integrated Wireless Information Network (iWIN) Lab
Applied Discrete Geometry Lab

Distributed Segmentation and Applications in 3D Wireless Sensor Networks

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OUTLINE

- **Introduction**
- Segmentation Algorithm
  - Distributed Algorithm to Estimate Bottleneck parts of a 3D sensor network
  - Distributed Segmentation algorithm along bottleneck areas
- Application and Simulation Results
- Conclusion

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INTRODUCTION

- Wireless sensor networks have irregular shape
- Shape bottleneck leads to performance bottleneck
  - greedy routing failures
  - unbalanced load in-network data storage and query
- Segmentation algorithm: decompose the network based on geometric feature into segments

INTRODUCTION

- Related work
  - In [17], they proposed a shape segmentation scheme based on flow complex in 2D sensor networks
- This is the first work on segmentation in 3D sensor networks

[17] X. Zhu, R. Sarkar, and J. Gao, "Shape segmentation and applications in sensor networks," in *Proc. of Annual IEEE Conference on Computer Communications (INFOCOM)*, pp. 1838–1846, 2007.

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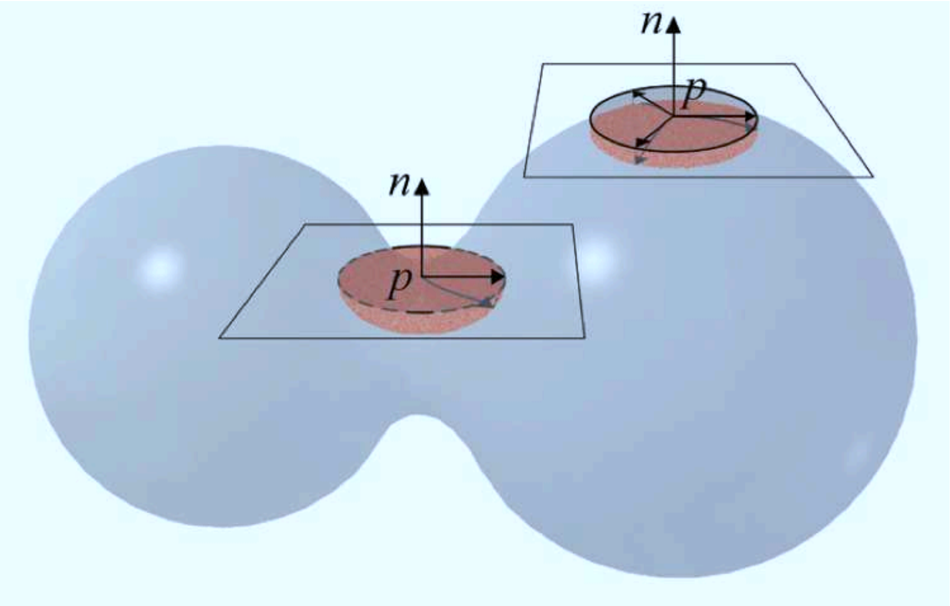
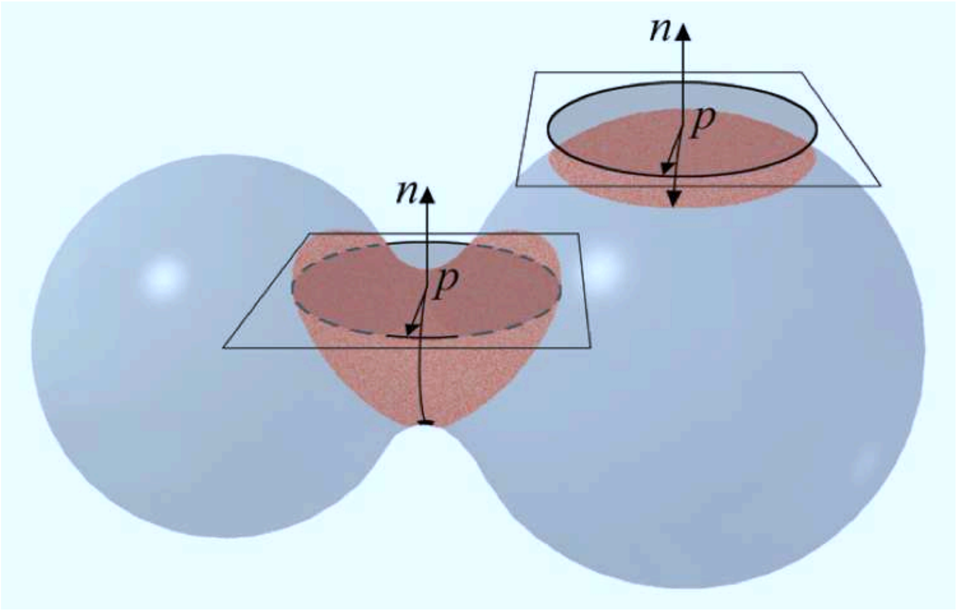
SEGMENTATION ALGORITHM

- Basic idea
  - Identified bottlenecks based on *injectivity radius*





  - *injectivity radius*: indicates the narrowness of a given part of the network boundary, in a 3D network setting.

OUTLINE

- Introduction
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  - **Distributed Algorithm to Estimate Bottleneck parts of a 3D sensor network**
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Preparation

- Application and Simulation Results
- Conclusion

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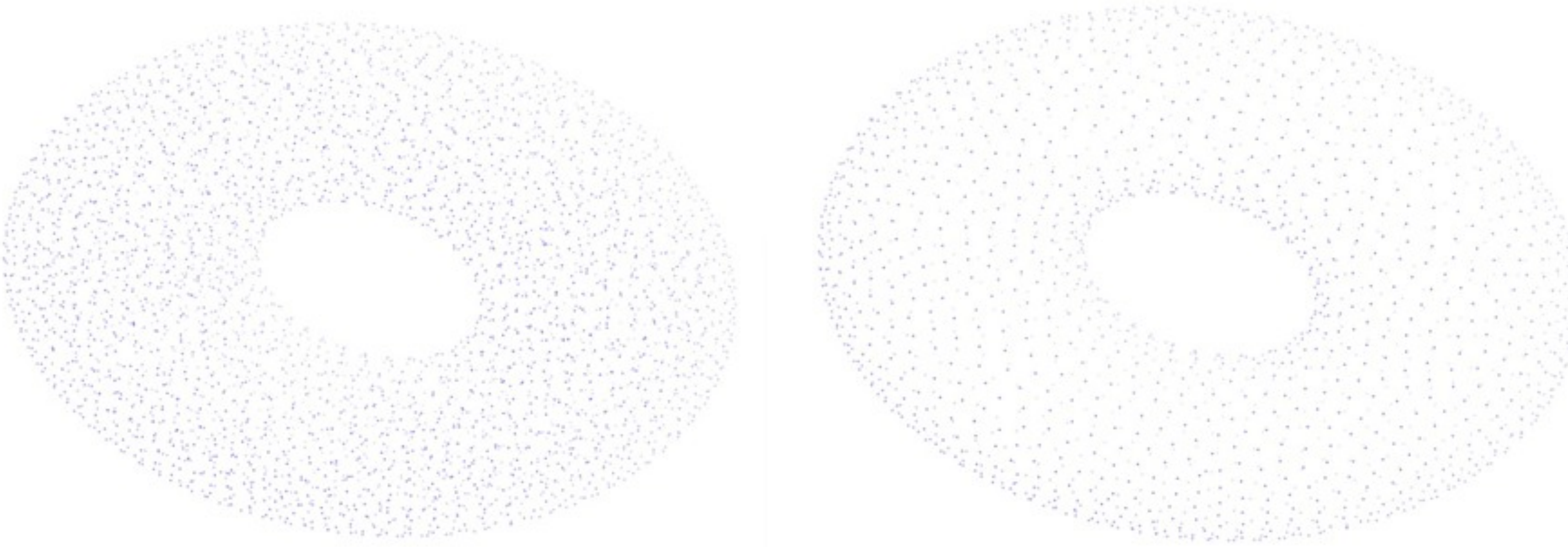
SEGMENTATION ALGORITHM

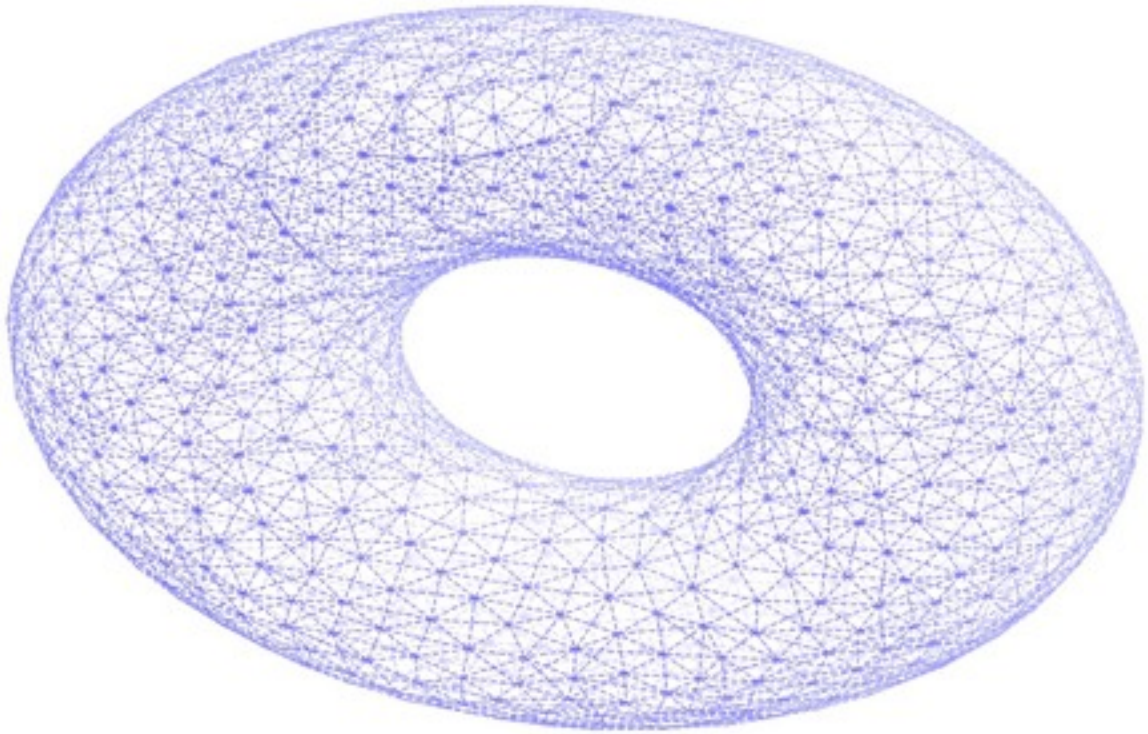
- Boundary Detection [12]

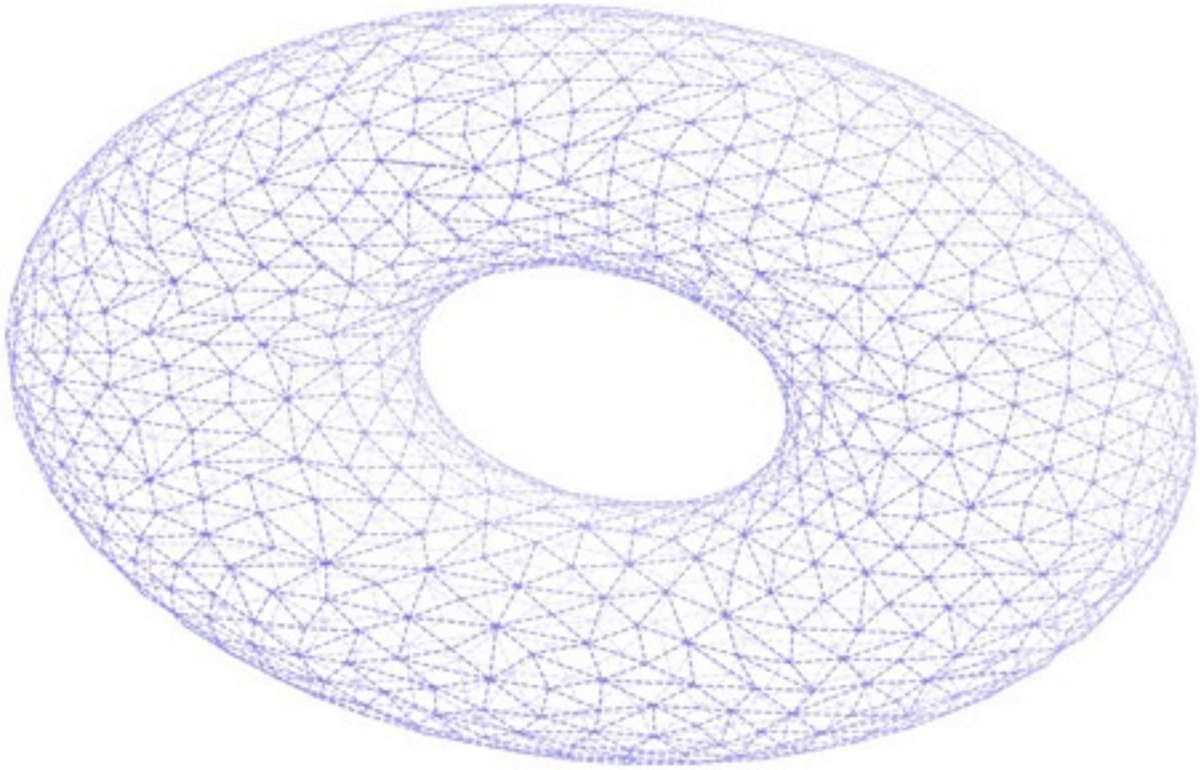


[12] H. Zhou, S. Xia, M. Jin, and H. Wu, "Localized Algorithm for Precise Boundary Detection in 3D Wireless Networks," in *Proc. of The 30th International Conference on Distributed Computing Systems (ICDCS)*, 2010.

SEGMENTATION ALGORITHM

- Triangulation[16]

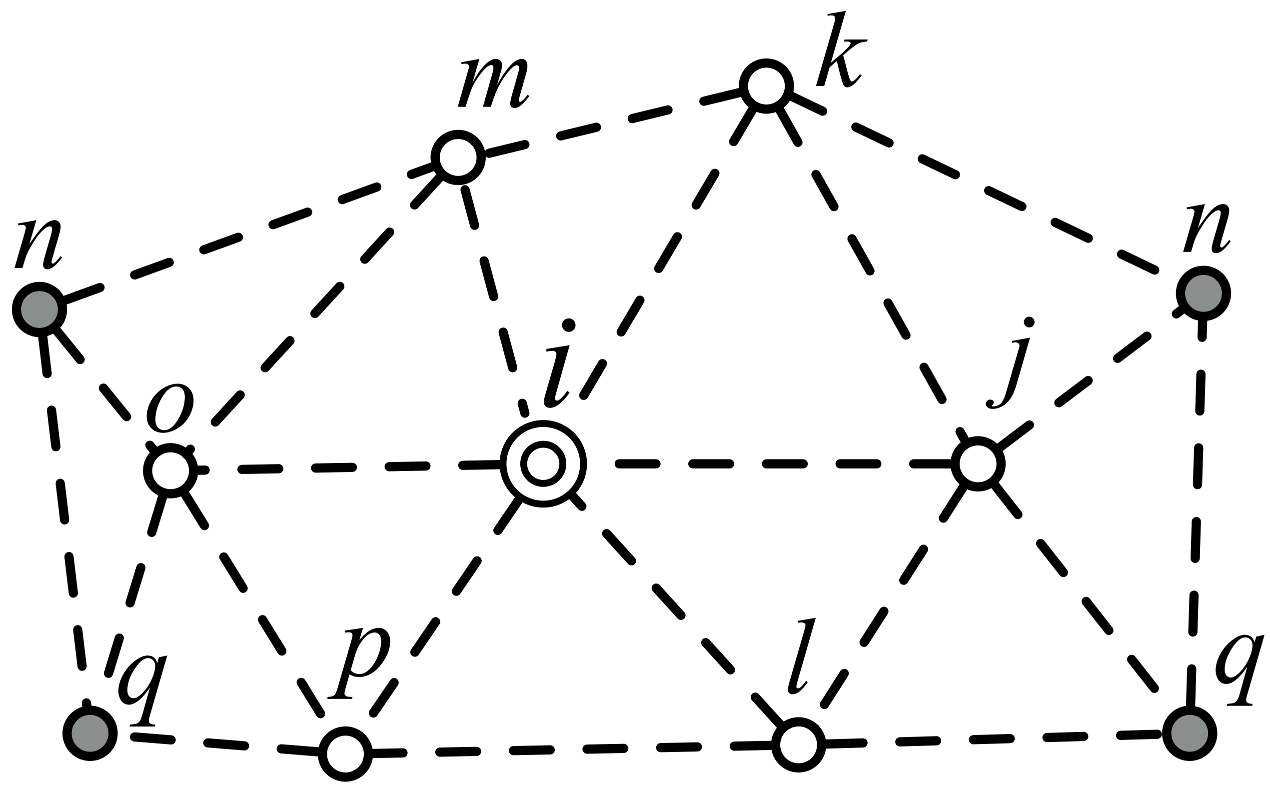




[16] H. Zhou, H. Wu, S. Xia, M. Jin, and N. Ding, “A Distributed Triangulation Algorithm for Wireless Sensor Networks on 2D and 3D Surface,” in Proc. of Annual IEEE Conference on Computer Communications (INFOCOM), 2011.

SEGMENTATION ALGORITHM

- Distributed Algorithm to Estimate *Injectivity Radius*



$$L_i = \emptyset$$

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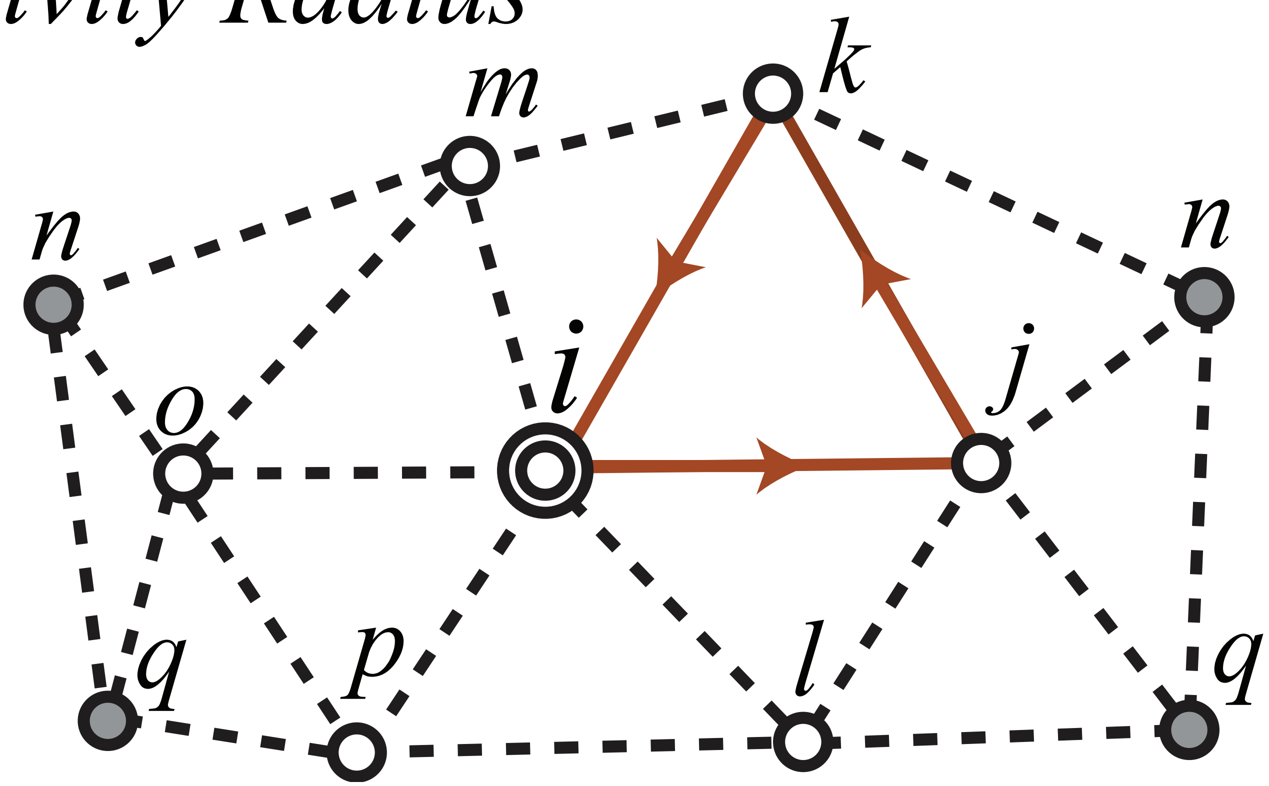
Segmentation Algorithm

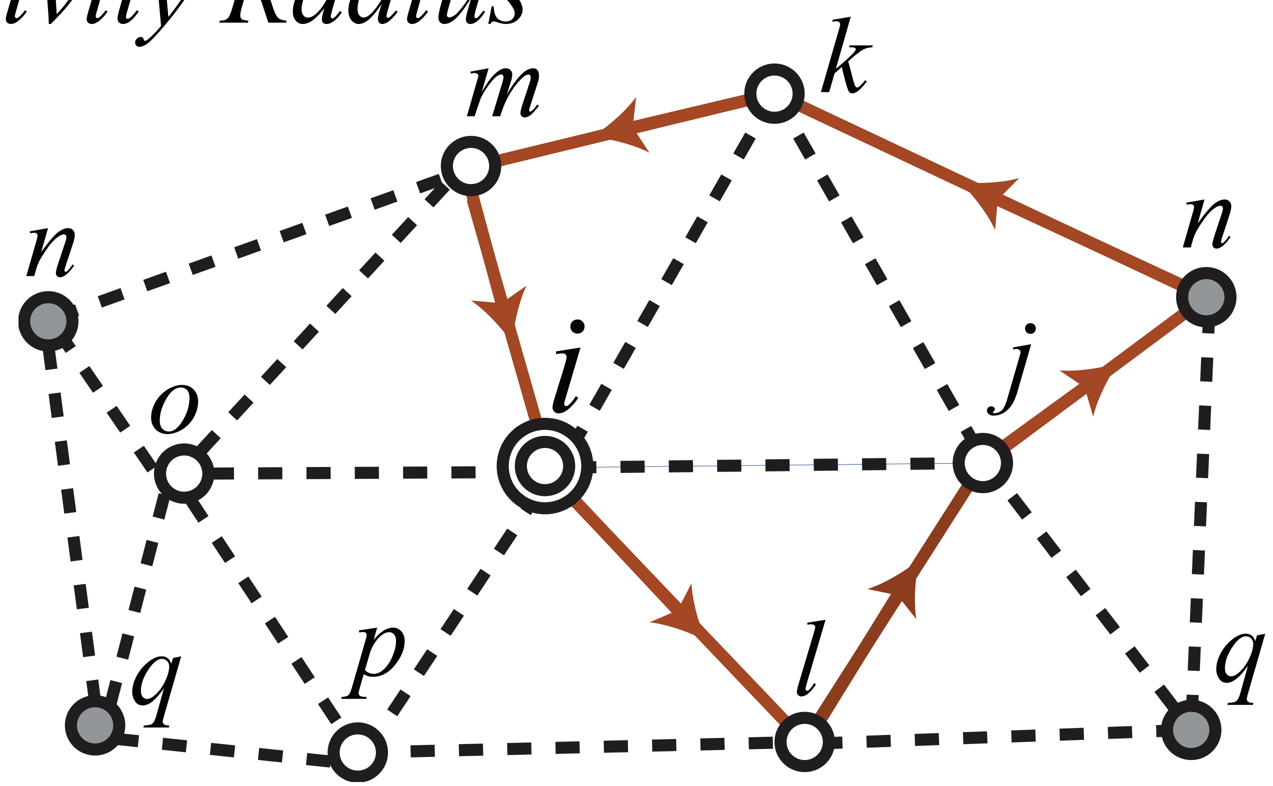
- Distributed Algorithm to Estimate *Injectivity Radius*



$$L_i = \{ e_{ij}, e_{jk}, e_{ki} \}$$

Segmentation Algorithm

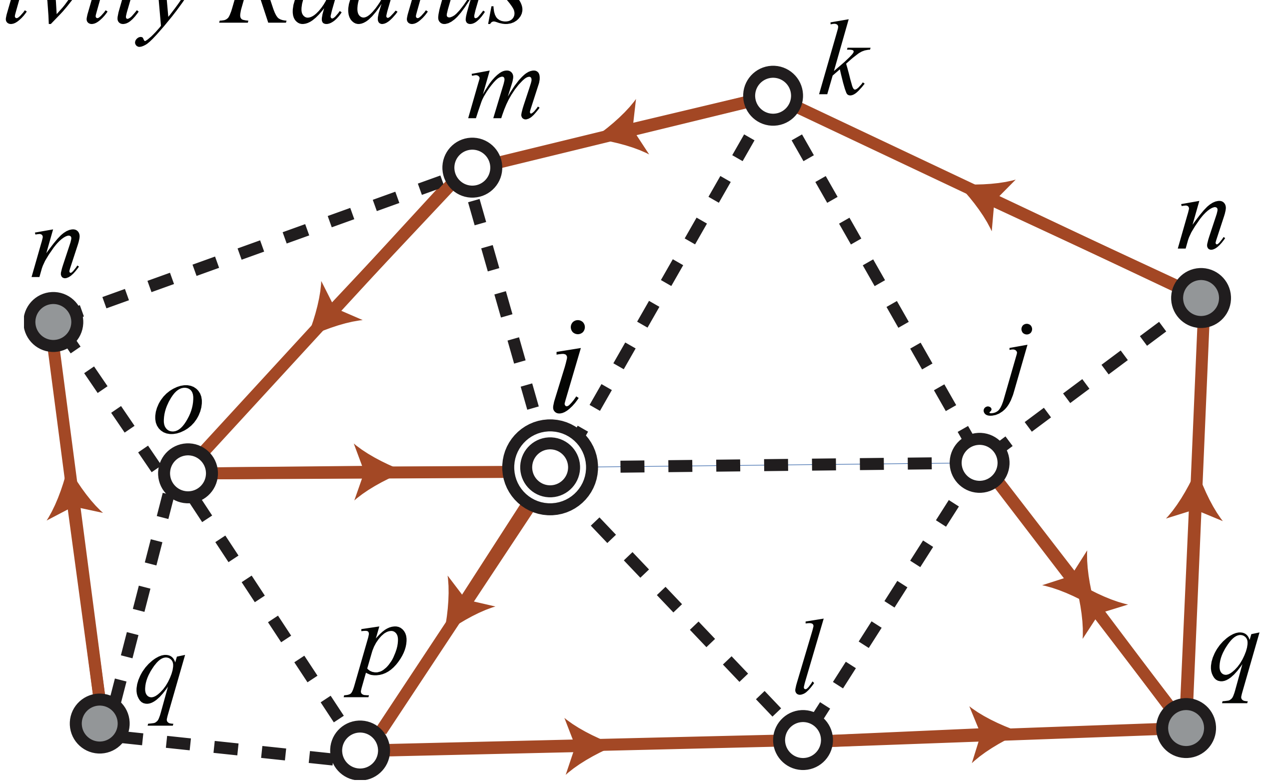
- Distributed Algorithm to Estimate *Injectivity Radius*



$$L_i = \{\, e_{il},\ e_{lj},\ e_{jn},\ e_{nk},\ e_{km},\ e_{mi} \,\}$$

SEGMENTATION ALGORITHM

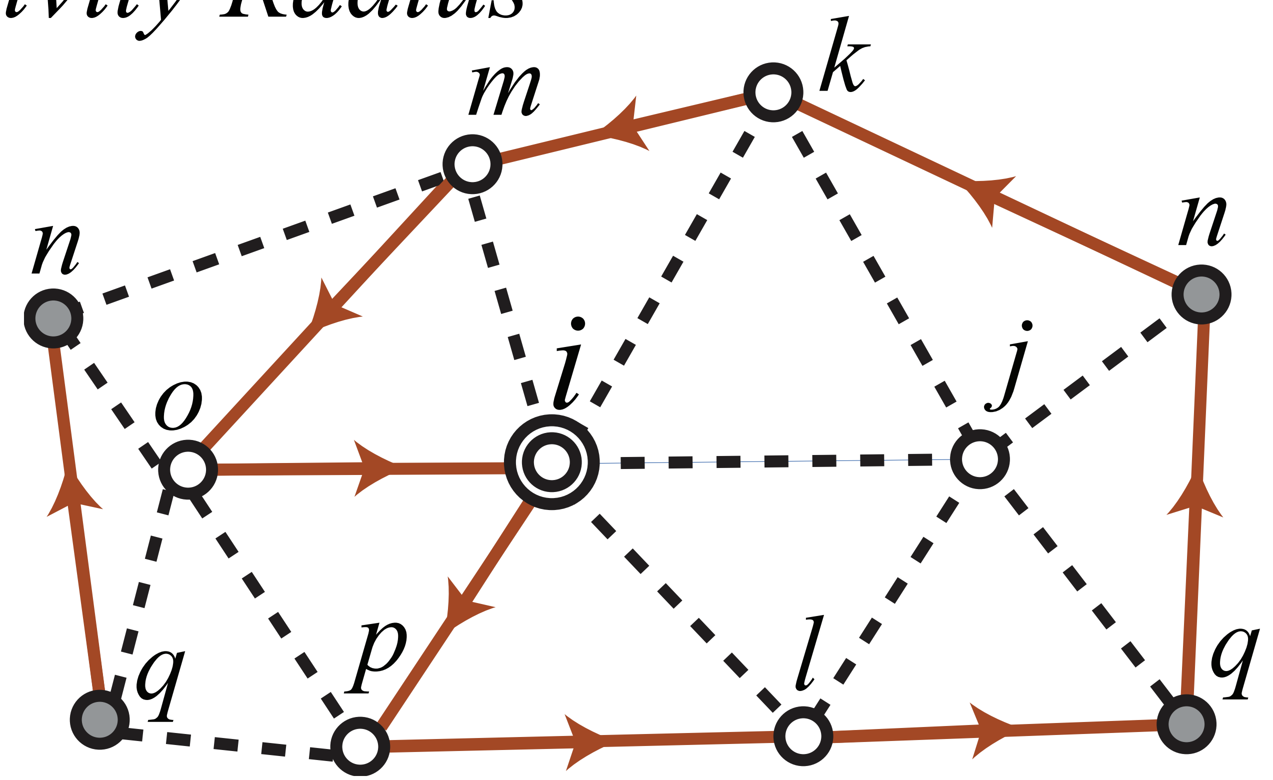
- Distributed Algorithm to Estimate *Injectivity Radius*



$$L_i = \{\, e_{ip},\ e_{pl},\ e_{lq},\ \underline{\boldsymbol{e_{qj}}},\ \underline{\boldsymbol{e_{jq}}},\ e_{qn},\ e_{nk},\ e_{km},\ e_{mo},\ e_{oi} \,\}$$

Segmentation Algorithm

- Distributed Algorithm to Estimate *Injectivity Radius*



$$L_i = \{\, e_{ip},\ e_{pl},\ e_{lq},\ e_{qn},\ e_{nk},\ e_{km},\ e_{mo},\ e_{oi} \,\}$$

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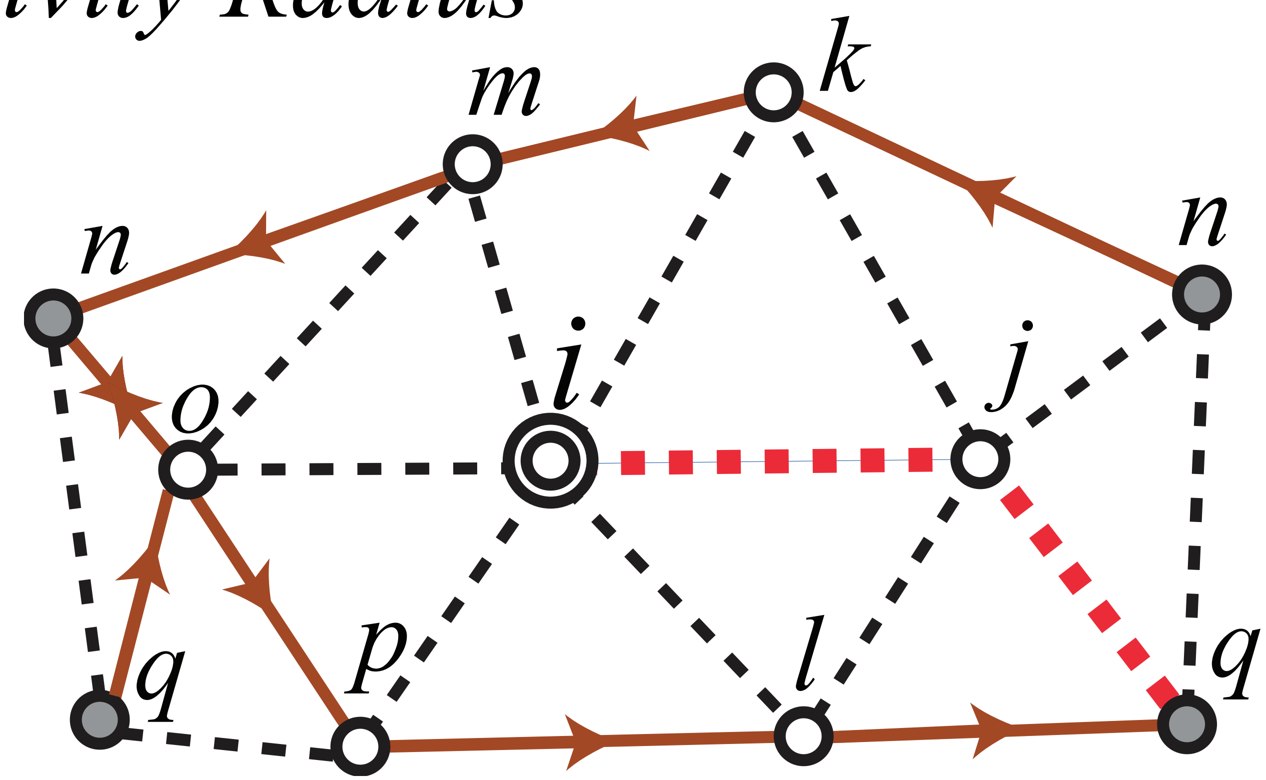
Segmentation Algorithm

- Distributed Algorithm to Estimate *Injectivity Radius*



$$L_i = \{\ e_{nk},\ e_{km},\ e_{mn},\ \underline{\mathbf{e_{no}}},\ e_{op},\ e_{pl},\ e_{lq},\ e_{qo},\ \underline{\mathbf{e_{on}}}\ \}$$

$R_i = 2$ (between Node v_i and v_q)

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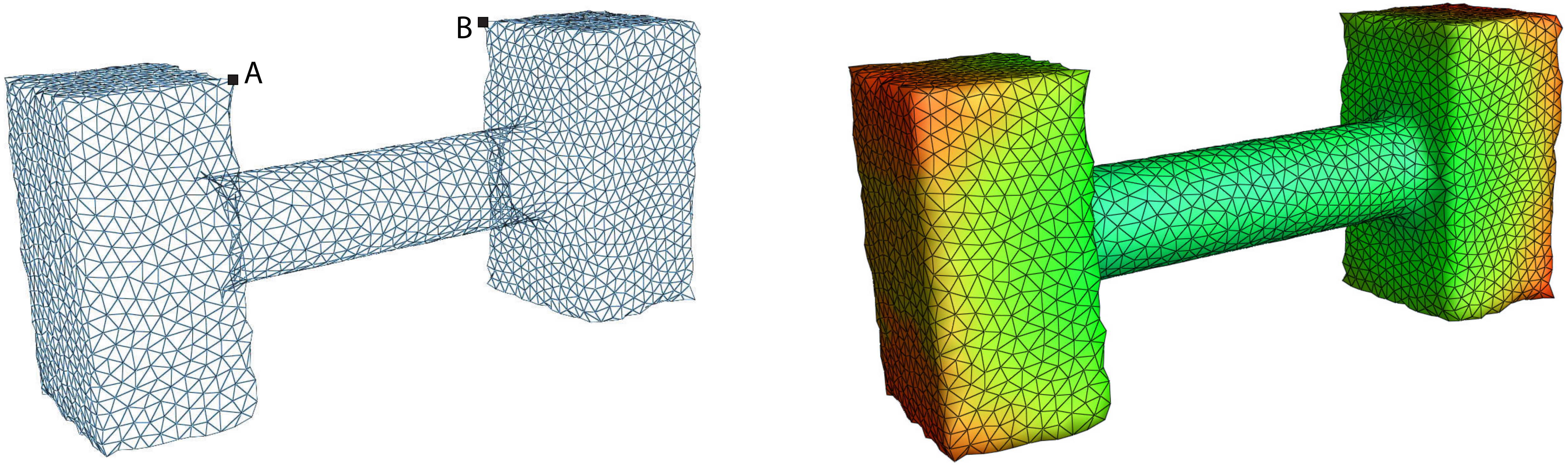
SEGMENTATION ALGORITHM

- Distributed Algorithm to Estimate *Injectivity Radius*



(a) boundary triangulation mesh

(b) color-coded radii

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SEGMENTATION BASE ON INJECTIVE RADIUS

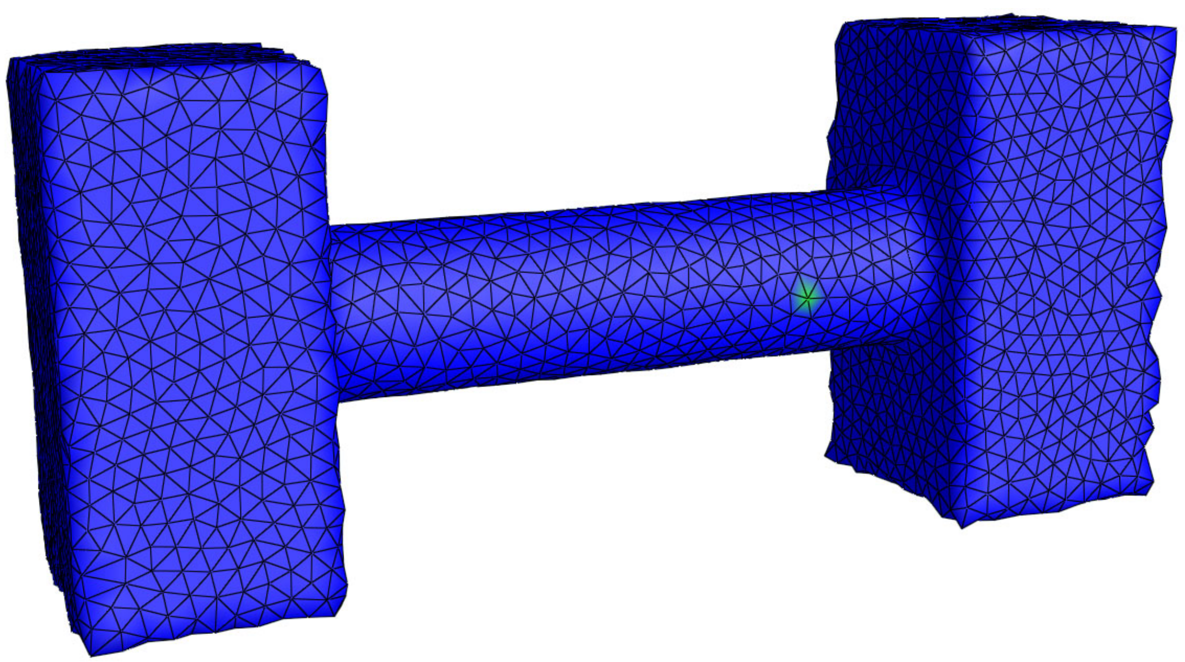
- Each node is associated with three parameters: SID, α, β.
    - SID : segment ID
    - α : boolean variable to indicate whether the node is marked as bottleneck
    - β : boolean variable to indicate whether the node should be exclude from further processing
- $\Phi = \{v_i | \alpha_i = FALSE, \beta_i = FALSE\}$

SEGMENTATION BASE ON INJECTIVE RADIUS

- Step (a) *Identification of minimum radius.*
- Step (b) *α-expansion.*
- Step (c) *Identification of segment boundary.*
- Step (d) *β-expansion.*
- Step (e) *Assignment of segment ID.*
- Step (f) *Segmentation of internal nodes.*

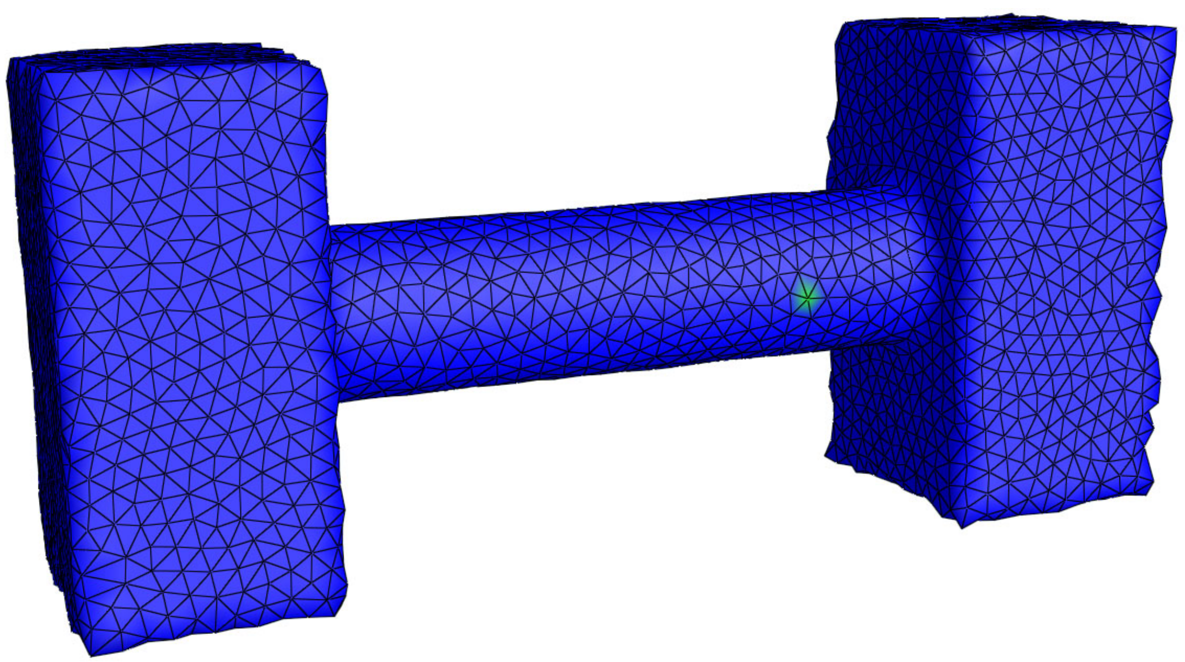
Segmentation Base on Injective Radius

- Step (a) *Identification of minimum radius.*
  - *Controlled flooding*: every node keeps and forwards the smallest radius value, drops the others in Φ
  - Find the node with the smallest radius value, v_0



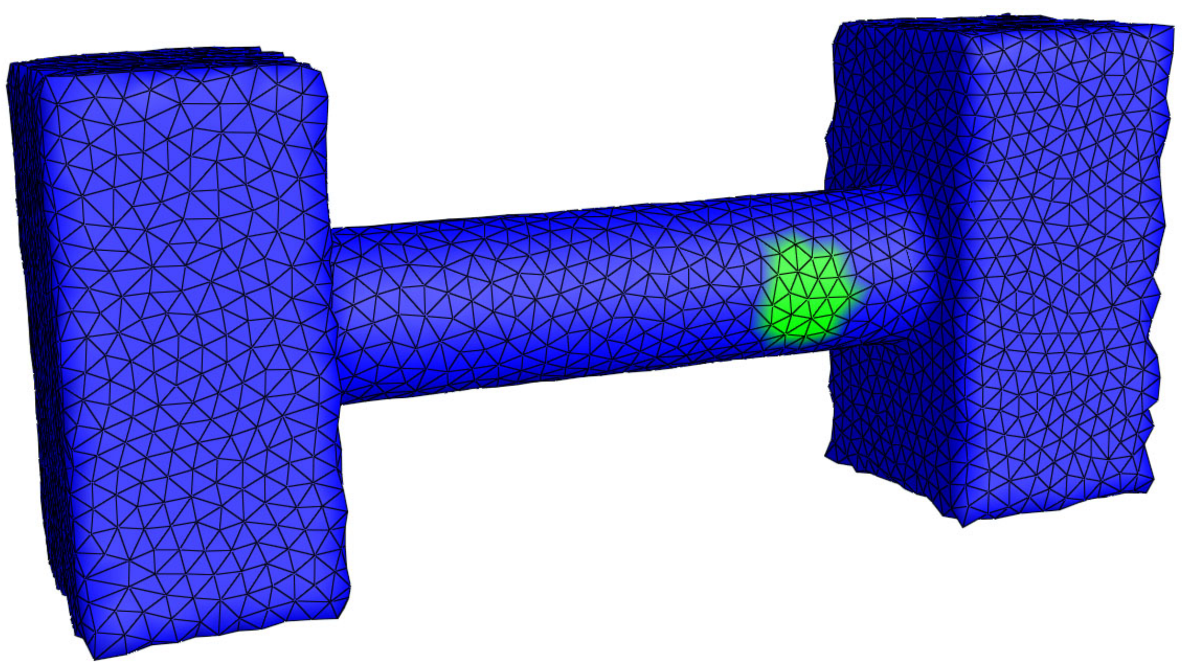
SEGMENTATION BASE ON INJECTIVE RADIUS

- Step (b) *α-expansion*.
  - Set v_0's SID_0 and $\alpha_0 = TRUE$
  - Expands the segment by merging any neighboring nodes whose radius $\leq R_{min} + \delta$
  - Set emerged nodes' $SID_i = SID_0$ and $\alpha_i = TRUE$



Segmentation Base on Injective Radius

- Step (b) *α-expansion*.
  - Set v_0's SID_0 and α_0 = *TRUE*
  - Expands the segment by merging any neighboring nodes whose radius $\leq R_{min} + \delta$
  - Set emerged nodes' $SID_i = SID_0$ and α_i = *TRUE*



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Segmentation Base on Injective Radius

- Step (b) *α-expansion*.
  - Set v_0's SID_0 and α_0 = *TRUE*
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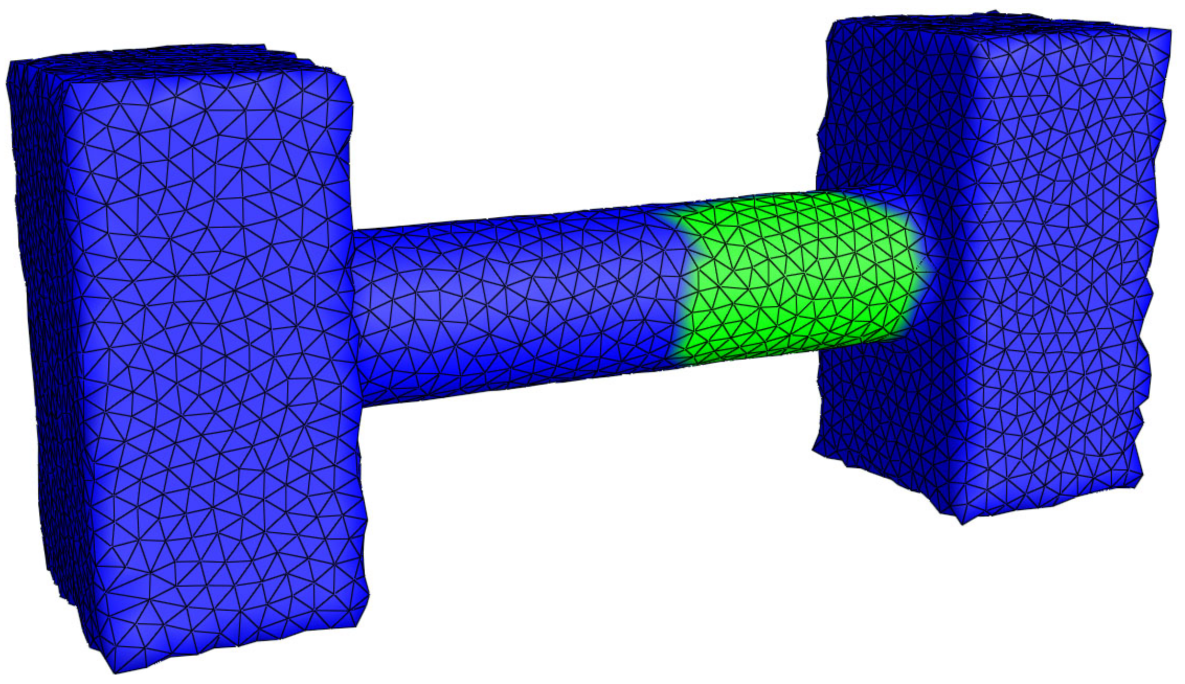
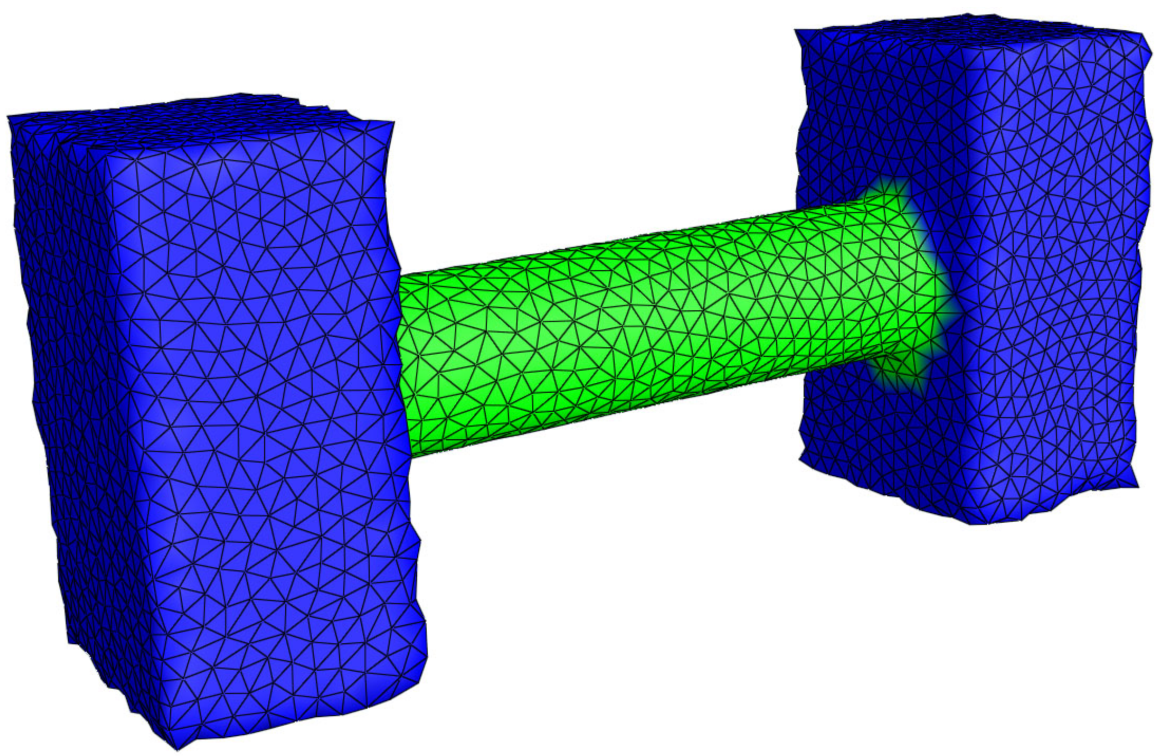


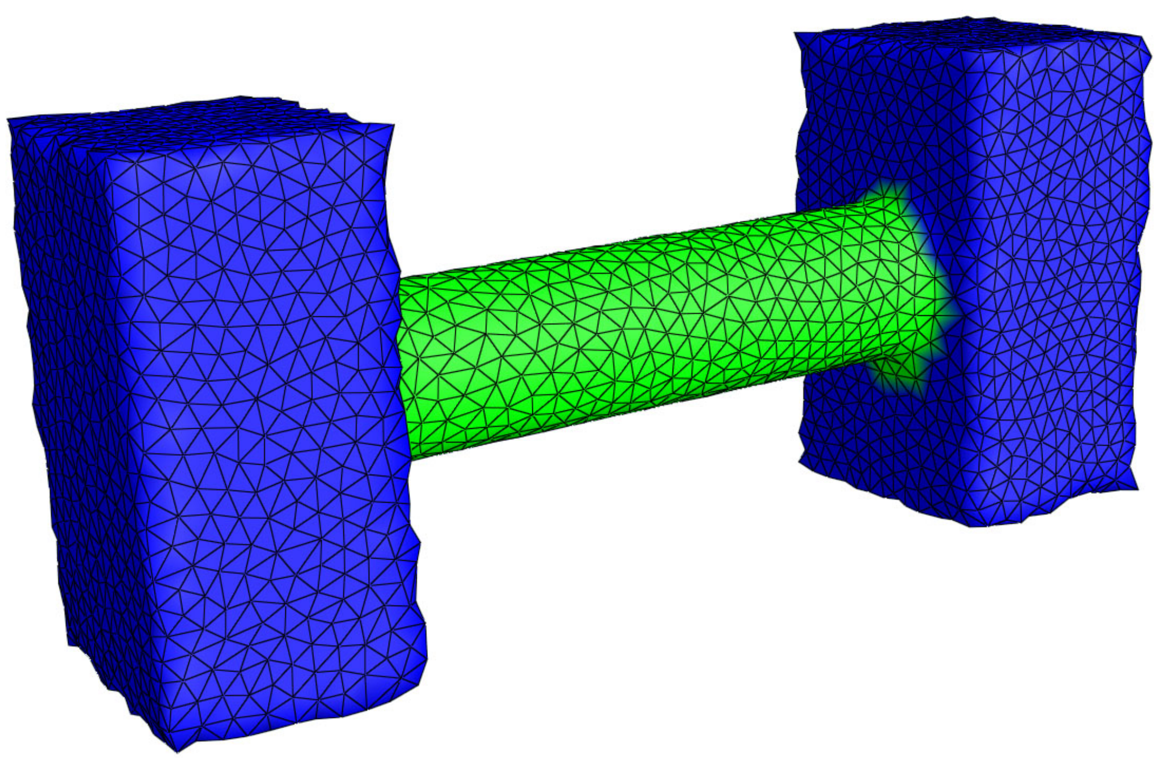
Segmentation Base on Injective Radius

- Step (b) *α-expansion*.
  - Set v_0's SID_0 and α_0 = *TRUE*
  - Expands the segment by merging any neighboring nodes whose radius $\leq R_{min} + \delta$
  - Set emerged nodes' $SID_i = SID_0$ and α_i = *TRUE*



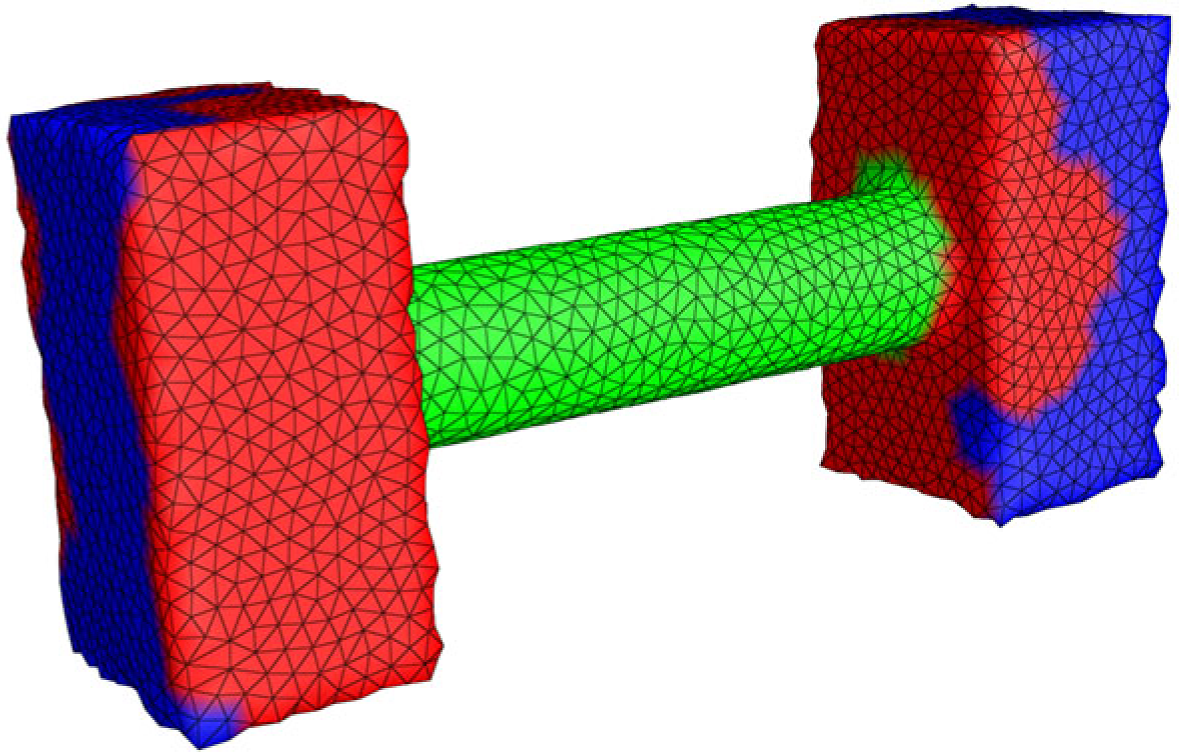
Segmentation Base on Injective Radius

- Step (c) *Identification of segment boundary.*
  - Node v_i ($\alpha_i = TRUE$) is on the segment boundary if it has neighbor(s) with $\alpha = FALSE$



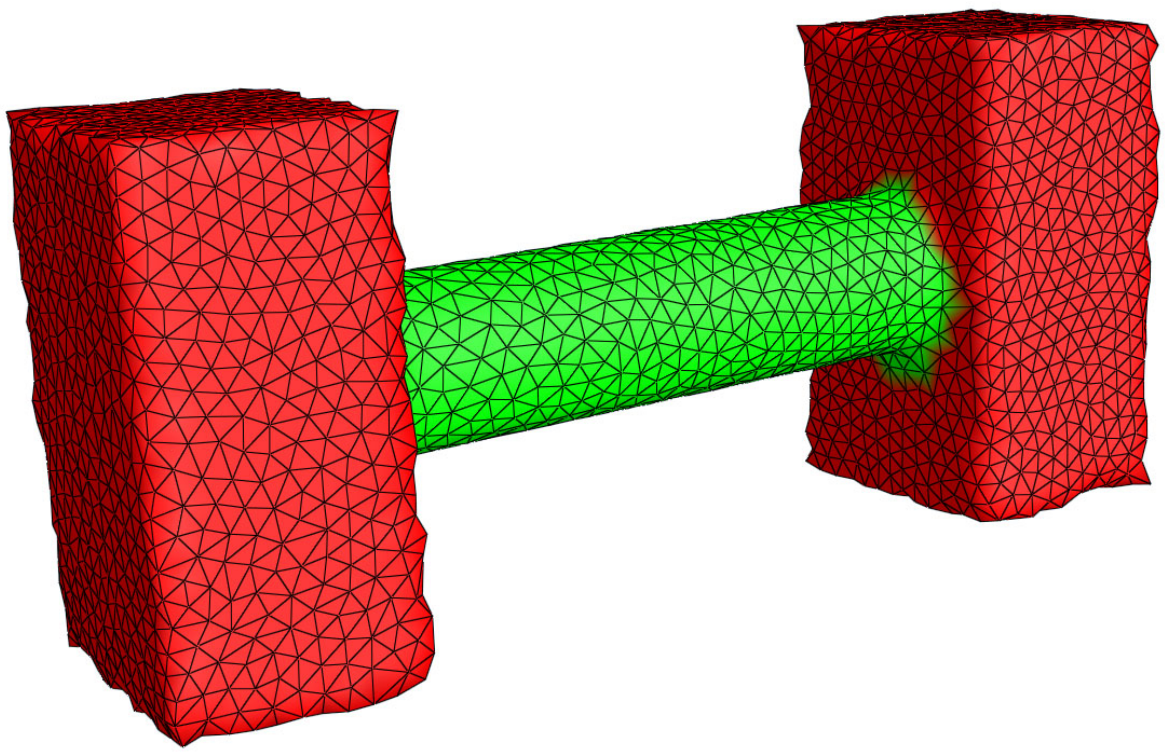
Segmentation Base on Injective Radius

- Step (d) *β-expansion*.
  - Start from segment boundary nodes v_i with radius R has a neighbor node v_j with $\alpha_j = FALSE$ and $R_j > R$, then set $\beta_j = TRUE$
  - Expansion is hop by hop until no further expansion



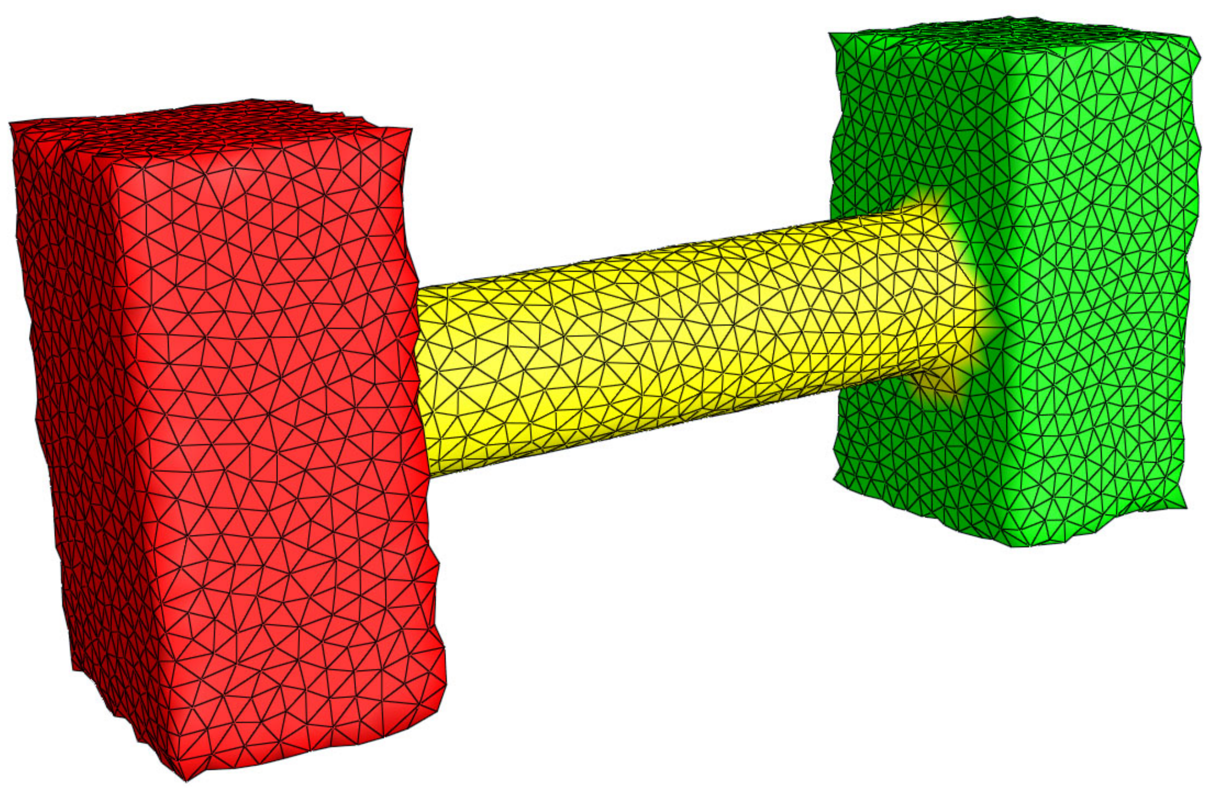
Segmentation Base on Injective Radius

- Step (e) *Assignment of segment ID*.
  - Repeat steps (a) - (d) based on updated Φ, until $\Phi = \emptyset$.
  - Node v_i has either $\alpha_j = TRUE$ or $\alpha_j = FALSE$ and $\beta_j = TRUE$



Segmentation Base on Injective Radius

- Step (f) *Segmentation of internal nodes*.
  - internal node assigns itself to its nearest segment on the boundary surface



Segmentation Base on Injective Radius

- Time and Communication Complexity

	Time	Communication
boundary detection	$O(k^3)$	$O(k)$
triangulation mesh	$O(m)$	$O(m^2)$
injectivity radius	$O(m)$	$O(m^2)$
segmentation and refinement	$O(n)$	$O(n)$
Over All	$O(n)$	$O(n)$

$$k \ll m \ll n,$$

k: average nodal degree, m: boundary nodes num, n: network nodes num

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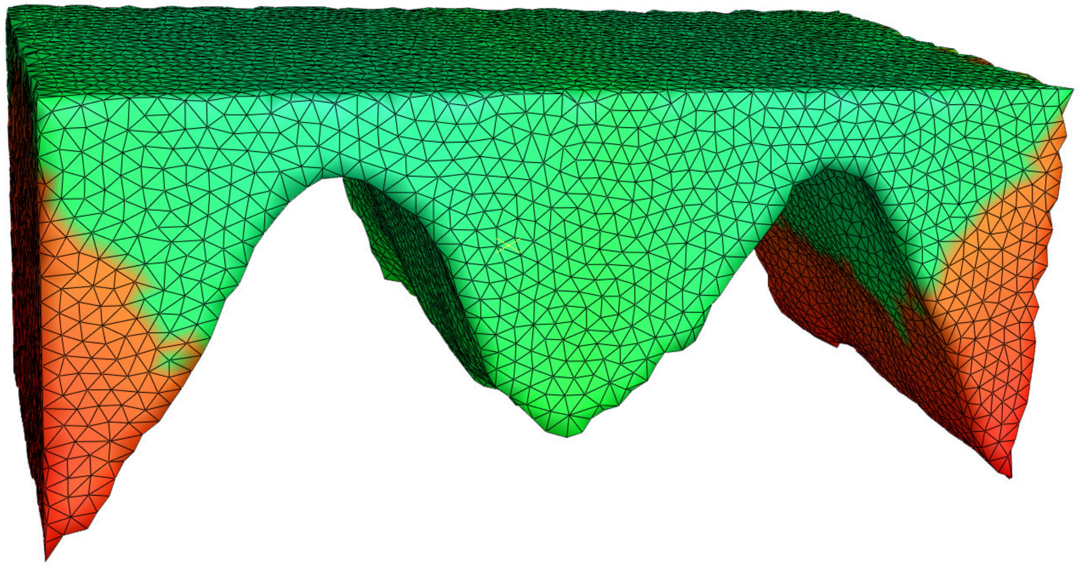
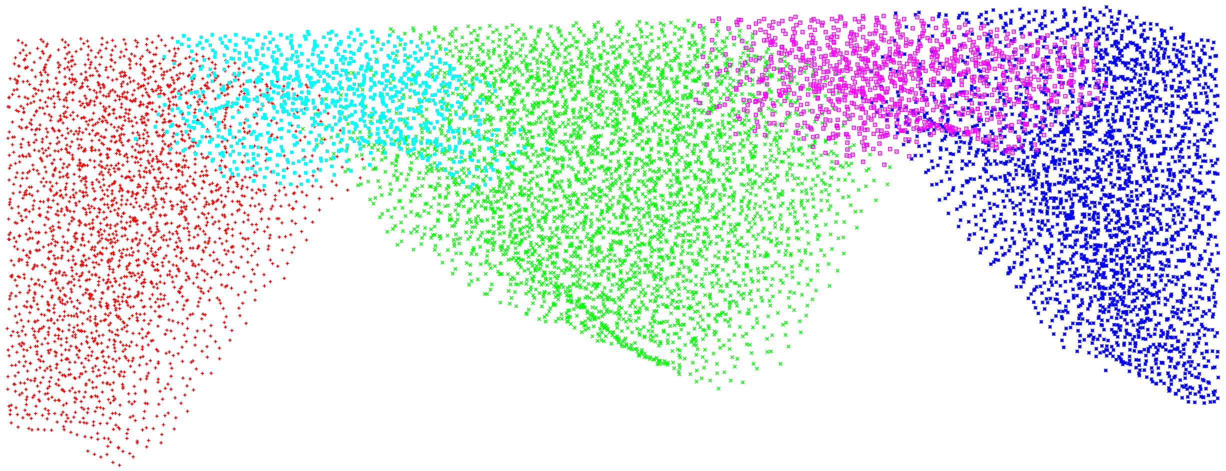
Simulation and Application Results

- Seabed model



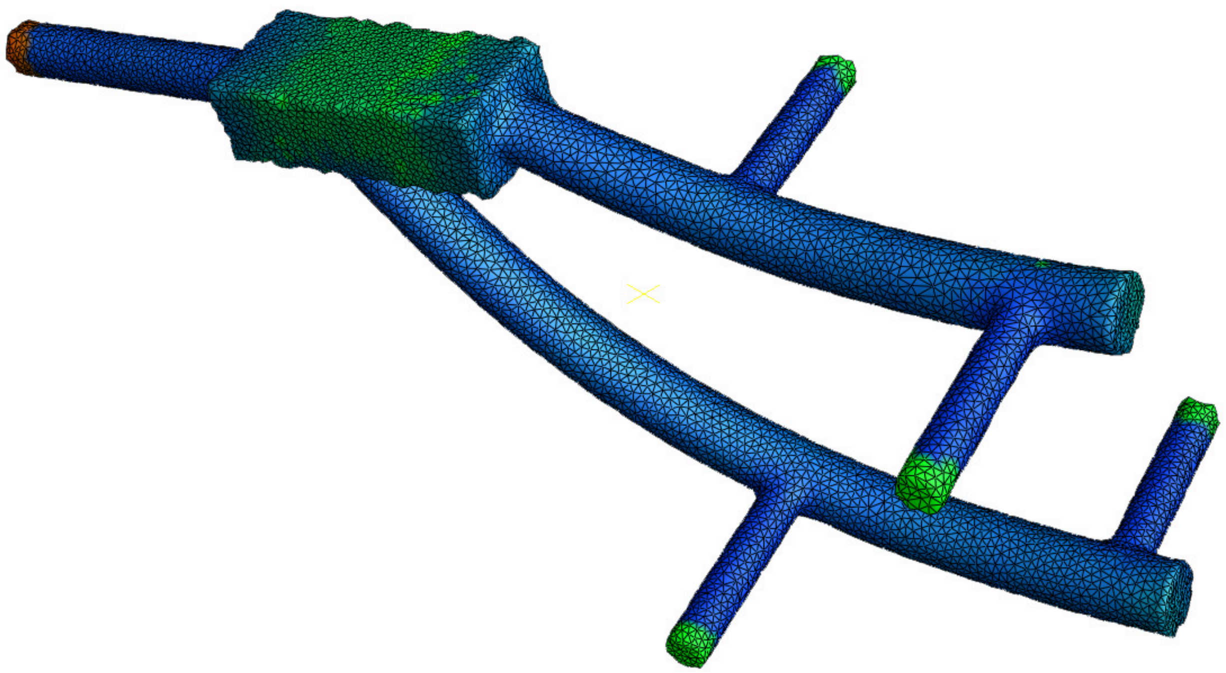
(a) color-coded radii



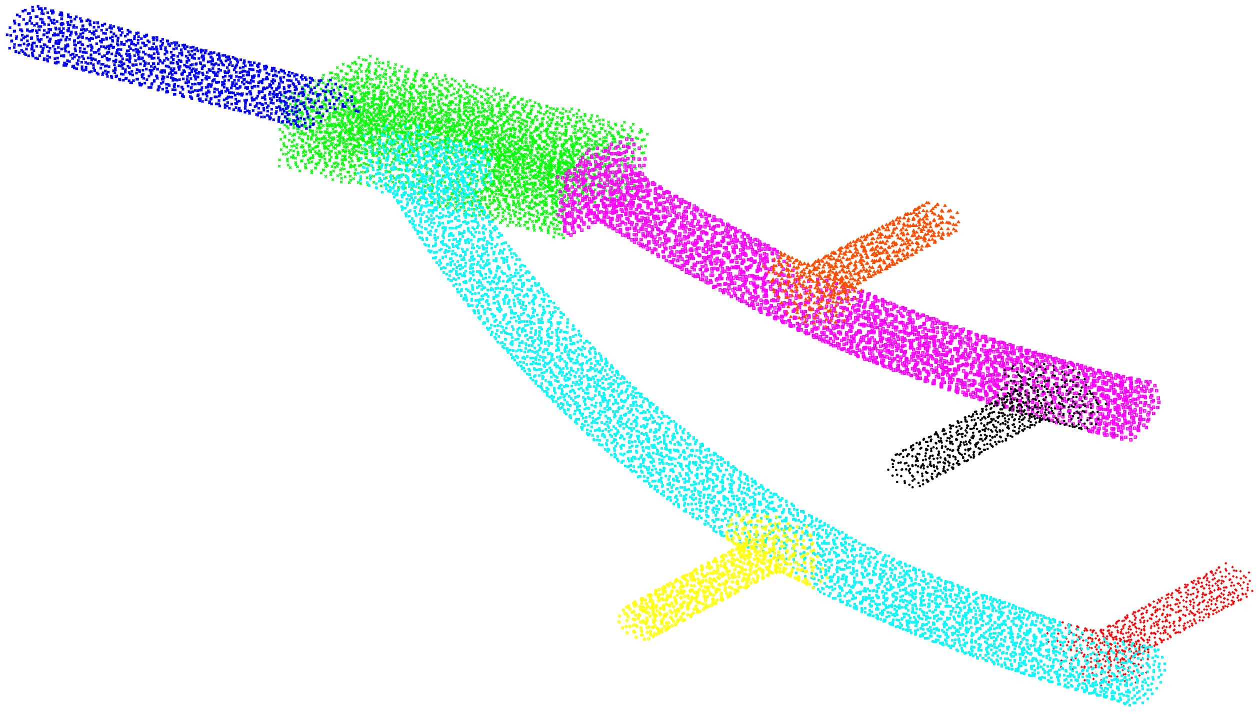
(b) segmentation
(5 segments)

SIMULATION AND APPLICATION RESULTS

- coal-mine tunnel model



(a) color-coded radii



(b) segmentation
(8 segments)

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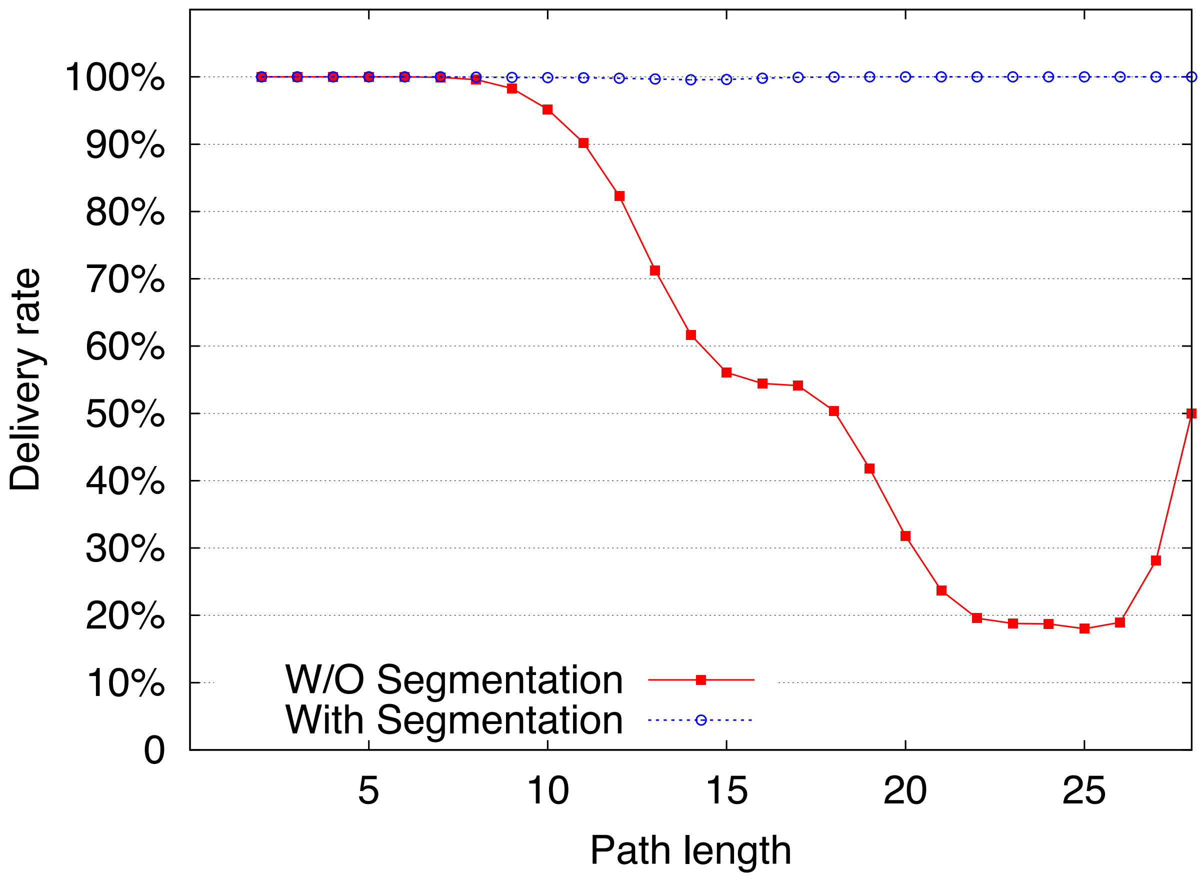
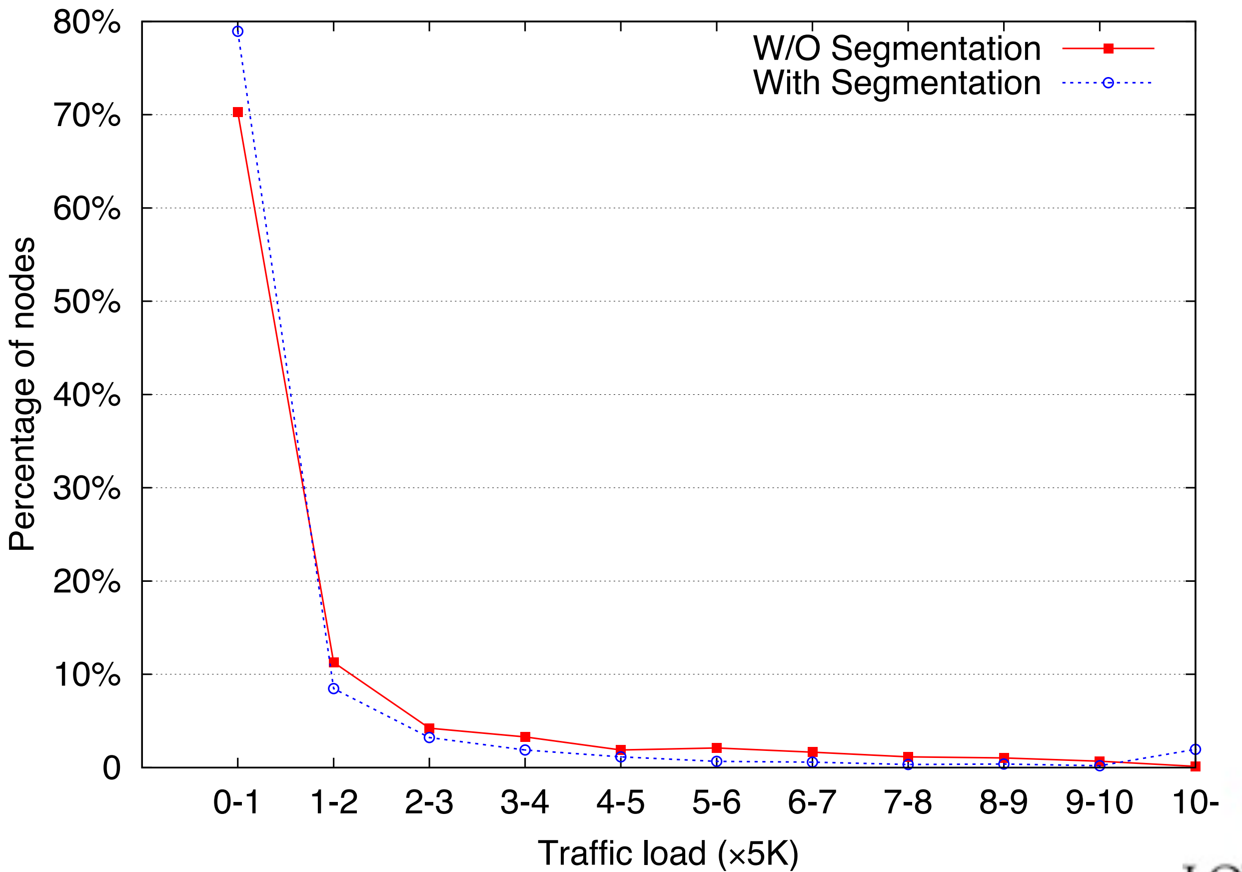
Simulation and Application Results

- Segment-Based Routing

COMPARISON OF ROUTING SUCCESS RATE

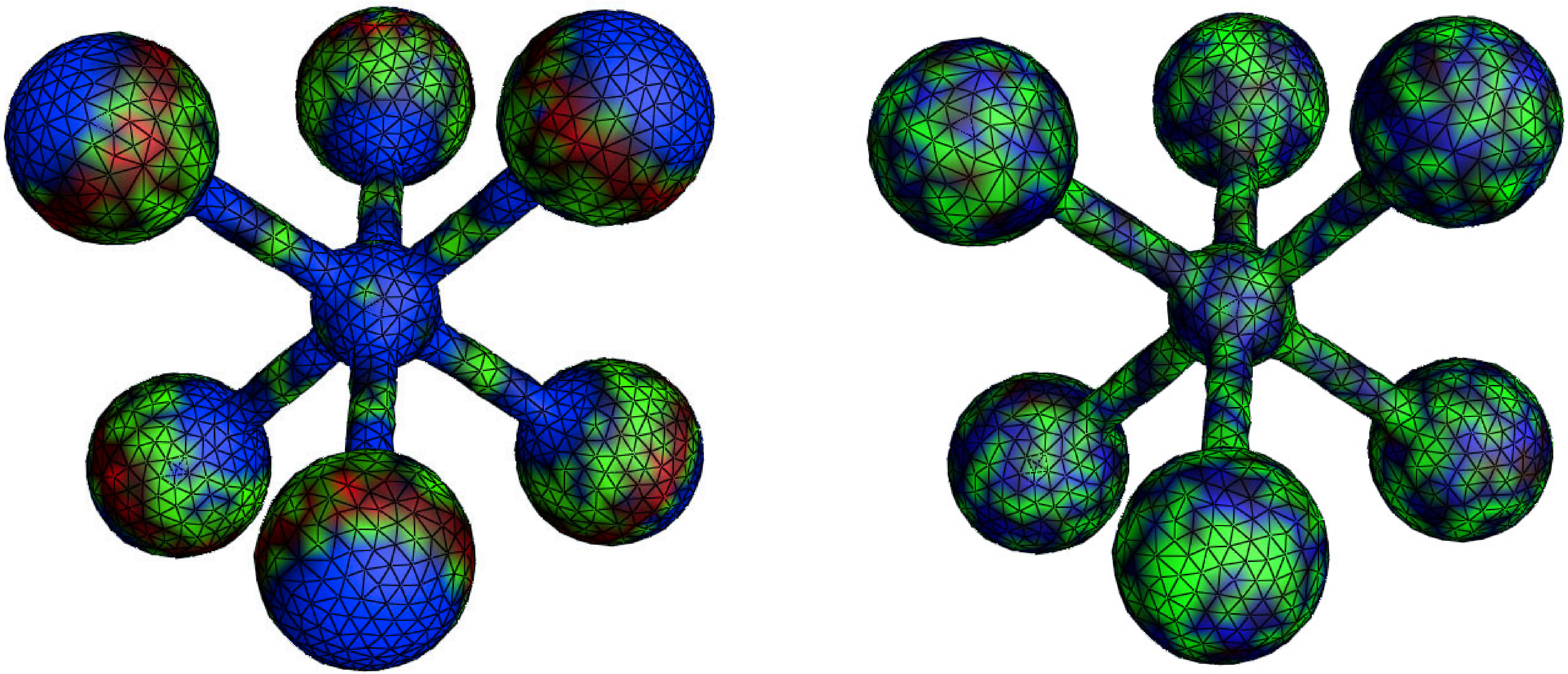
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Overall
With segmentation	100%	86%	100%	95.28%	99.92%	99.96%	99.72%
Without segmentation	96.07%	71.43%	57.69%	92.44%	62.78%	88.92%	86.69%





Simulation and Application Results

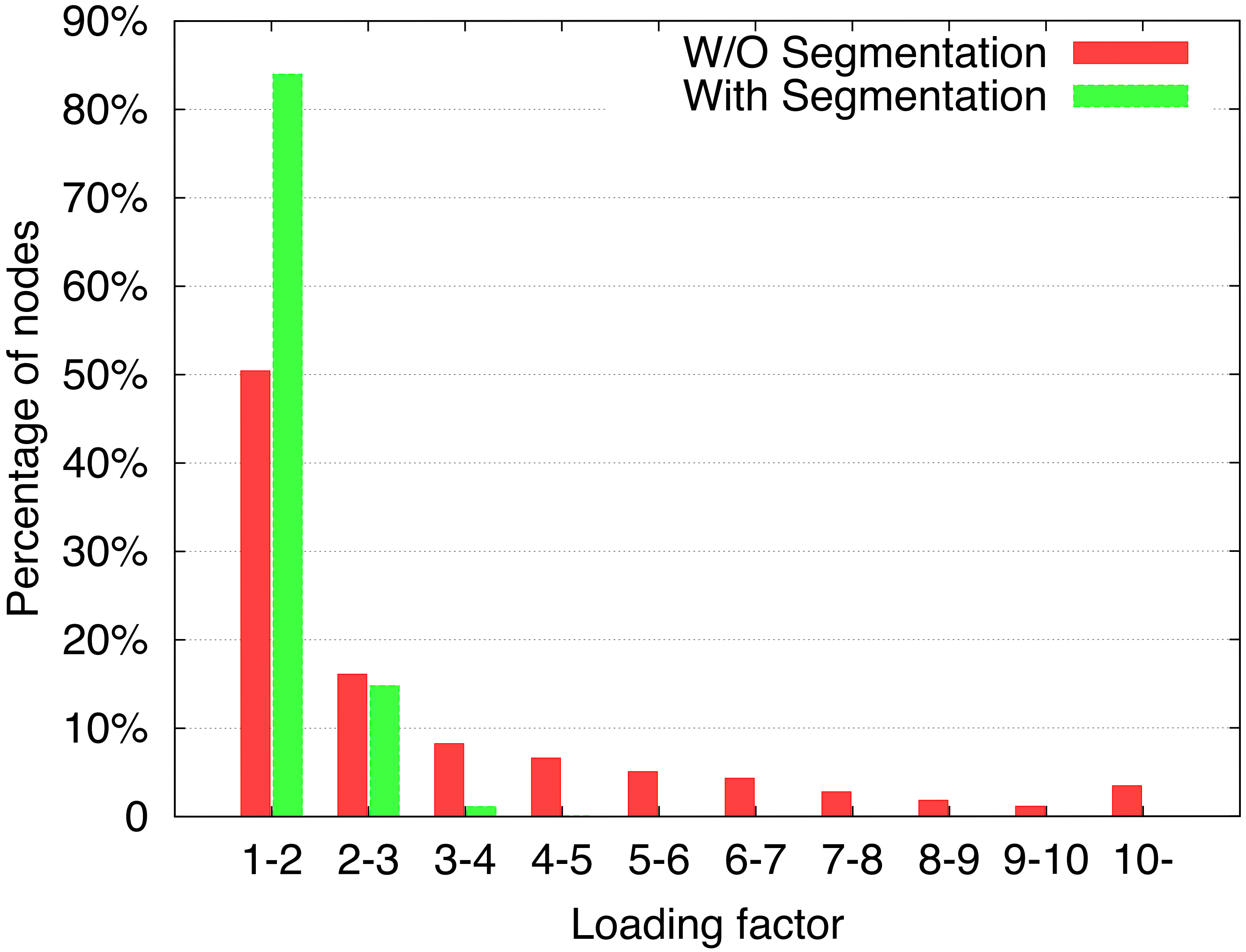
- Segment-Based Bounding in In-network Data Centric Storage and Retrieval



(a) without segmentation (b) with segmentation

Simulation and Application Results

- Segment-Based Bounding in In-network Data Centric Storage and Retrieval



In-network storage load distribution

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Conclusion

- This is the first effective solution to identify bottleneck areas in a 3D wireless sensor network and segment it into a set of subnetworks without bottlenecks.
- Many applications can benefit from the segmentation.