical neighbor)
- Then for each pair the movement control algorithm for case 2 is called

2.3 – Two ore more critical neighbors (Example)



- Nodes 1, 5, 6 are critical heads
- Resulting pairs are (1,3), (5,4) and (6,4)

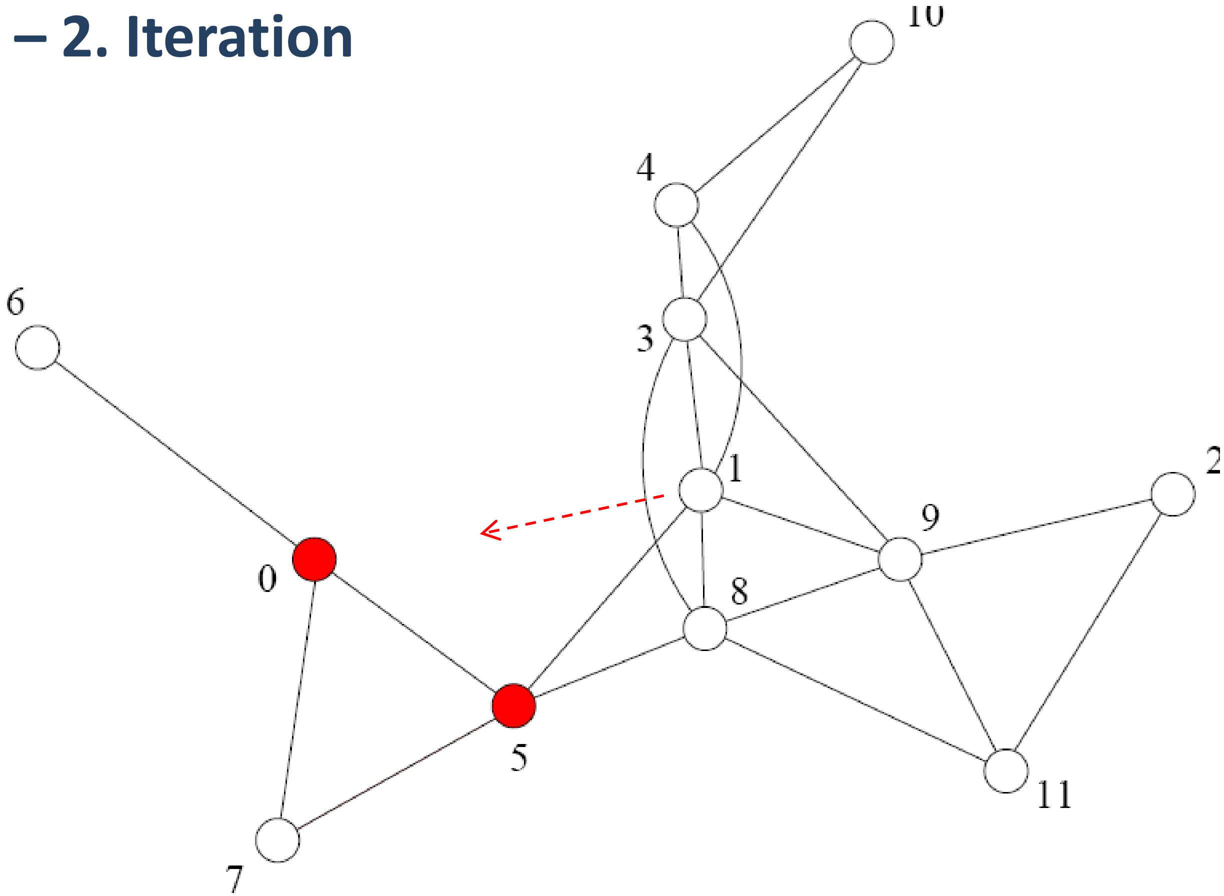
Example – 1. Iteration



- Nodes 0, 4, 9 are critical nodes
- For every critical node case 1 holds

[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 7]

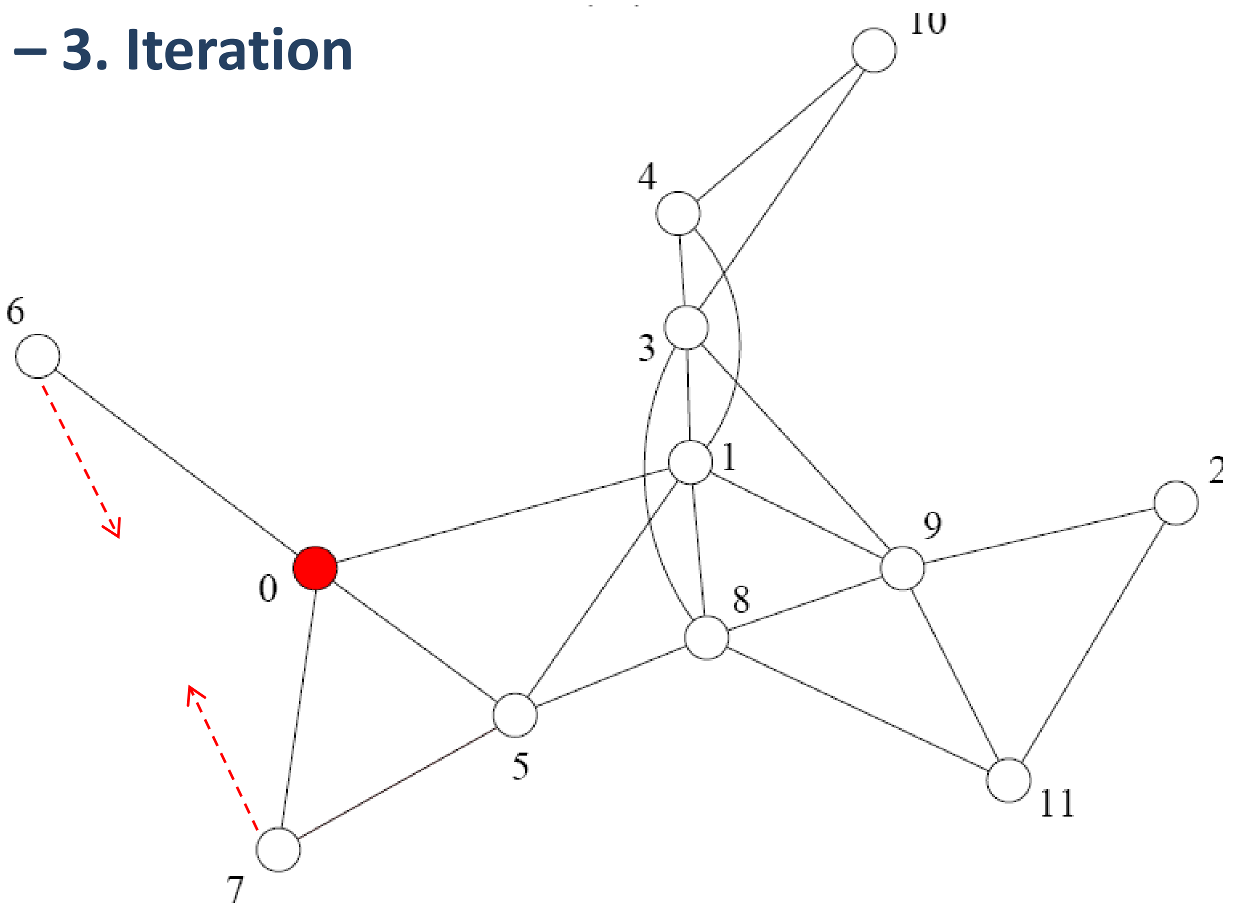
Example – 2. Iteration



- Nodes 0 and 5 are critical nodes
- For these nodes case 2 holds

[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 7]

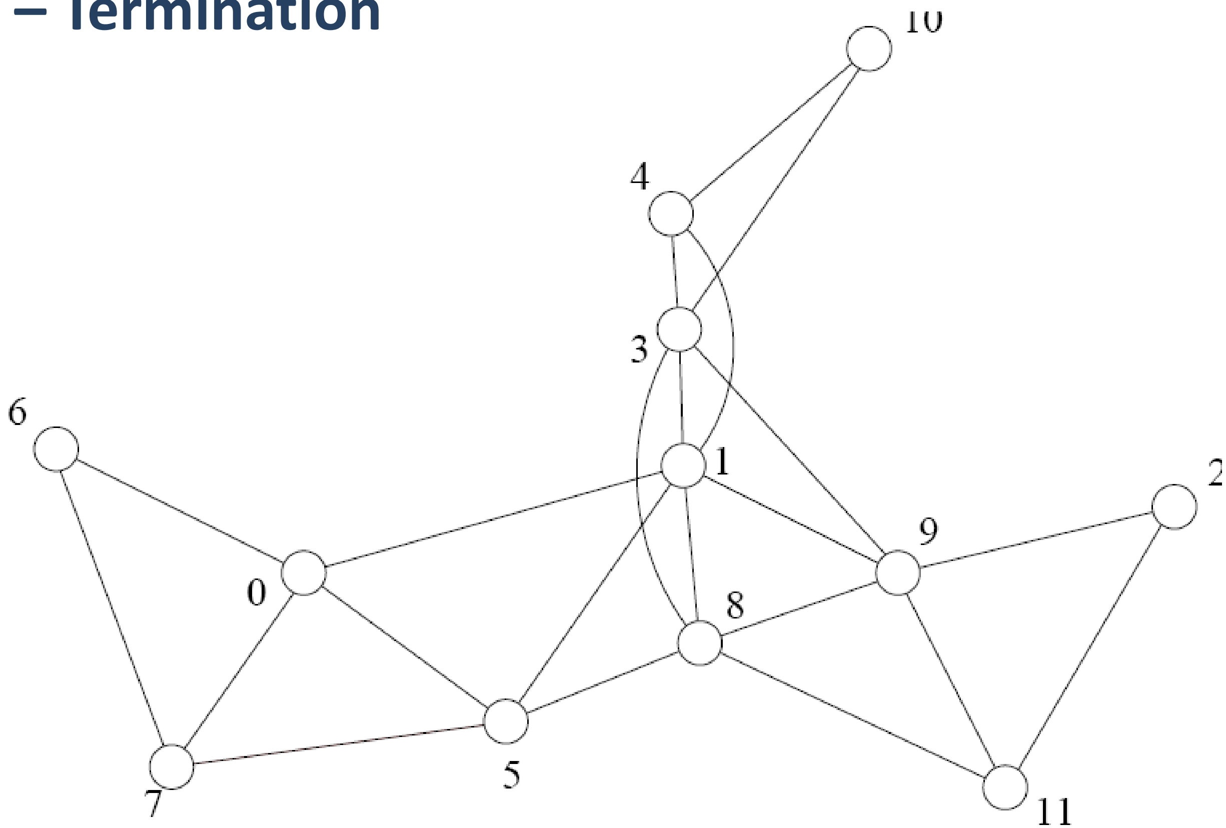
Example – 3. Iteration



- Node 0 is the only critical node
- For this node case 1 holds

[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 7]

Example – Termination



- There is no critical node left

➡ Algorithm terminates

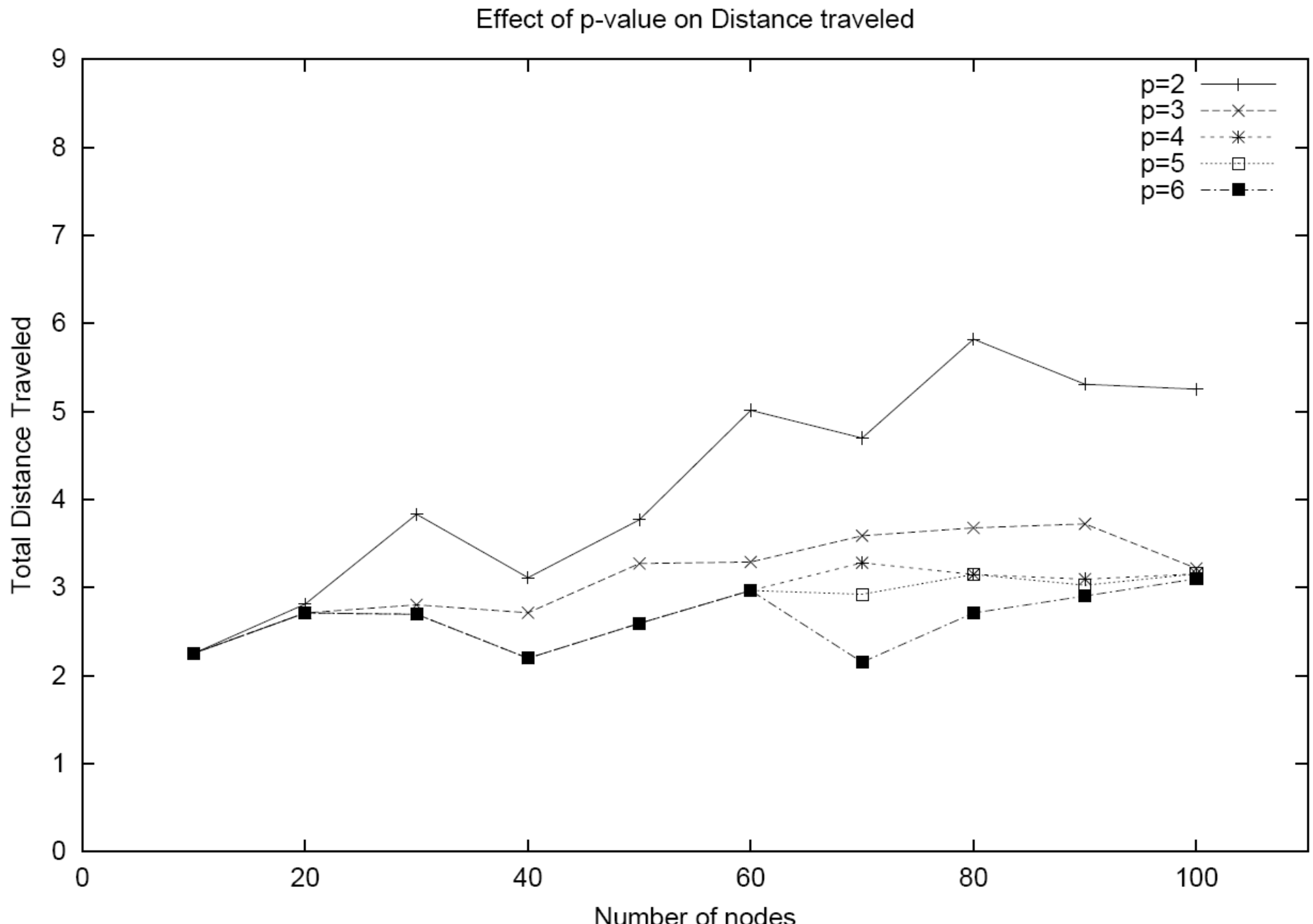
[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 7]

Simulation Environment

- Varying number of nodes (from n=10 to n=100)
- Sensor field size scaled according to number of nodes
  (300 m^2 for n=10 up to 3000 m^2 for n=100)
- Network density $d \approx 10$ (i.e. an average of 10 neighbors per node)
- Communication range $r = 10$ m
- Various values of p
- Networks generated by random placement
  (100 different networks for each parameter setting)

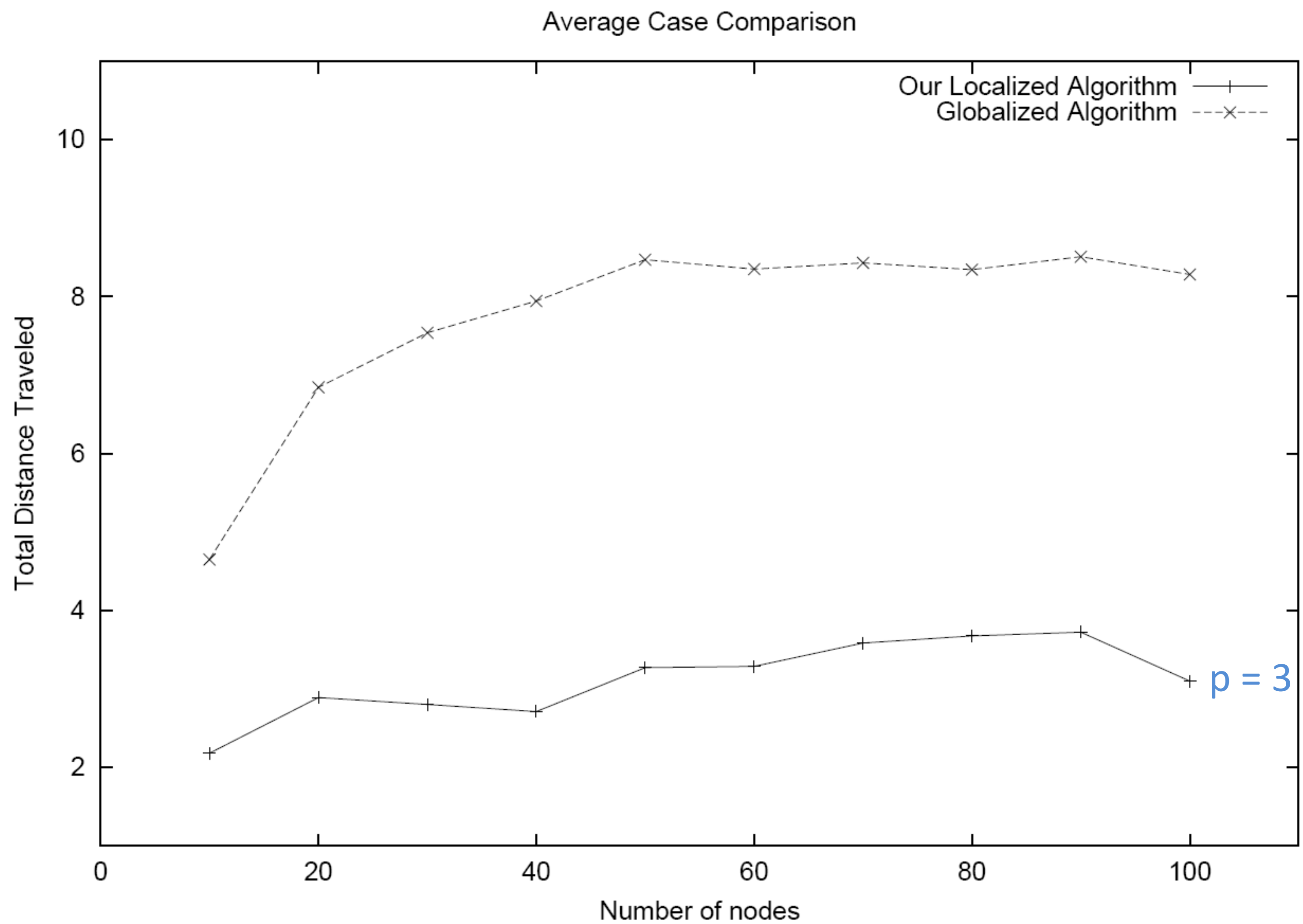
Simulation Results

- Value of p affects the performance to a great extent!
  (if p is mall many globally non-critical nodes are detected as p-hop critical)



[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 9]

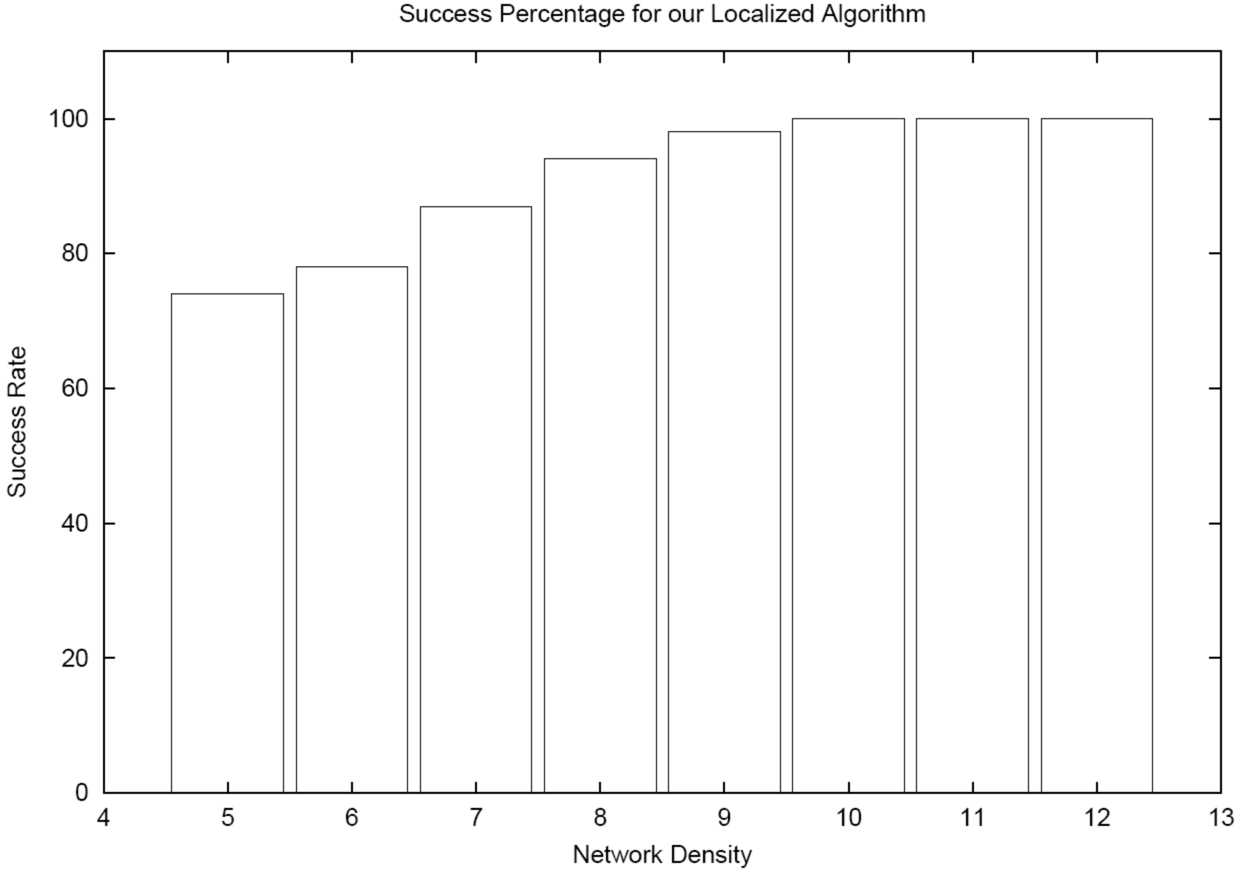
Comparison with globalized algorithm



[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 10]

Performance on sparse networks

- On networks with smaller density (i.e. *d < 10*) the algorithm ist not always successful!



p = 3

[A Localized Algorithm for Bi-Connectivity of Connected Mobile Robots, p. 10]

Critical view on the Simulation Results

- Value of p was set to 3 for most of the simulations
  - ➡ For $d \approx 10$ and $n = 100$ it can be expected that most of the network topology is within the *3-hop* neighborhood of a node!
  - ➡ For smaller values of *d* the algorithm was not always successful! (network not bi-connected or even disconnected)
  - ➡ What if $d << 10$ or $n >> 100$?

Critical view on the algorithm

- For small values of p the success rate of the algorithm sinks
  - ➡ Not applicable for small networks or networks with small density
  - ➡ Density of 10 is not very realistic for current applications of mobile robots
- Algortihm can cause "coverage holes" in the considered network area
  - ➡ Especially worse for sensor networks!

Thank you for your attention!