

Clustering in Cooperative Networks

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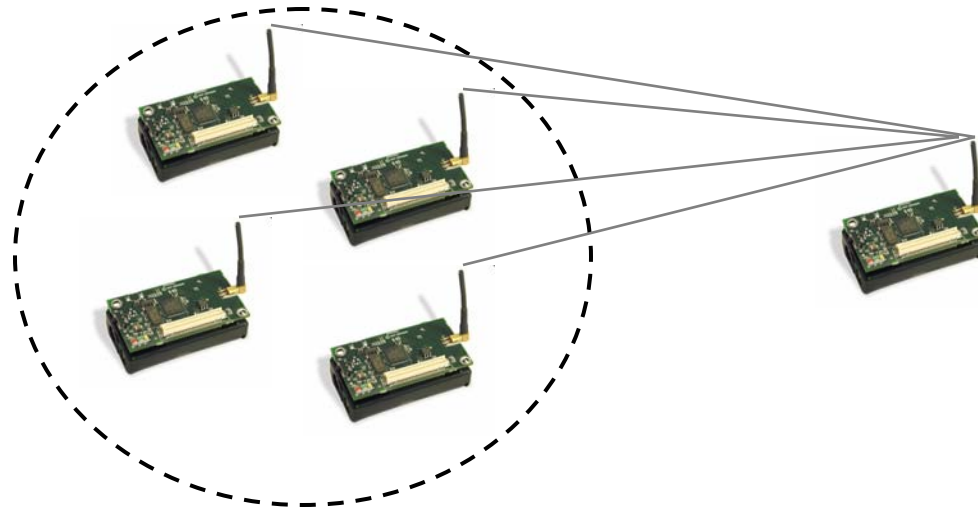
Introduction

- Low power ad hoc wireless networks operate on channels subject to **fading**
- **Diversity** mitigates fading
 - Redundant channels between transmitter and receiver
 - Temporal, frequency, and **spatial diversity** (multi-antenna array)



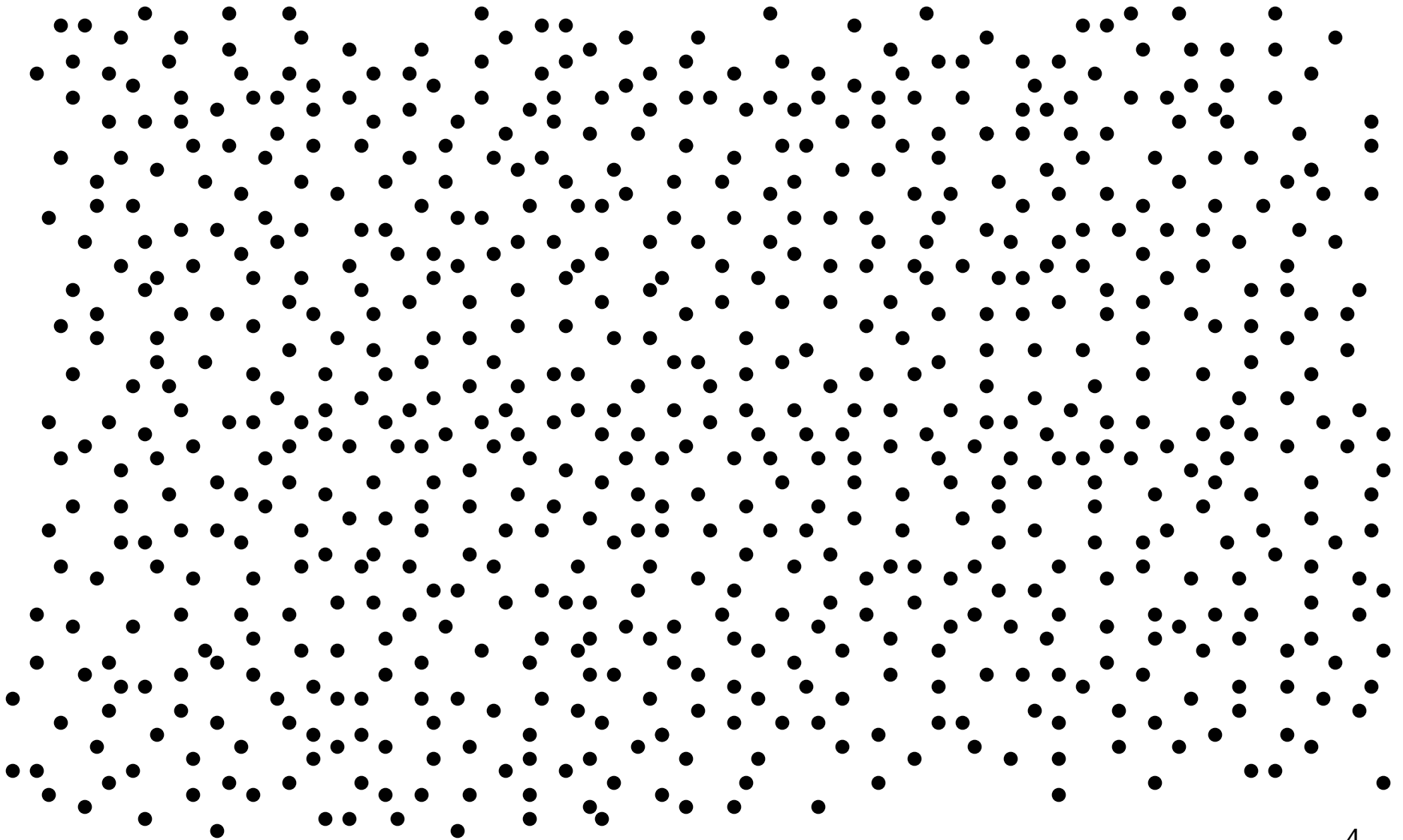
(source: <http://www.steelintheair.com>)

Introduction

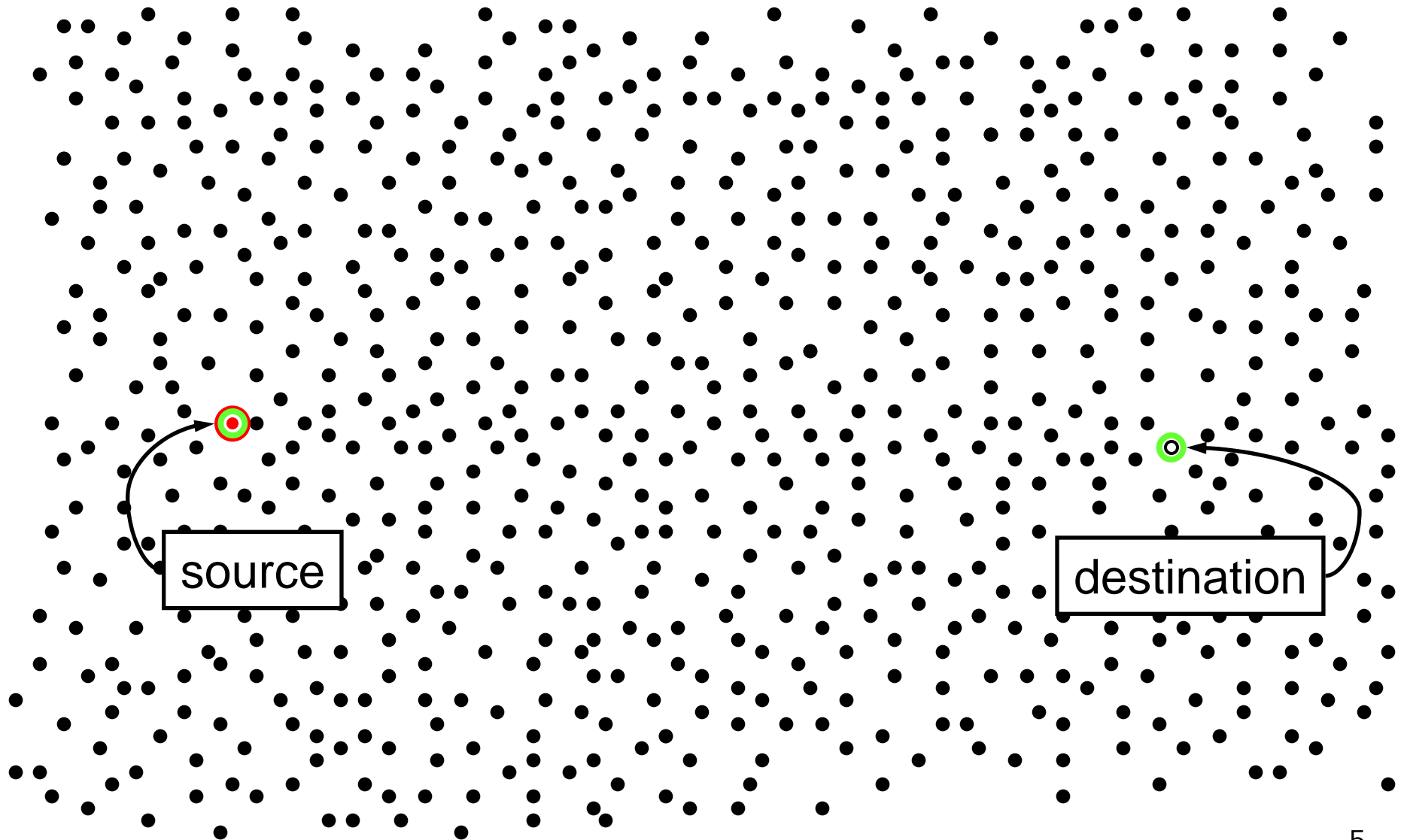


- Traditional diversity not feasible for many small low power devices
- Employ **cooperative** diversity: a **cluster** of coordinated single-antenna devices implementing a multi-antenna array
- ***Big Challenge: resource provisioning in cooperative networks***

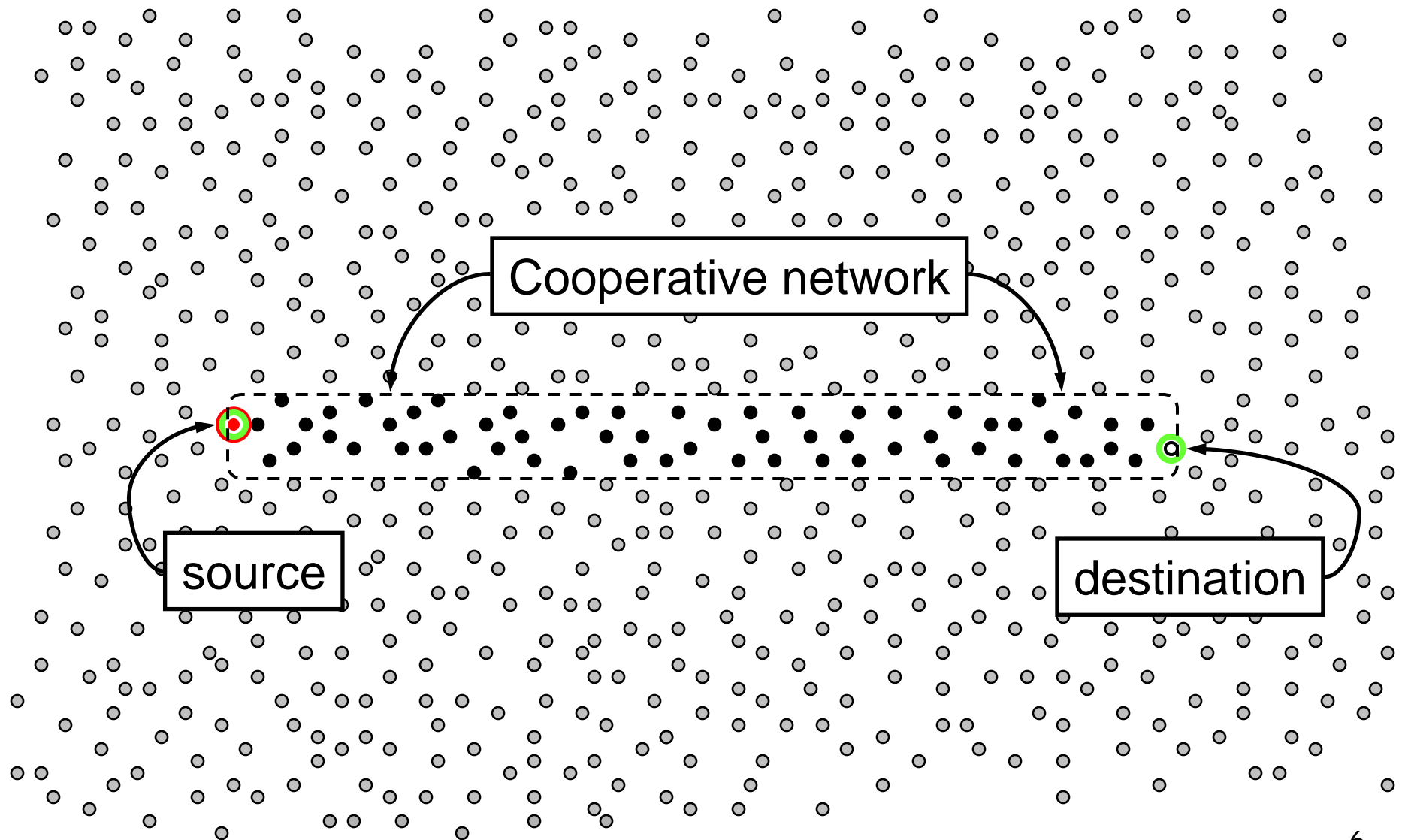
Example network scenario



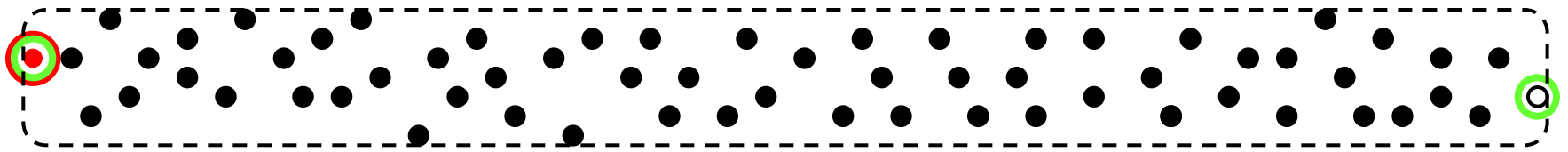
Example network scenario



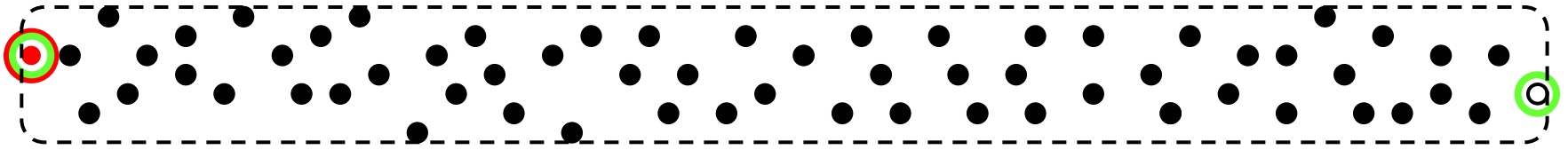
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Example network scenario

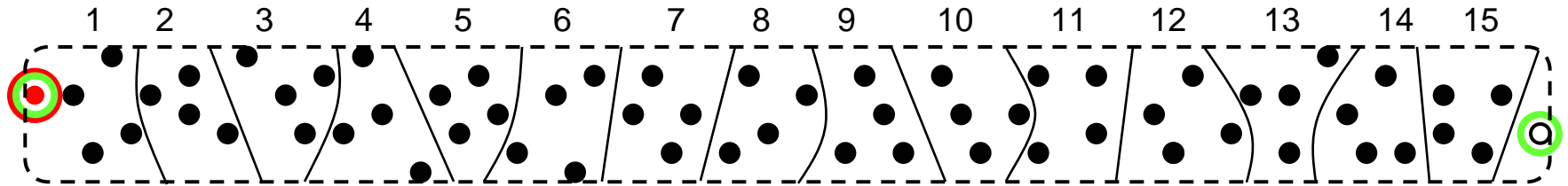


Clustering



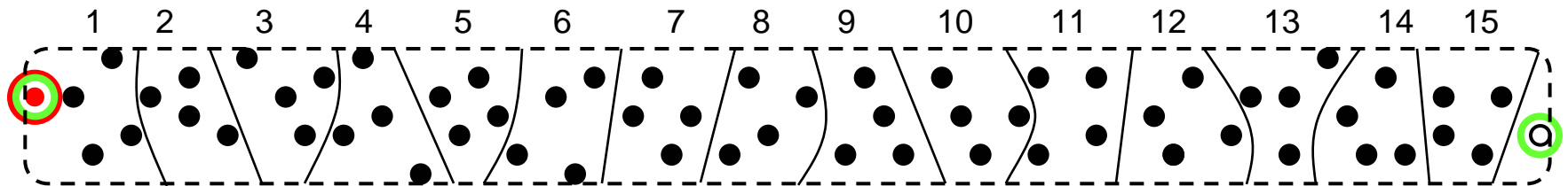
- Cluster: collection of nodes in the network that are transmitting the same packet

Static Clustering



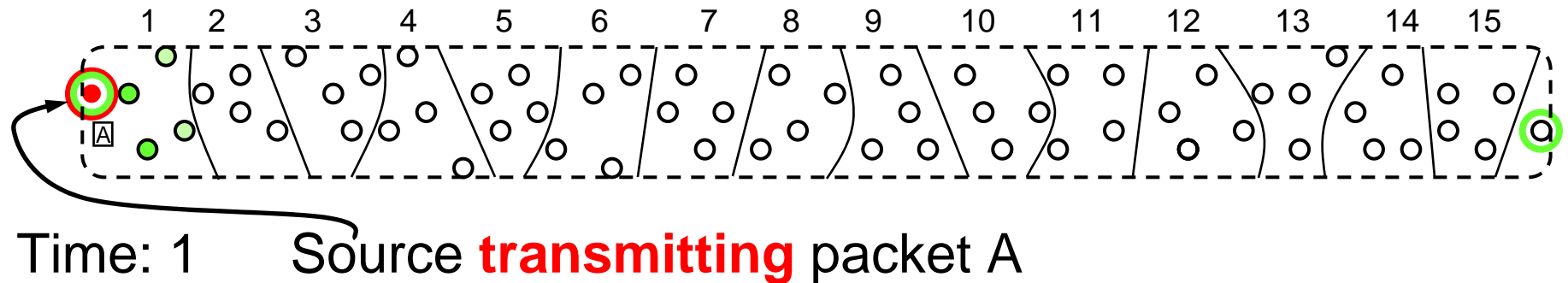
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 - Network divided into rigid clusters (by some algorithm)

Static Clustering



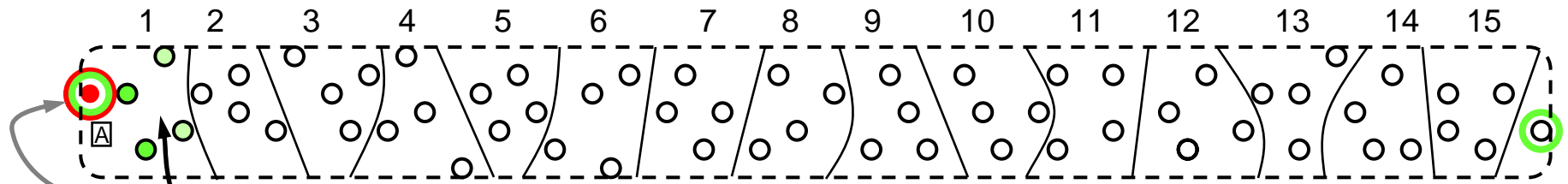
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Static Clustering



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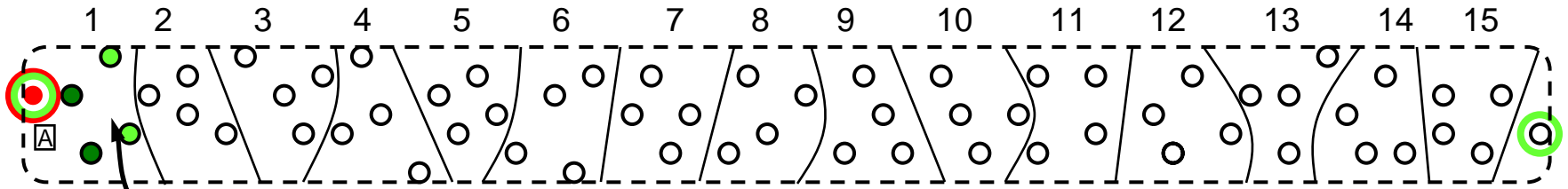
Static Clustering



Time: 1 Source transmitting packet A
 Cluster 1 **receiving** packet A
 Rest of network idle

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

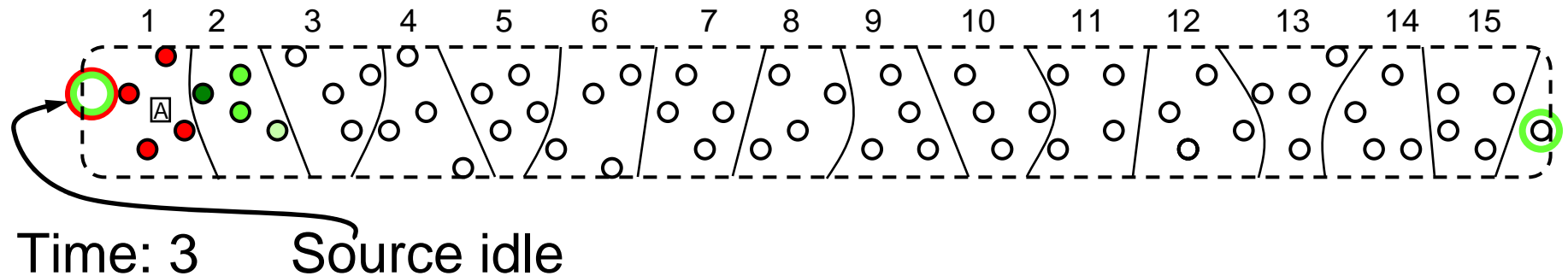
Static Clustering



Time: 2 Source transmitting packet A
 Cluster 1 continues **receiving** packet A
 Rest of network idle

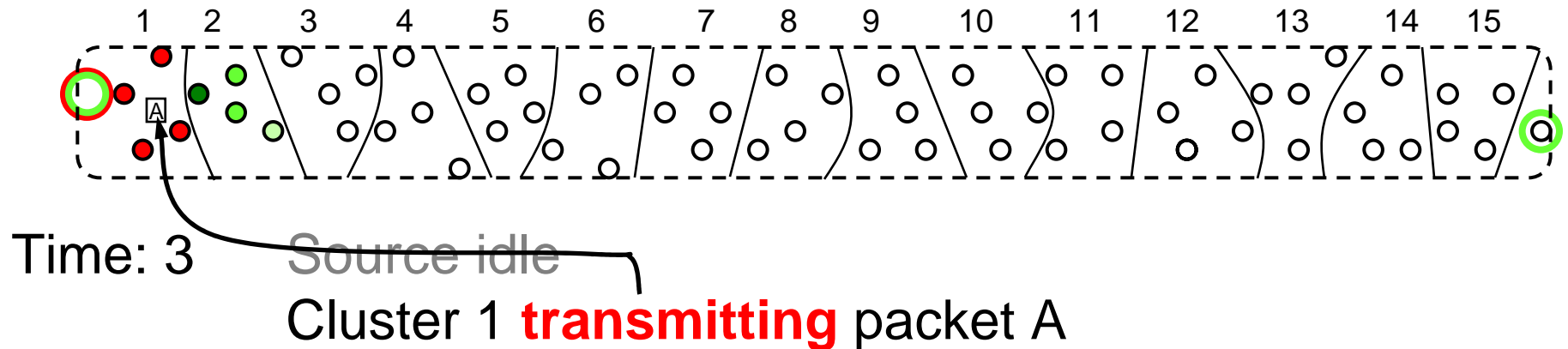
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Static Clustering



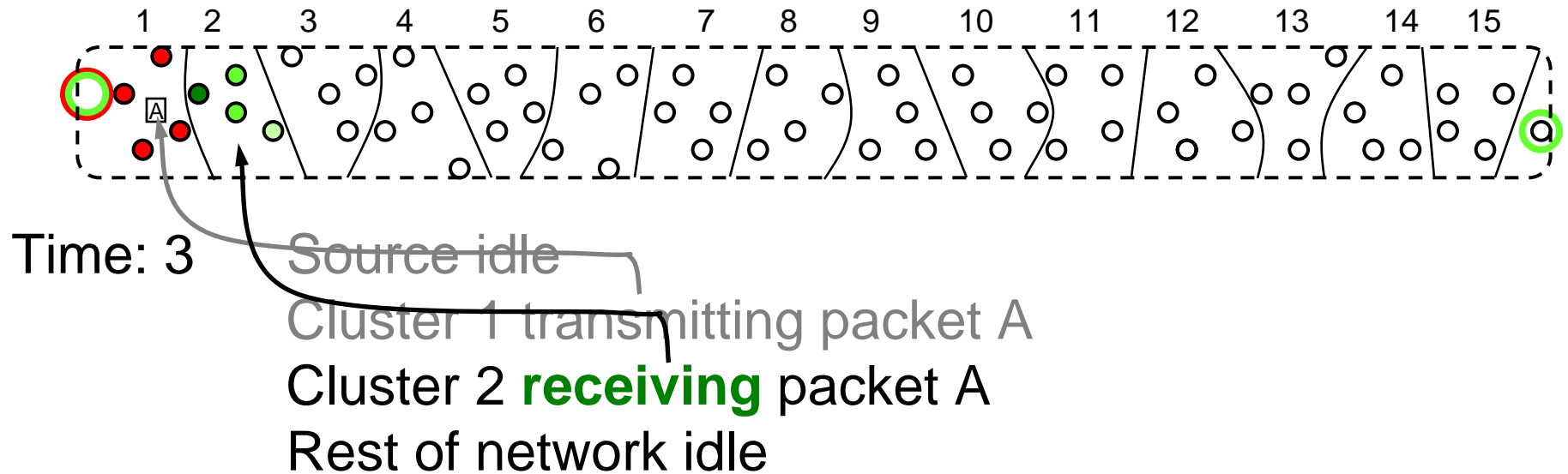
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Static Clustering



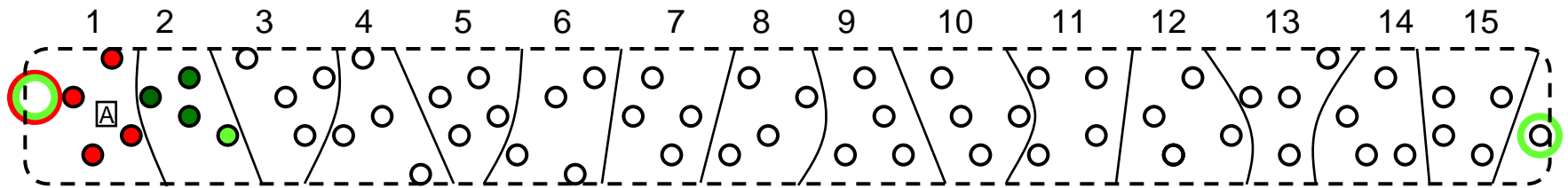
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Static Clustering



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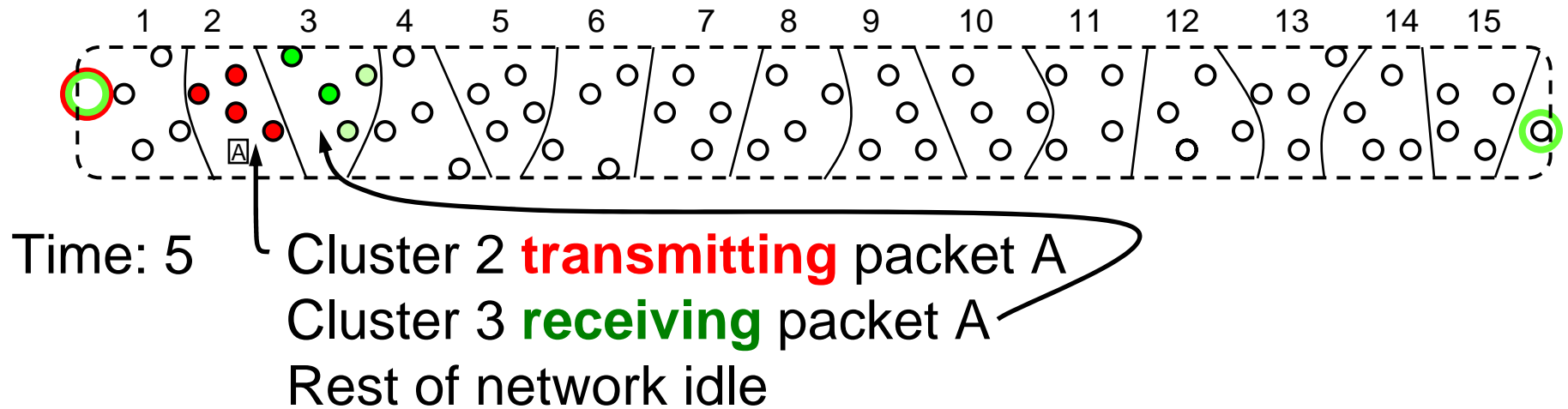
Static Clustering



Time: 4

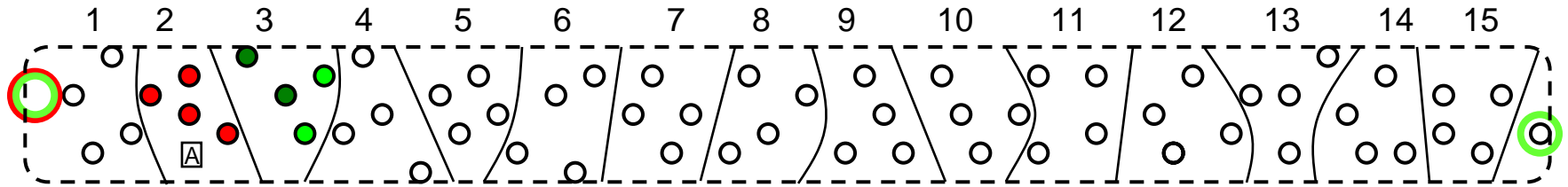
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Static Clustering



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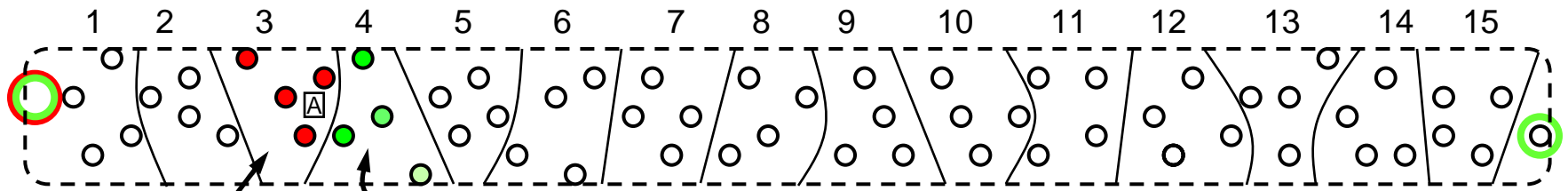
Static Clustering



Time: 6

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

Static Clustering



Time: 7

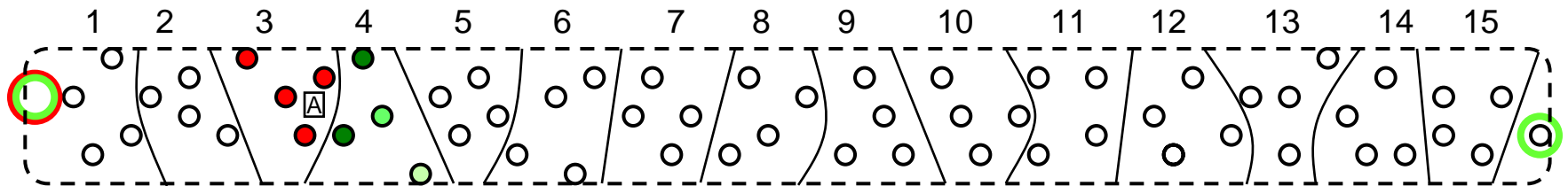
Cluster 3 **transmitting** packet A

Cluster 4 **receiving** packet A

Rest of network idle

- Static clustering:
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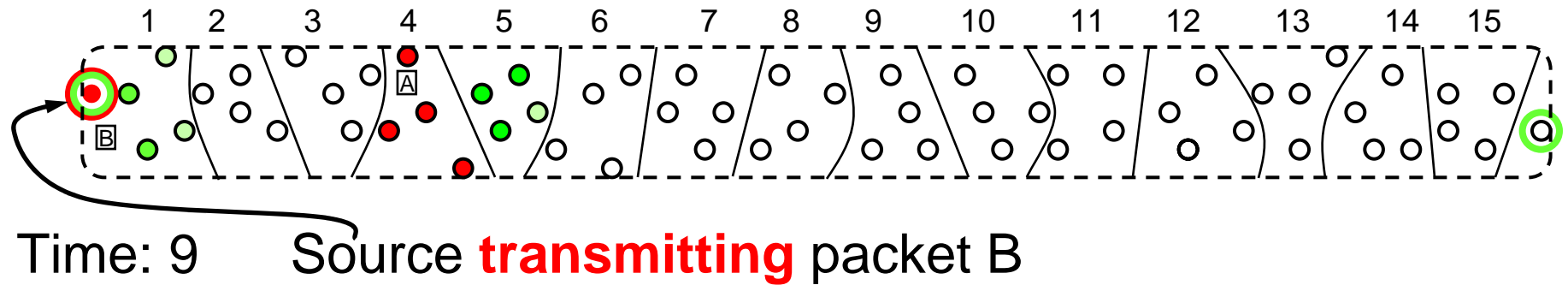
Static Clustering



Time: 8

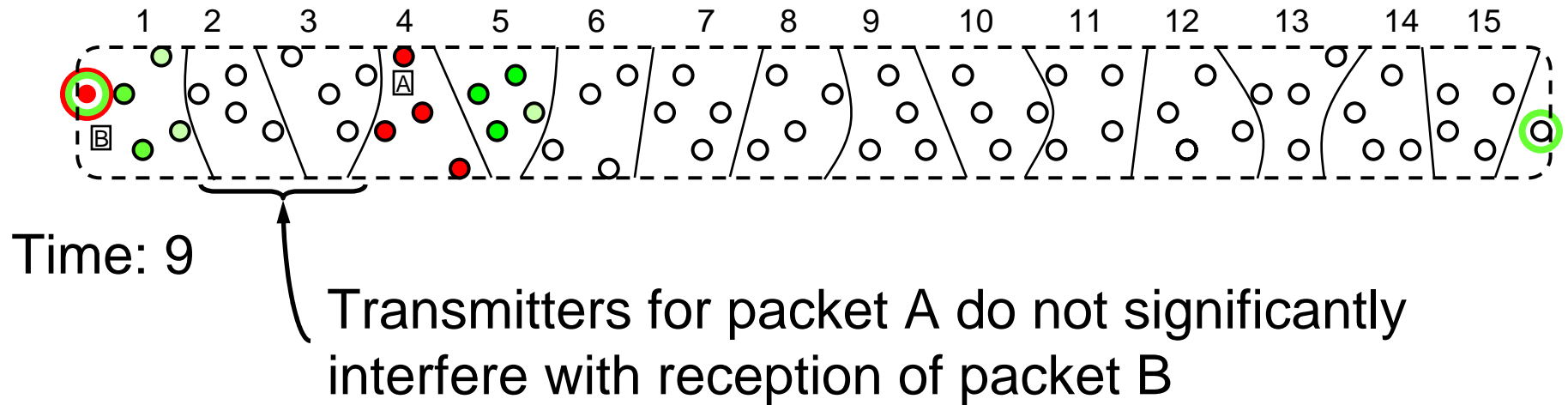
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Static Clustering



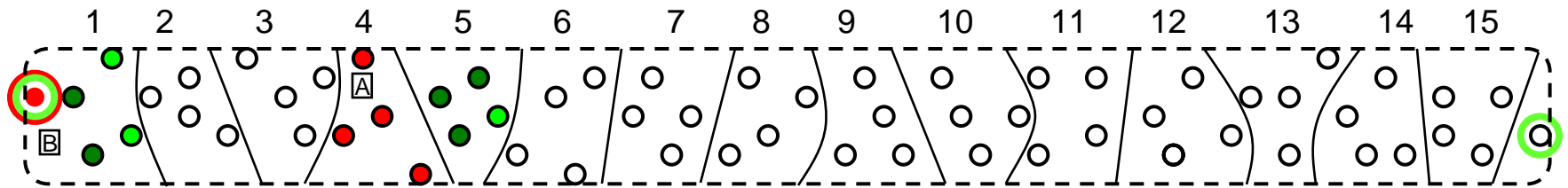
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Static Clustering



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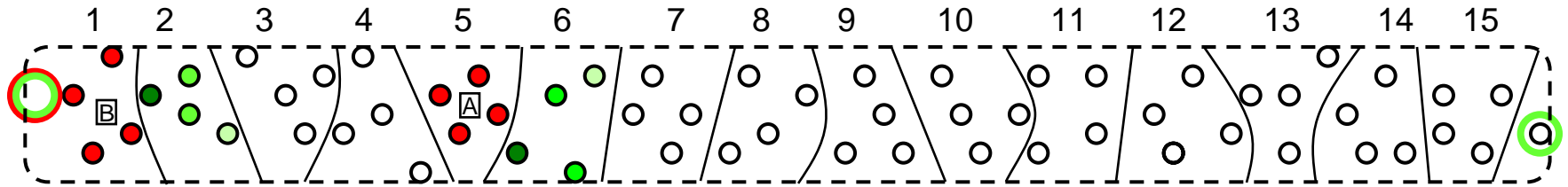
Static Clustering



Time: 10

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

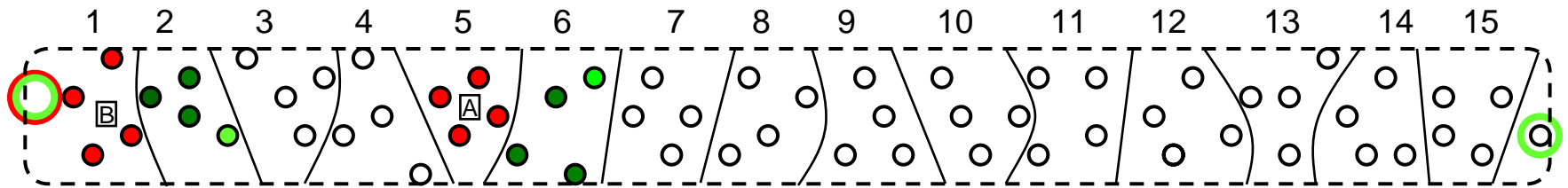
Static Clustering



Time: 11

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

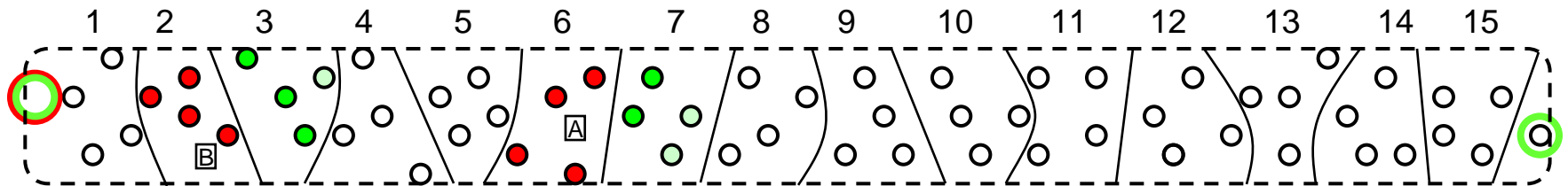
Static Clustering



Time: 12

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

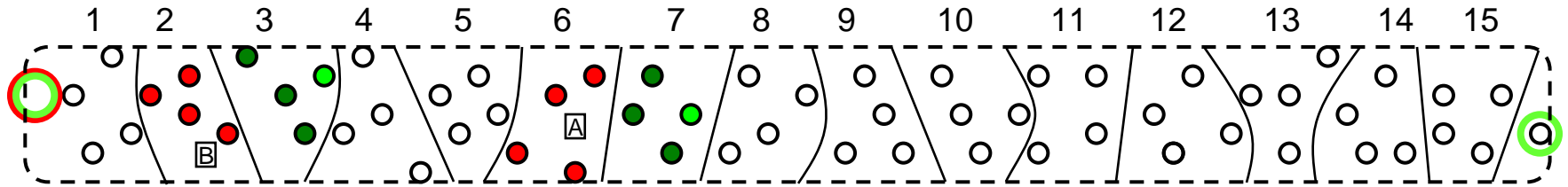
Static Clustering



Time: 13

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

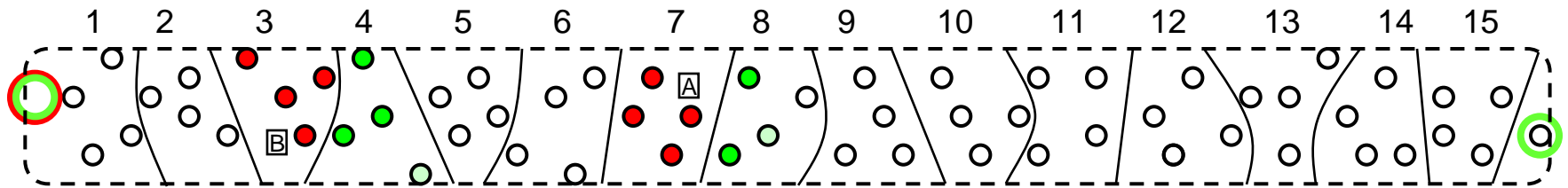
Static Clustering



Time: 14

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

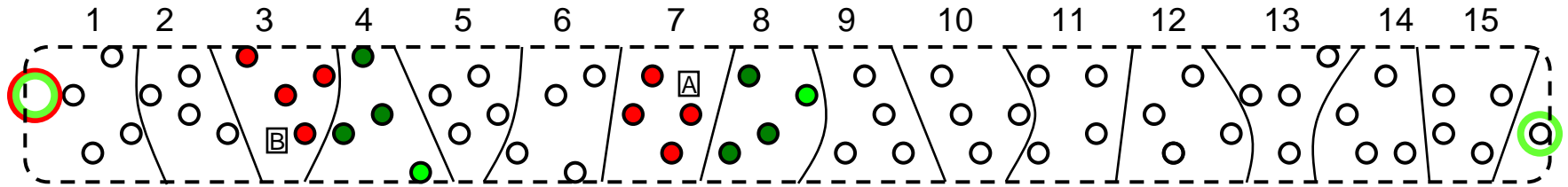
Static Clustering



Time: 15

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

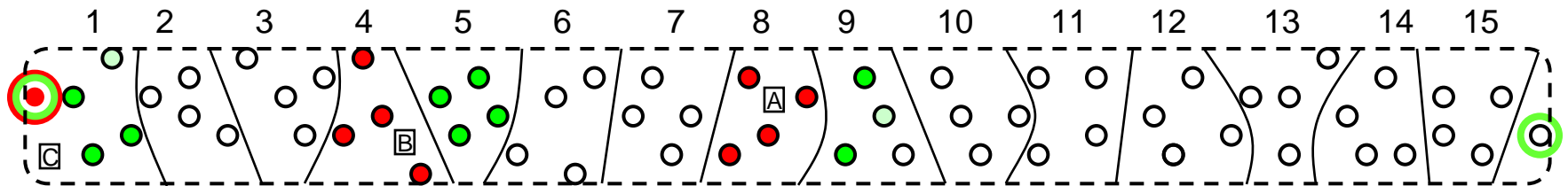
Static Clustering



Time: 16

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

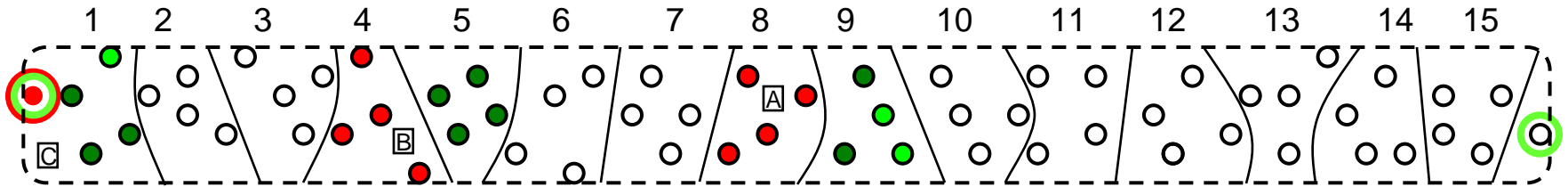
Static Clustering



Time: 17

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

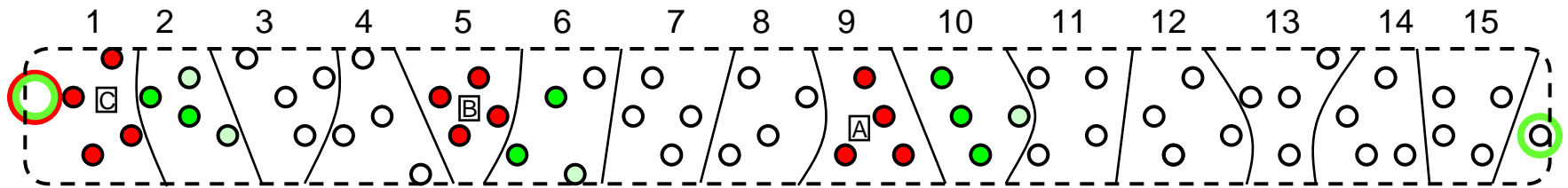
Static Clustering



Time: 18

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

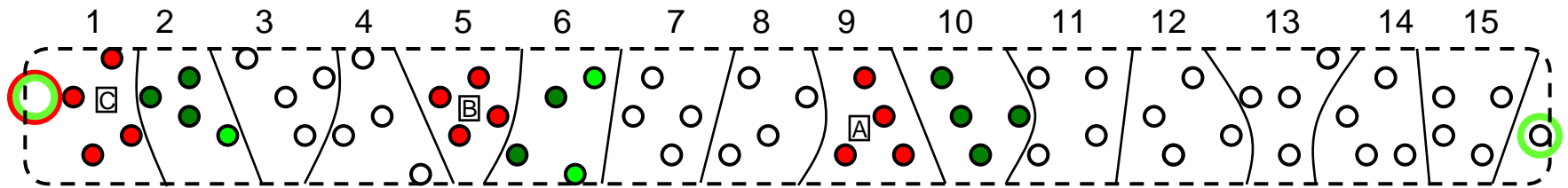
Static Clustering



Time: 19

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

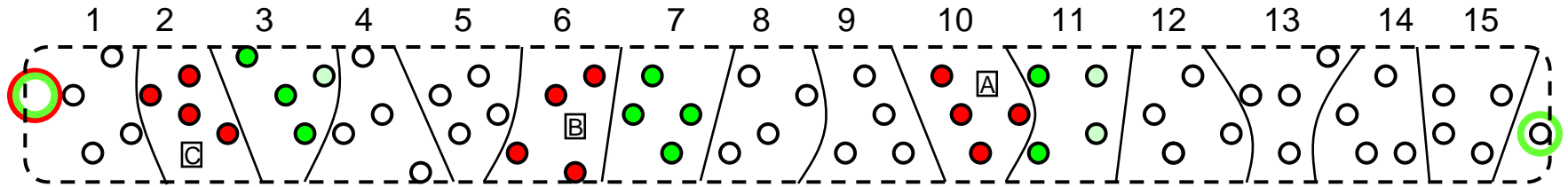
Static Clustering



Time: 20

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

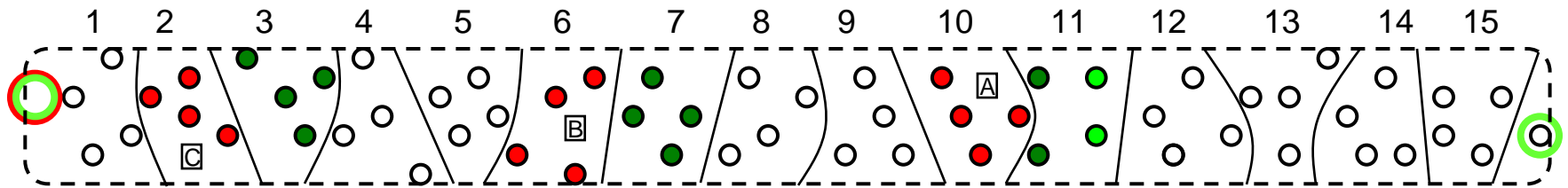
Static Clustering



Time: 21

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

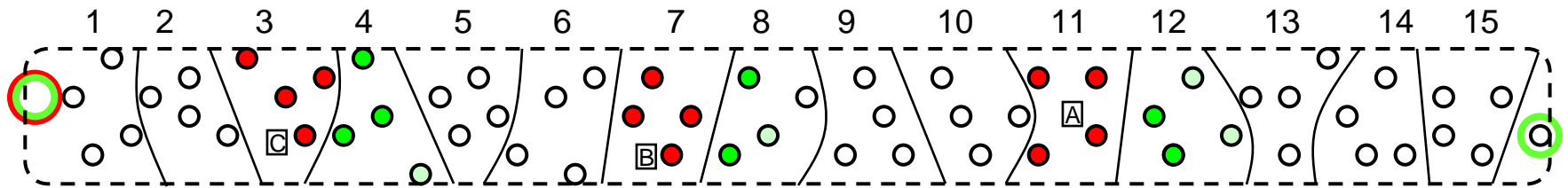
Static Clustering



Time: 22

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
 - Individual nodes restricted to transmitting and receiving during their cluster's turn (time slotted by cluster)

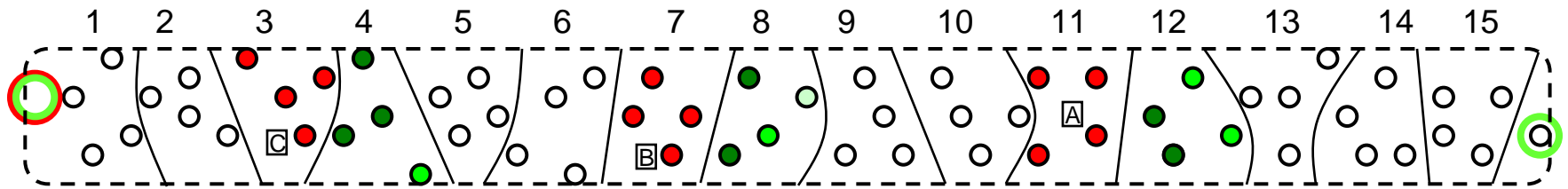
Static Clustering



Time: 23

- Static clustering:
 - Network divided into rigid clusters (by some algorithm)
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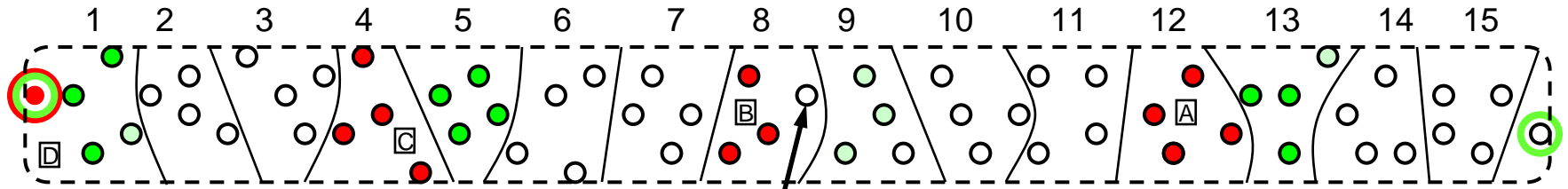
Static Clustering



Time: 24

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Static Clustering

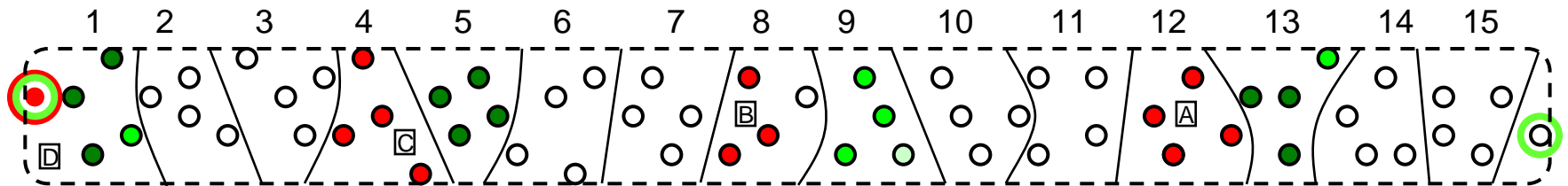


Time: 25

Node did not receive packet B
Only part of cluster 8 transmitting

- Static clustering:
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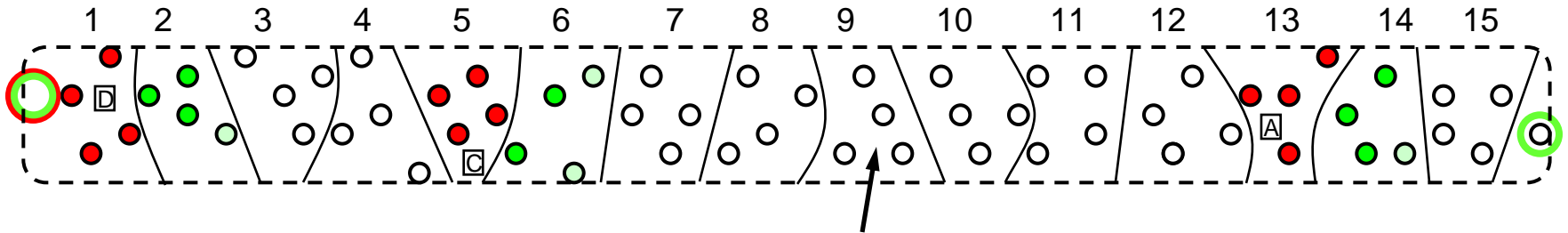
Static Clustering



Time: 26

- Static clustering:
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Static Clustering

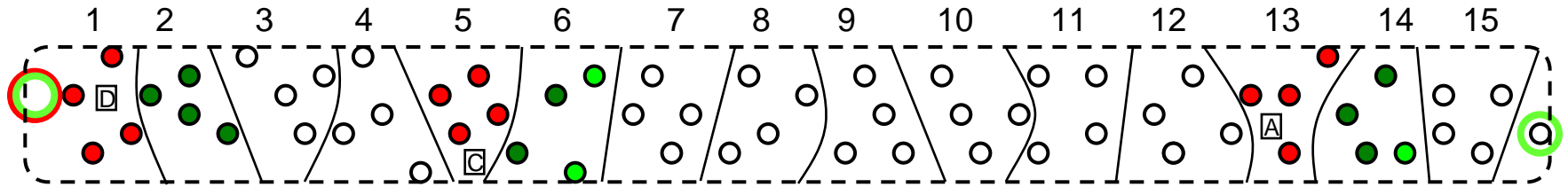


Time: 27

None of the nodes in cluster 9
received packet B,
Packet B dropped

- Static clustering:
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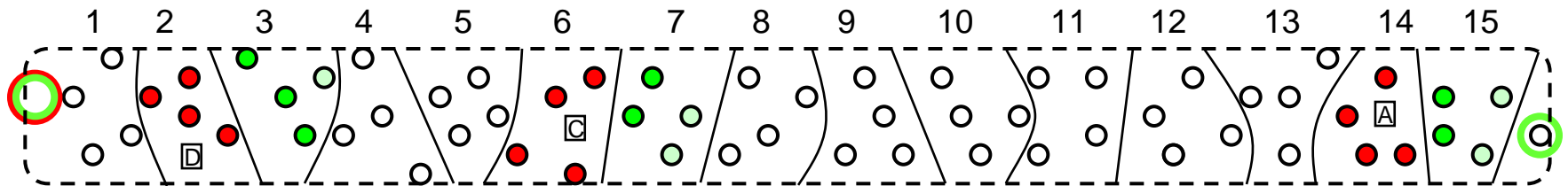
Static Clustering



Time: 28

- Static clustering:
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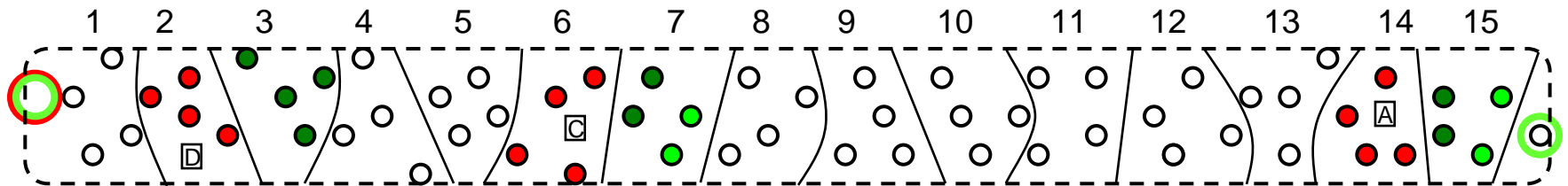
Static Clustering



Time: 29

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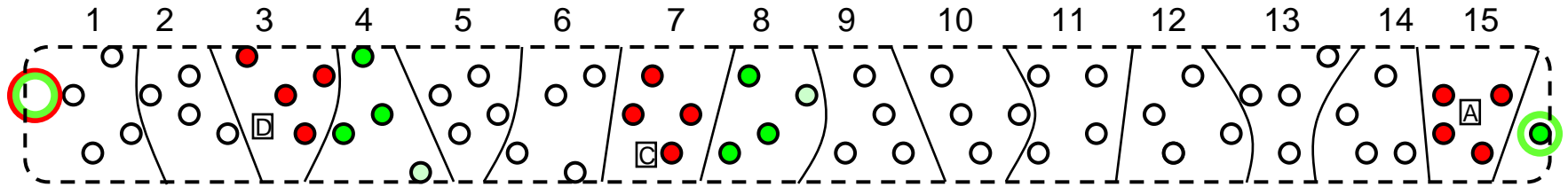
Static Clustering



Time: 30

- Static clustering:
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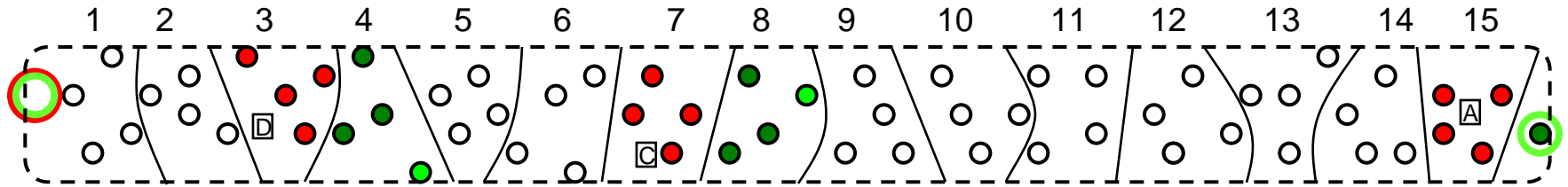
Static Clustering



Time: 31

- Static clustering:
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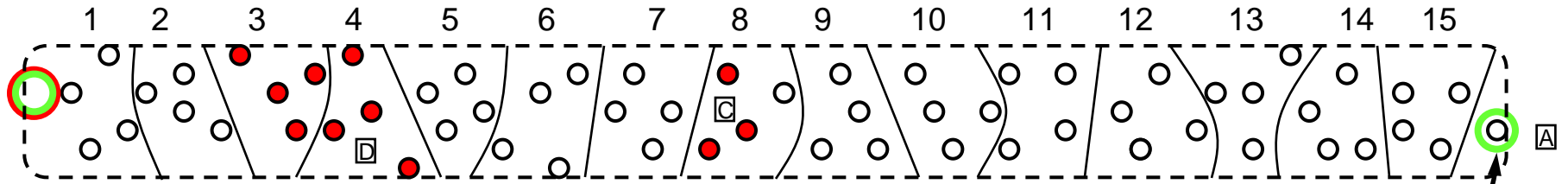
Static Clustering



Time: 32

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Static Clustering

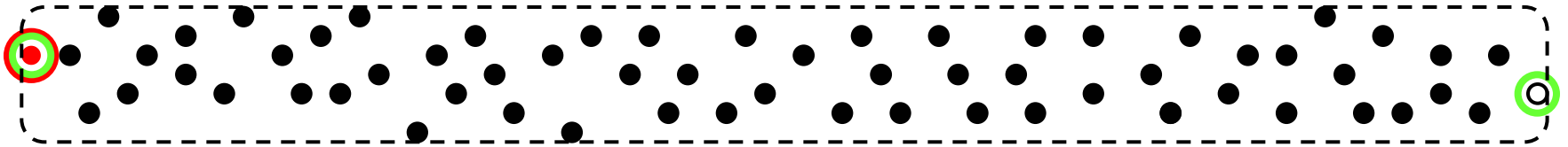


Time: 33

Destination receives packet A

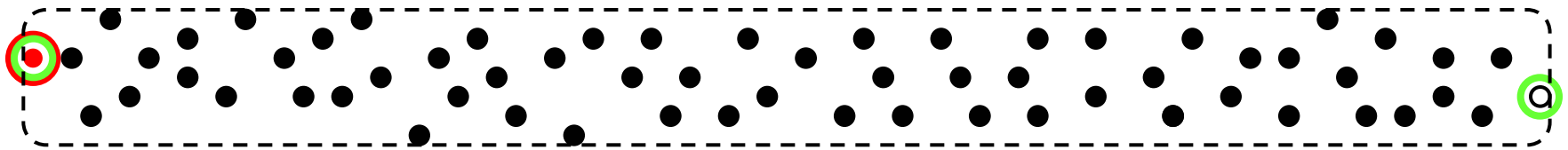
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Dynamic Clustering



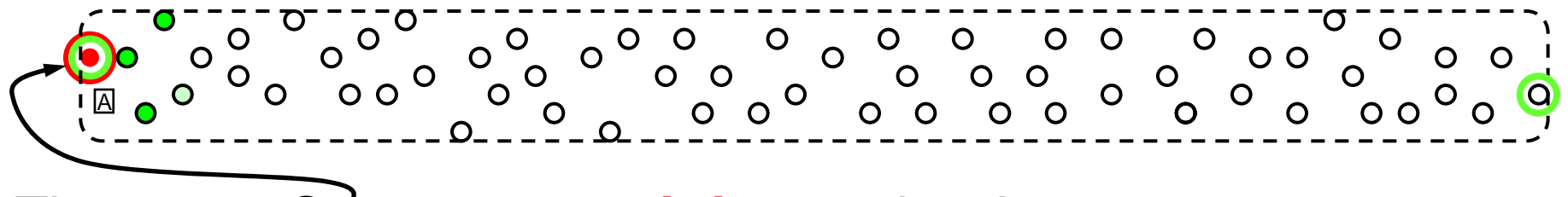
- Recall: Cluster is a collection of nodes in the network that are transmitting the same packet
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet

Dynamic Clustering



- Recall: Cluster is a collection of nodes in the network that are transmitting the same packet
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

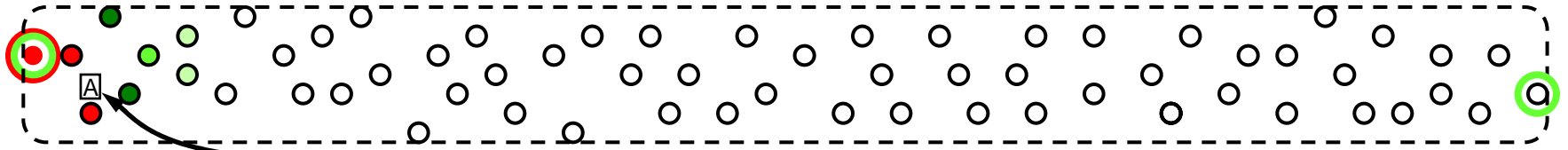
Dynamic Clustering



Time: 1 Source **transmitting** packet A
Rest of network **listening** opportunistically

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

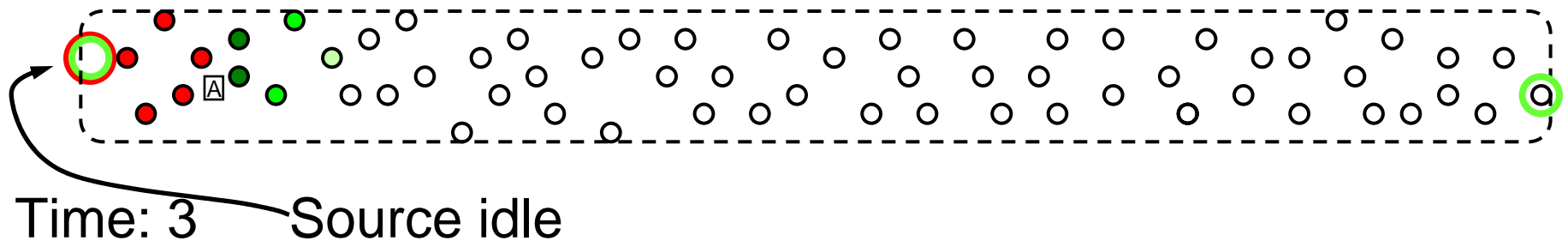
Dynamic Clustering



Time: 2 Source **transmitting** packet A
Some nodes receive A and join **transmission**
Rest of network **listening** opportunistically

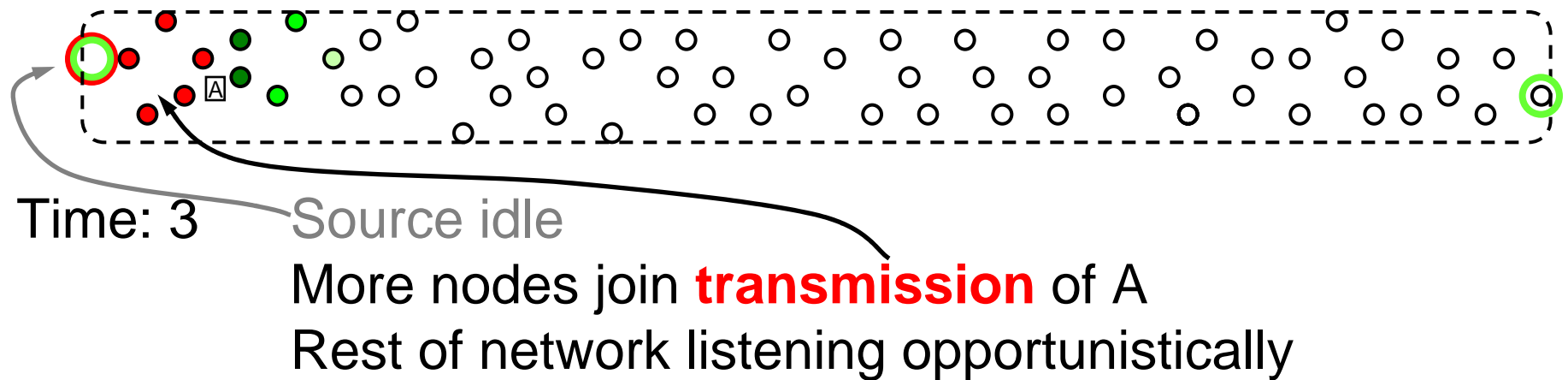
-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

Dynamic Clustering



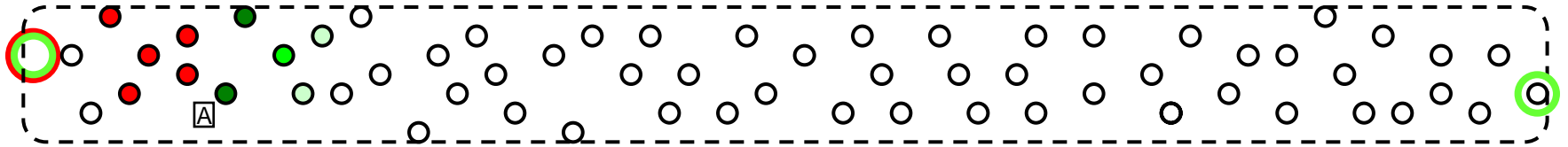
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- Dynamic clustering:
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Dynamic Clustering



- Dynamic clustering:
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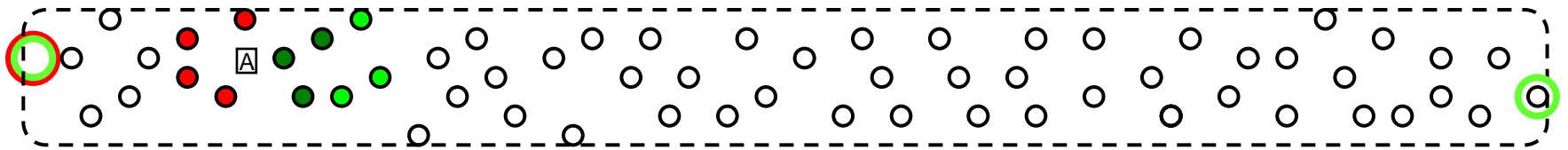
Dynamic Clustering



Time: 4 Cluster transmitting A evolves

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

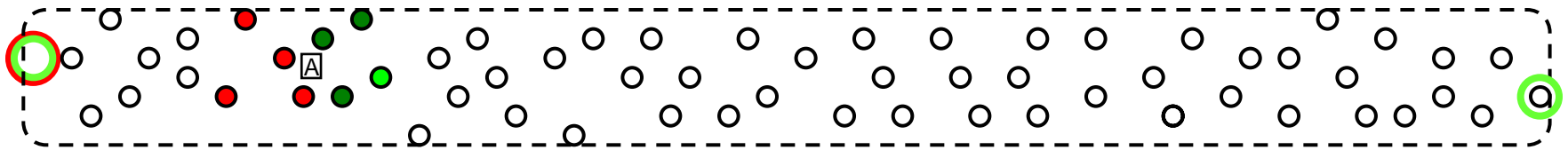
Dynamic Clustering



Time: 5 Cluster transmitting A evolves

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

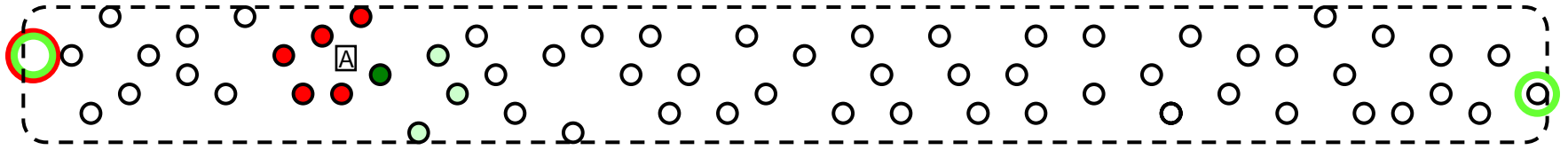
Dynamic Clustering



Time: 6 Cluster transmitting A evolves

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

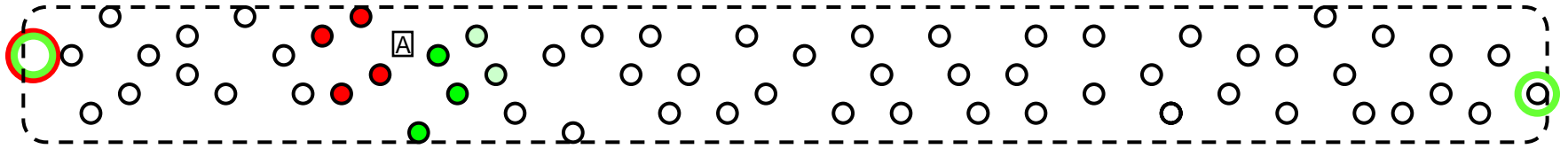
Dynamic Clustering



Time: 7 Cluster transmitting A evolves

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

Dynamic Clustering



Time: 8 Cluster transmitting A evolves

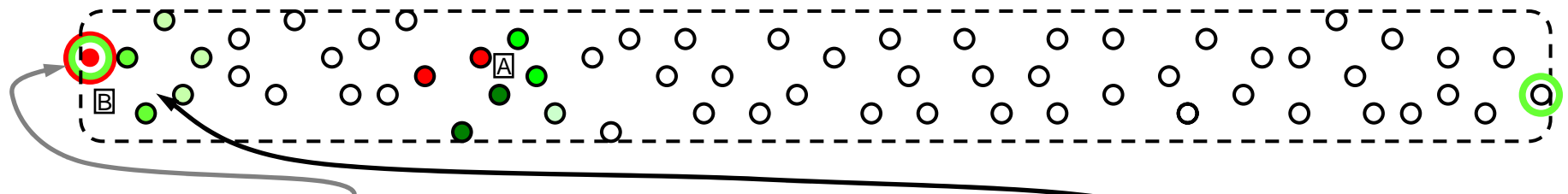
-
- Dynamic clustering:
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 - "Fluid" clusters
 - Increased complexity

Dynamic Clustering



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- Dynamic clustering:
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 - "Fluid" clusters
 - Increased complexity

Dynamic Clustering



Time: 9

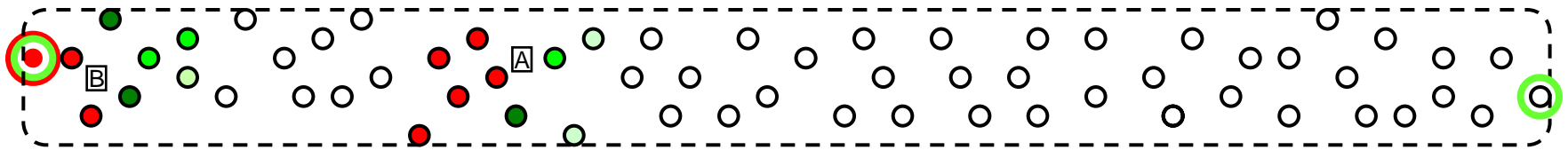
Source transmitting packet B

Nodes that have already received A **listen** for B

Cluster transmitting A continues evolving

- Dynamic clustering:
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 - "Fluid" clusters
 - Increased complexity

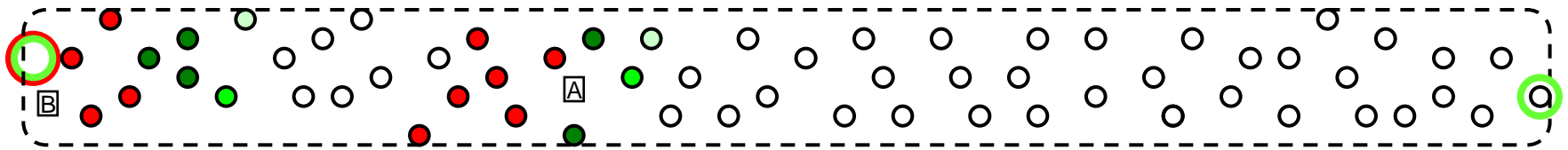
Dynamic Clustering



Time: 10

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

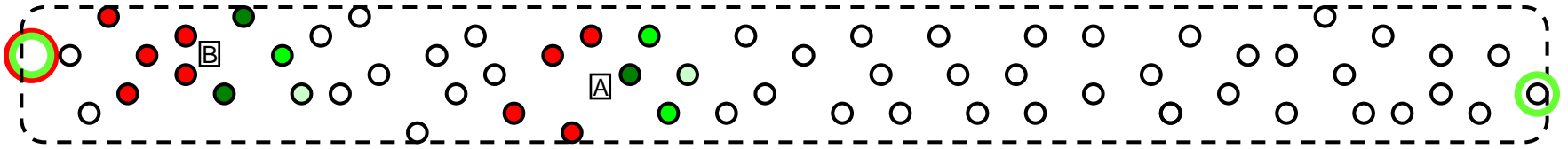
Dynamic Clustering



Time: 11

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

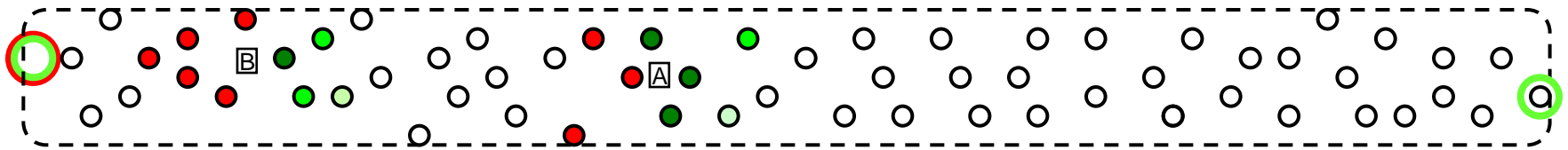
Dynamic Clustering



Time: 12

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

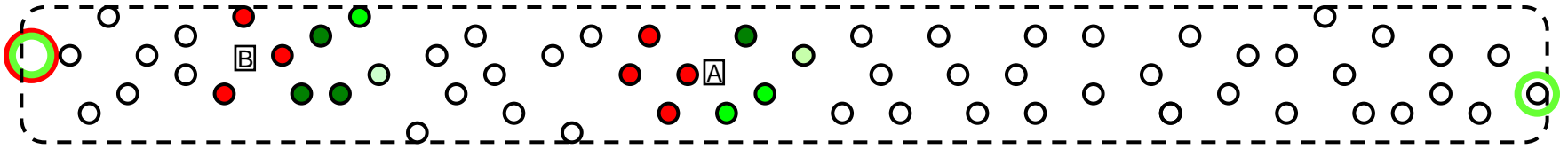
Dynamic Clustering



Time: 13

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

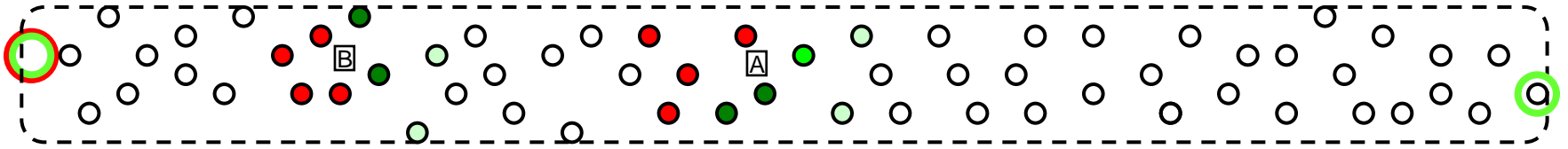
Dynamic Clustering



Time: 14

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

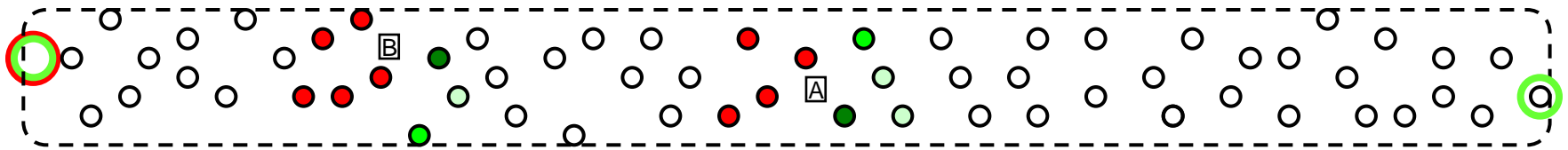
Dynamic Clustering



Time: 15

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

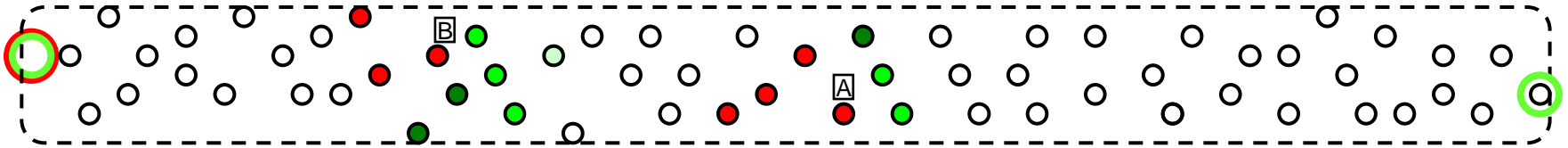
Dynamic Clustering



Time: 16

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

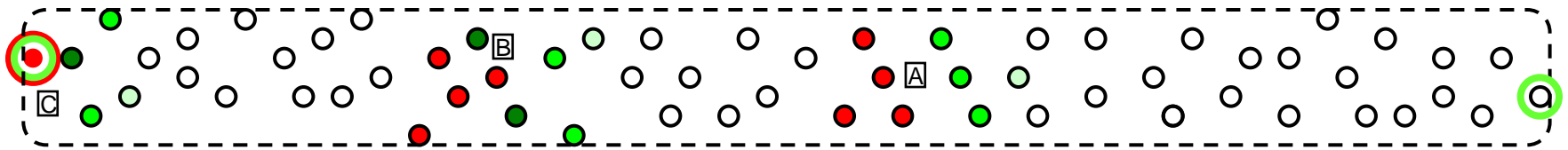
Dynamic Clustering



Time: 17

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

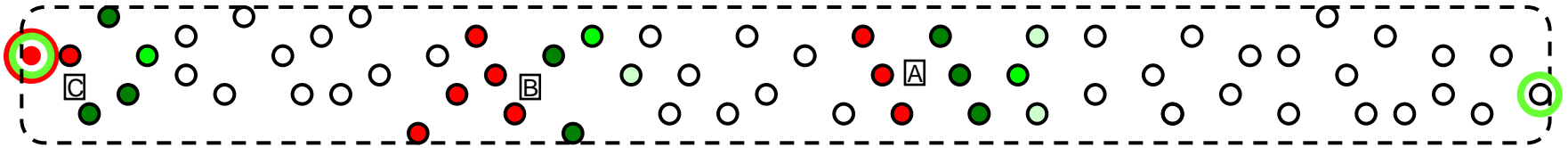
Dynamic Clustering



Time: 18

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

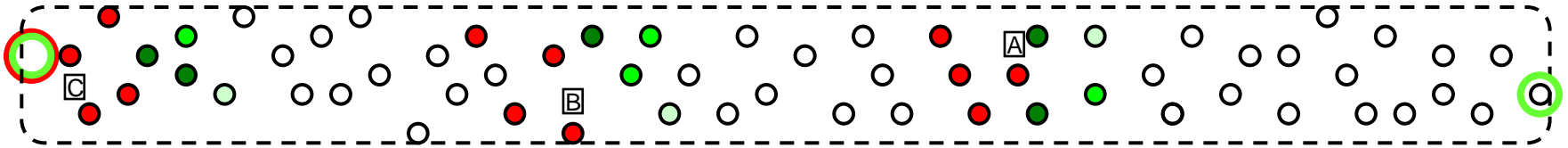
Dynamic Clustering



Time: 19

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

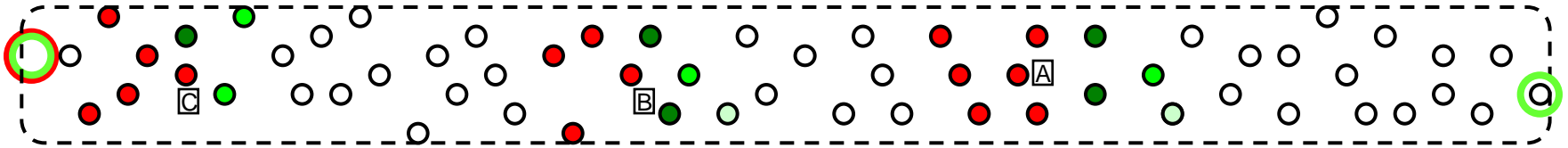
Dynamic Clustering



Time: 20

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

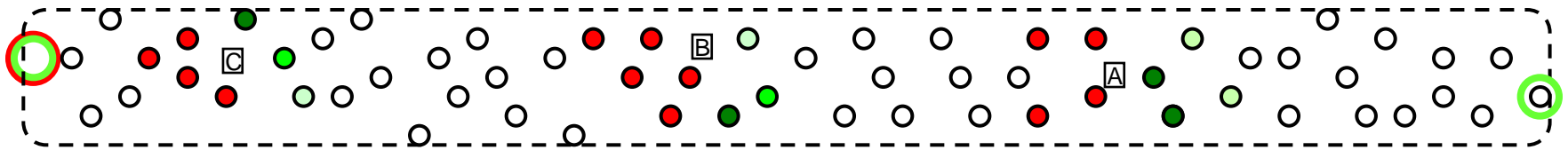
Dynamic Clustering



Time: 21

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

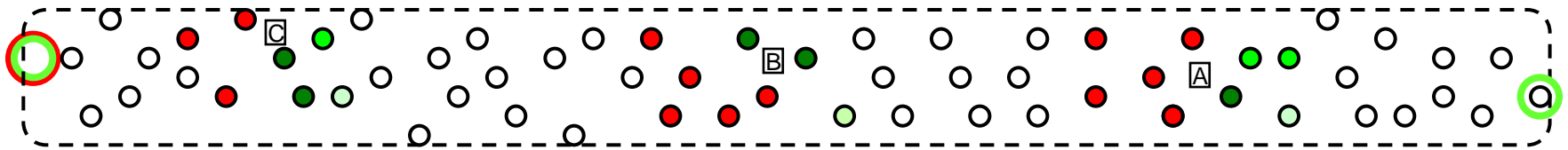
Dynamic Clustering



Time: 22

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

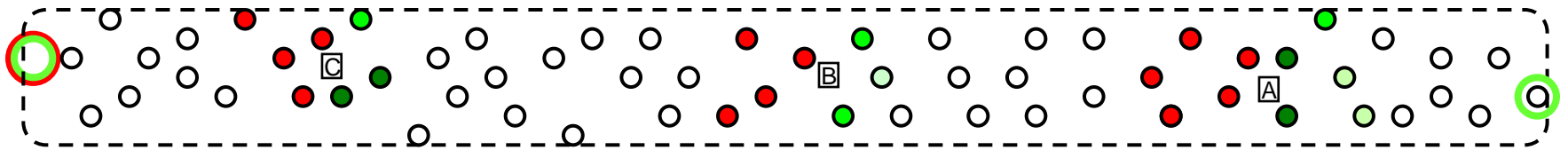
Dynamic Clustering



Time: 23

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

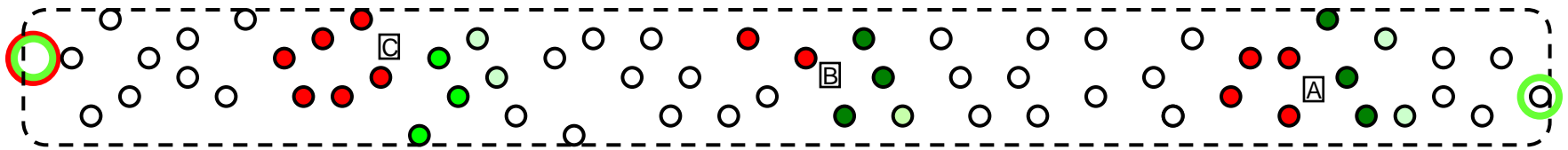
Dynamic Clustering



Time: 24

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

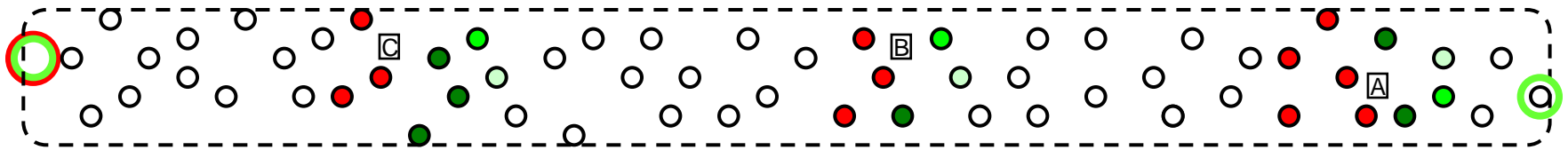
Dynamic Clustering



Time: 25

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

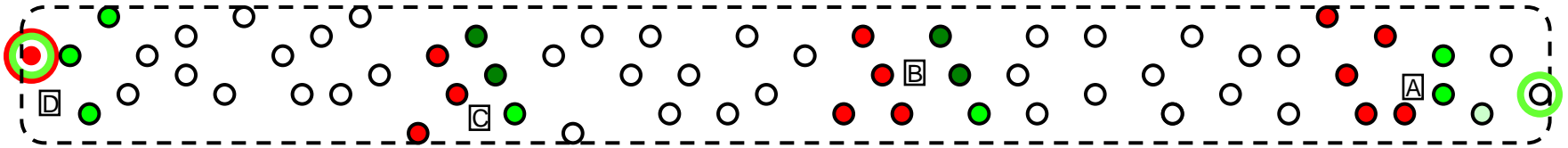
Dynamic Clustering



Time: 26

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

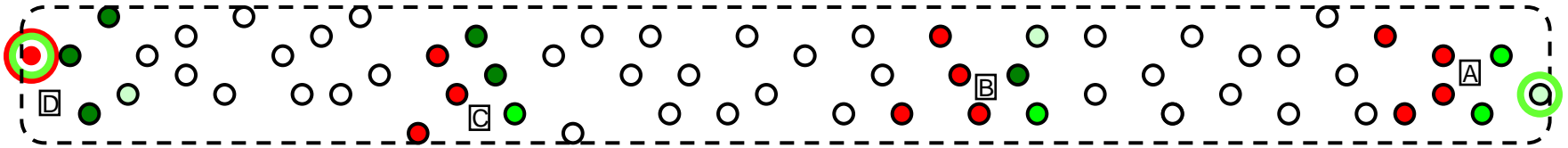
Dynamic Clustering



Time: 27

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

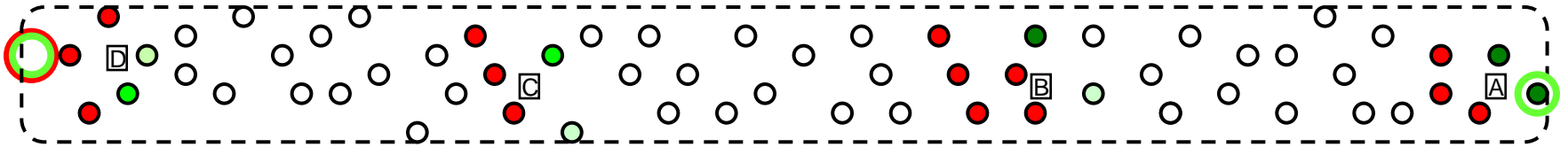
Dynamic Clustering



Time: 28

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

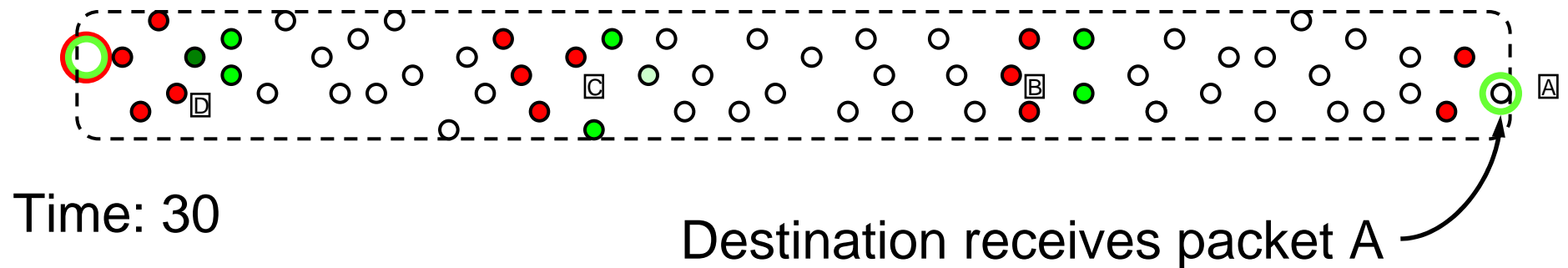
Dynamic Clustering



Time: 29

-
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

Dynamic Clustering



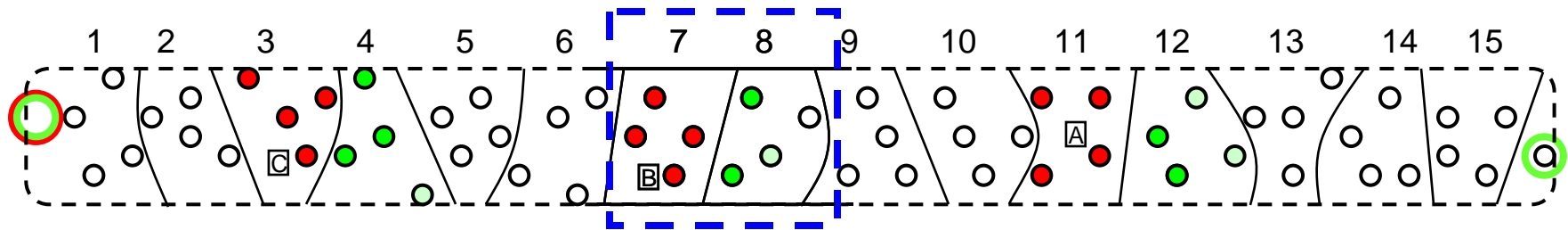
- Dynamic clustering:
 - Nodes join transmitting cluster opportunistically, upon decoding the packet
 - "Fluid" clusters
 - Increased complexity

Outline

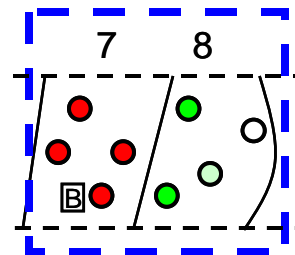
- Introduction
- Clustering methods
- **Our contribution: Which clustering method is better for organizing cooperation?**
 - Intuitive answer
 - Evaluation system description
 - Simulation results
- Conclusion

Comparison of Clustering Methods

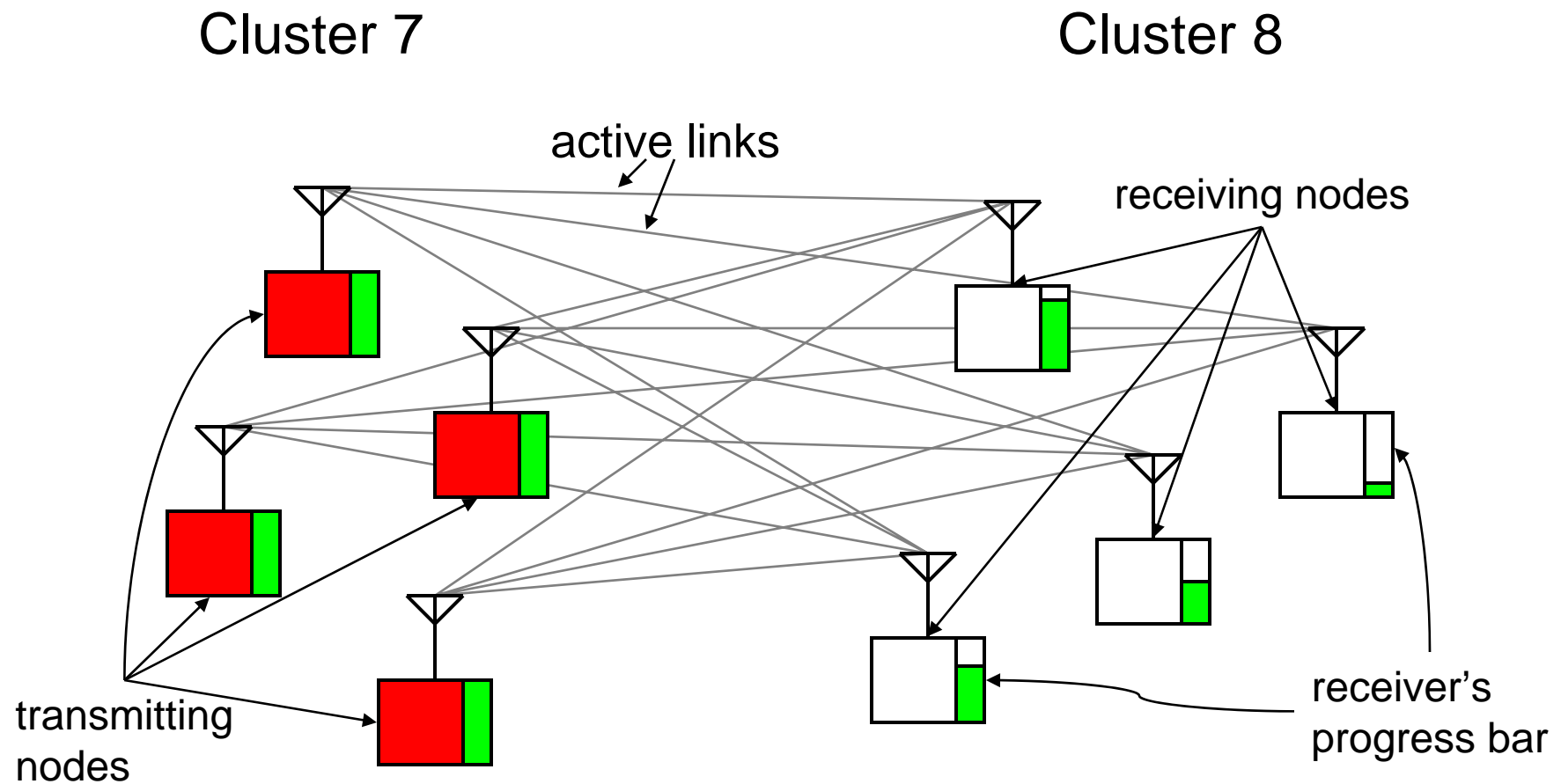
- Which clustering method is better for organizing cooperation?
- Dynamic clustering *seems* to be better, but why?
- Examine nodes making up static clusters 7&8 in example network configuration



Comparison of Clustering Methods

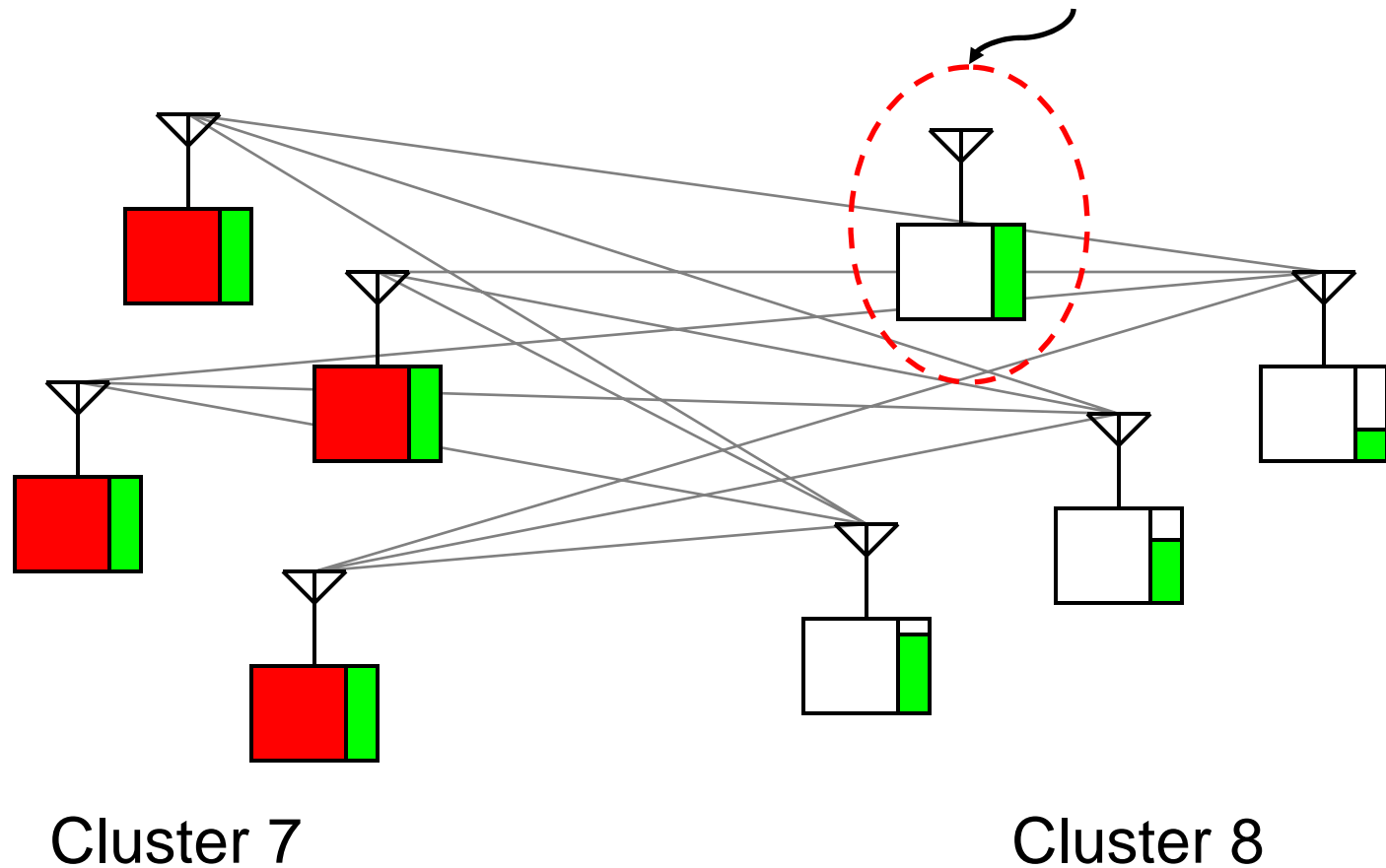


Static Clustering Detail



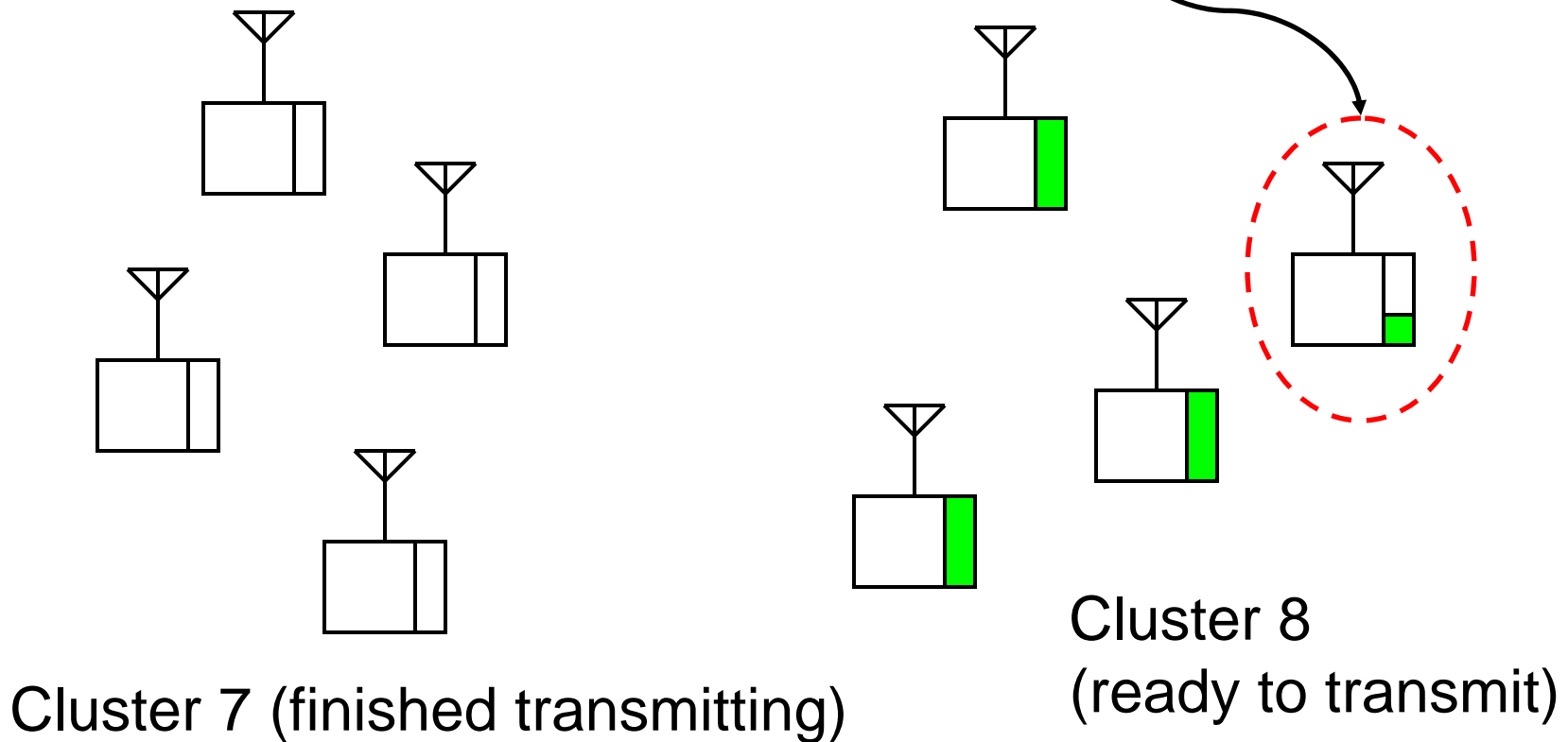
Static Clustering Detail

Node finished receiving,
waiting for cluster to start transmitting



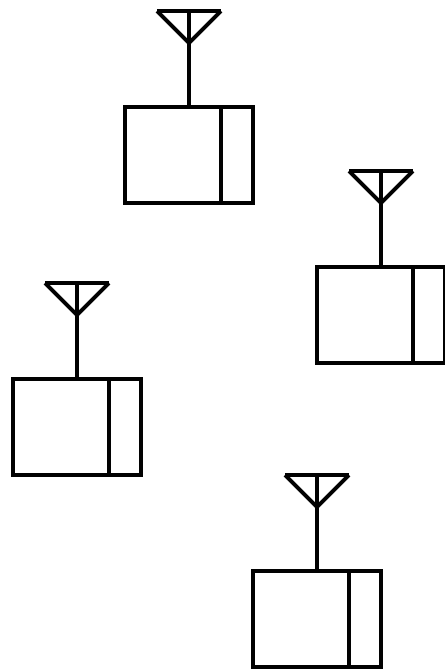
Static Clustering Detail

Node did not finish receiving packet before Cluster 7 stopped transmitting

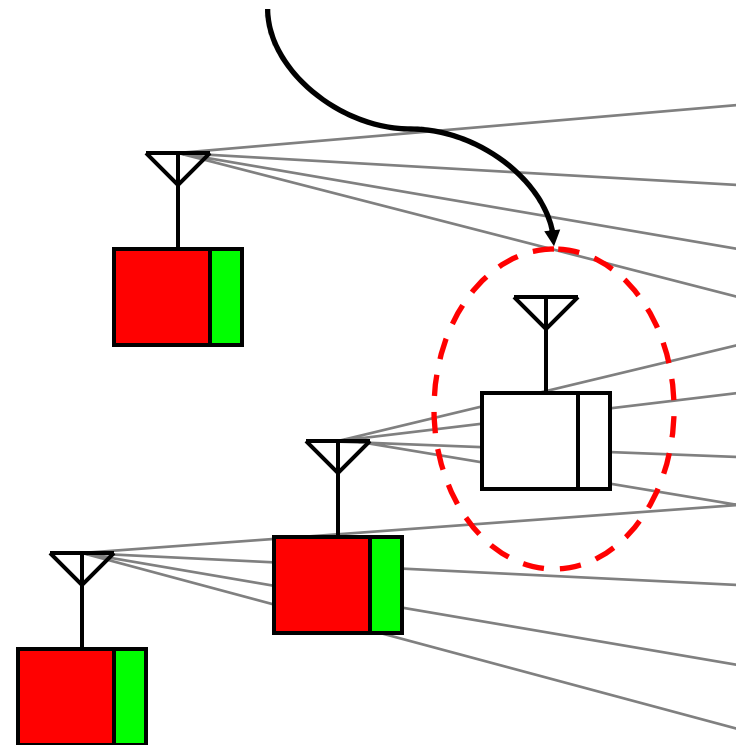


Static Clustering Detail

Node not participating in transmission



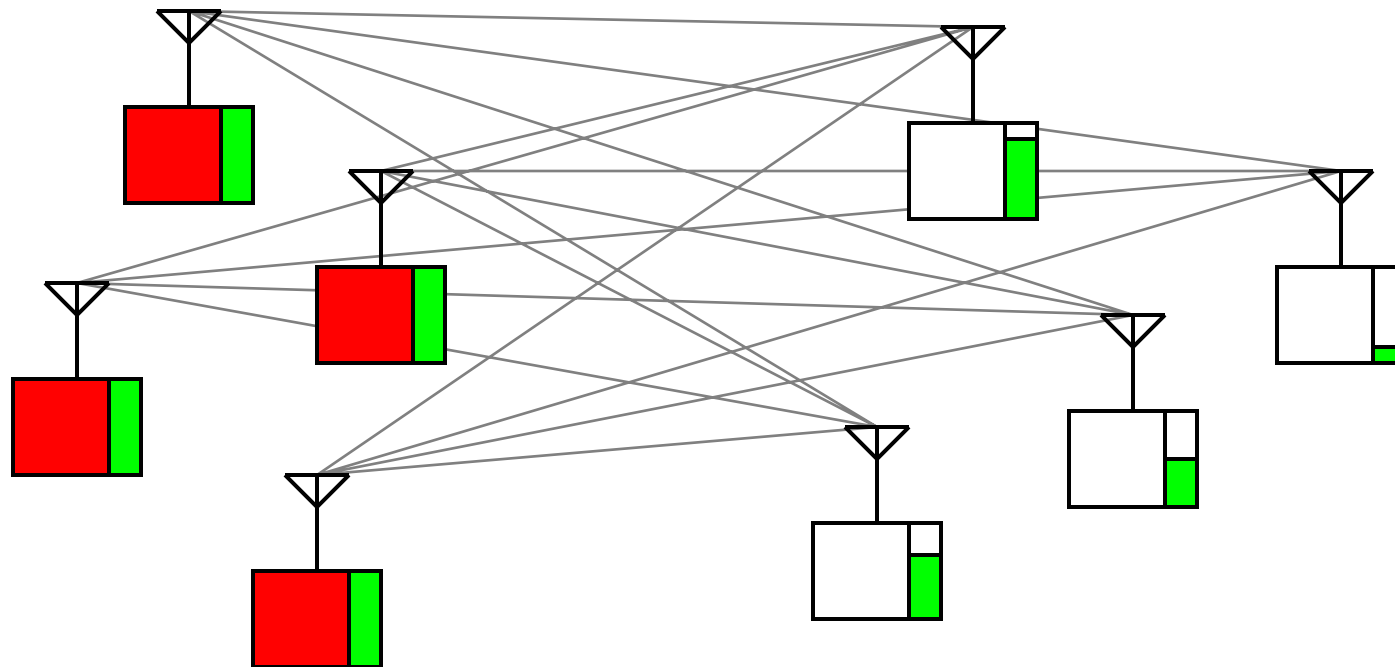
Cluster 7



Cluster 8

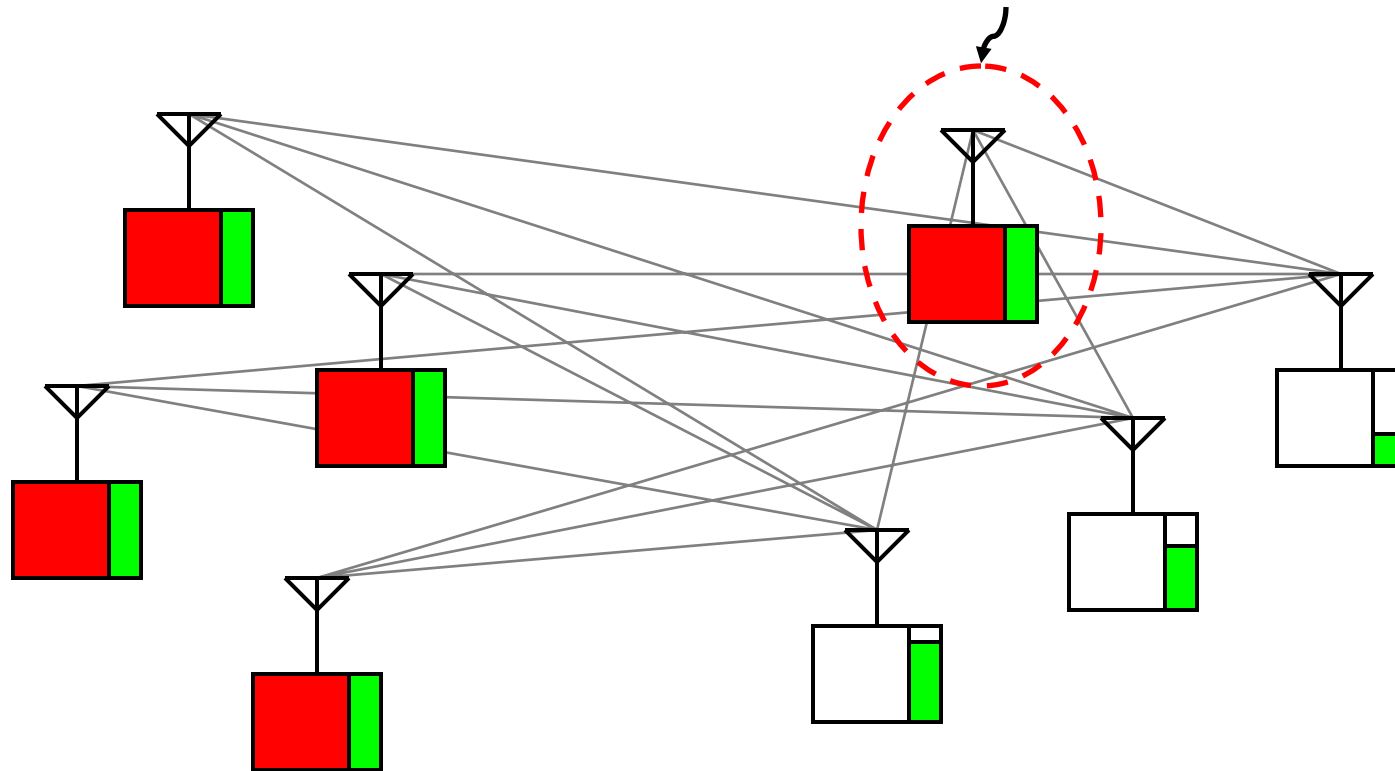
Dynamic Clustering Detail

Consider Dynamic Clustering
on the same set of nodes



Dynamic Clustering Detail

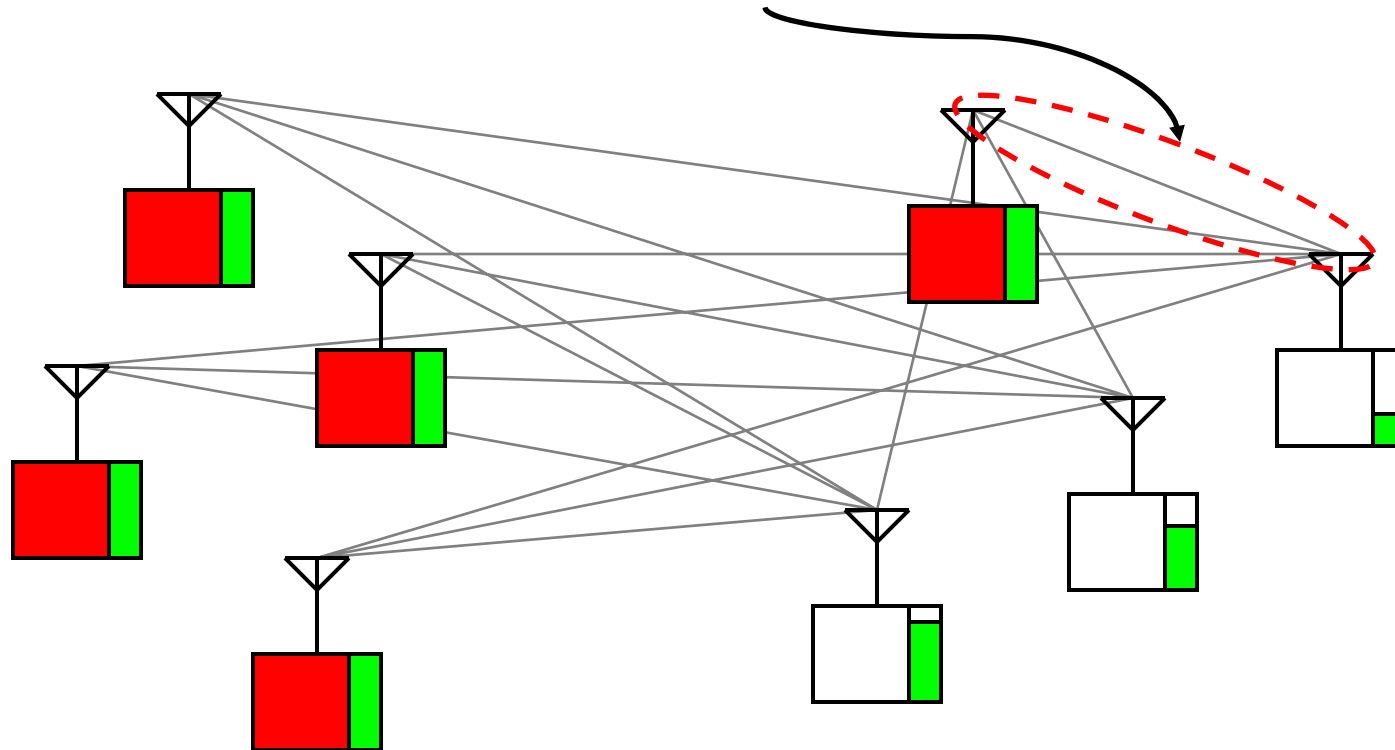
Node finished receiving,
joined cooperative transmission



Dynamic Clustering Detail

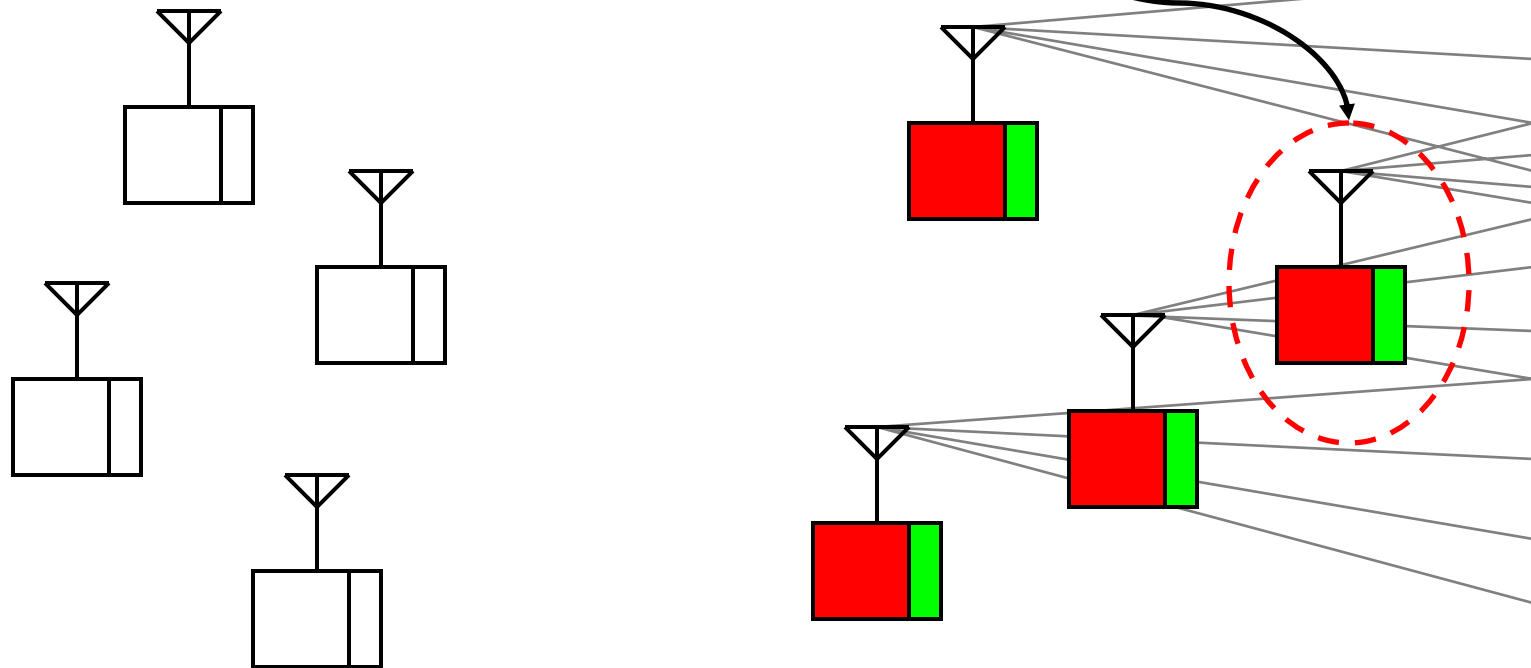
Better opportunity for the node to receive packet:

1. New, independent channel
2. Closer transmitter, more power received on average



Dynamic Clustering Detail

Node participating in transmission

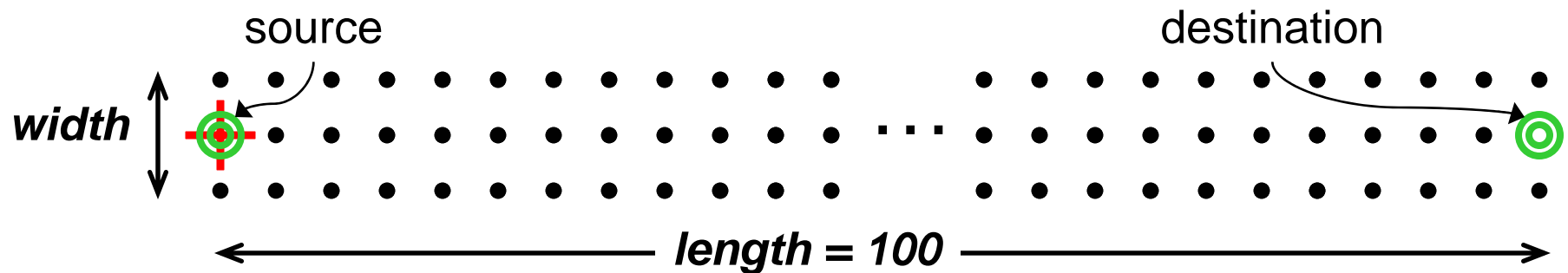


Outline

- Introduction
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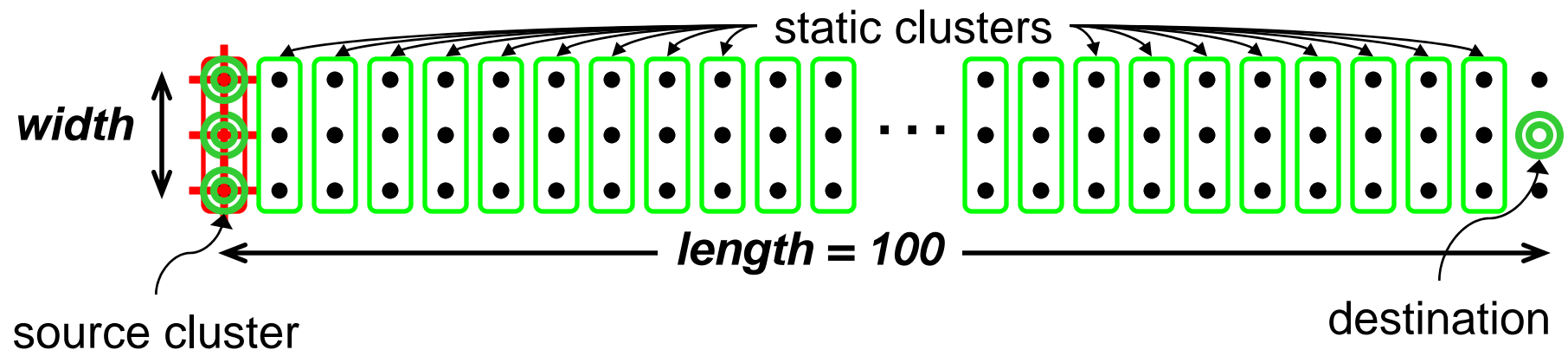
System Description

- **Objective:** evaluate static and dynamic clustering
- **Unique Tool:** large-network simulator with bit-level physical layer implementation
 - Topology: strip network for single flows



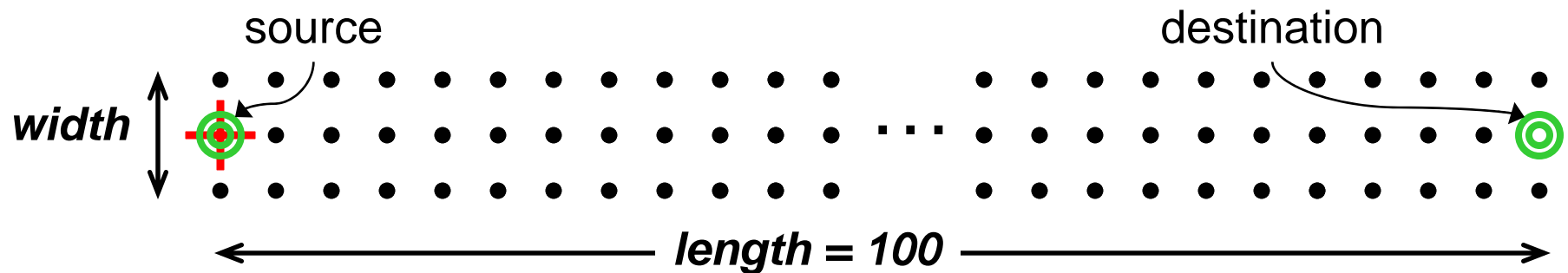
System Description

- **Objective:** evaluate static and dynamic clustering
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System Description

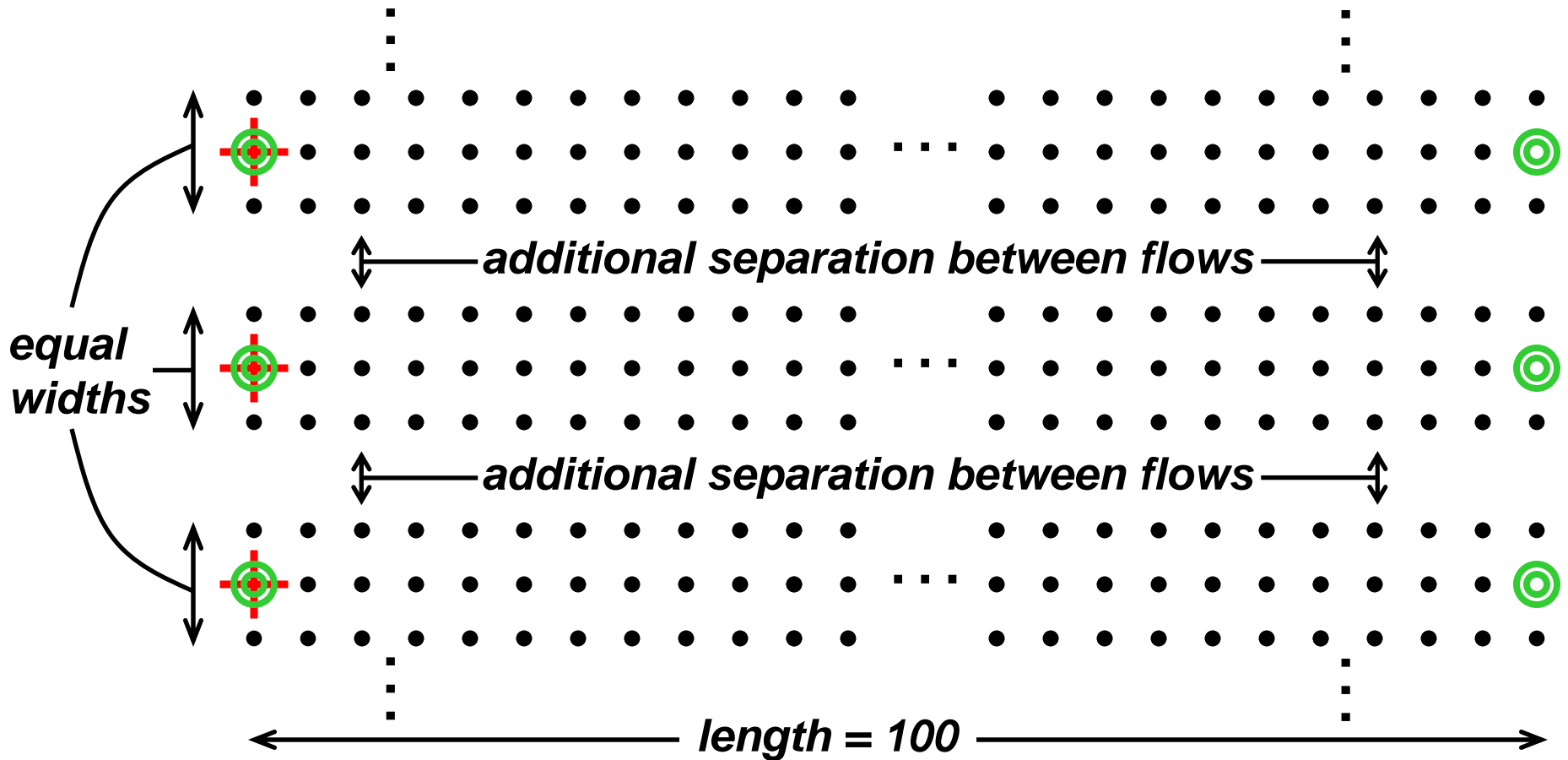
- **Objective:** evaluate static and dynamic clustering
- **Unique Tool:** large-network simulator with bit-level physical layer implementation
 - Topology: strip network for single flows



- Properties
 - Mathematical tractability
 - Independence from routing protocols
 - Extendibility to certain multiple flow settings

System Description

- Multiple flows: grid formed by stacking strips



Constraints and Performance

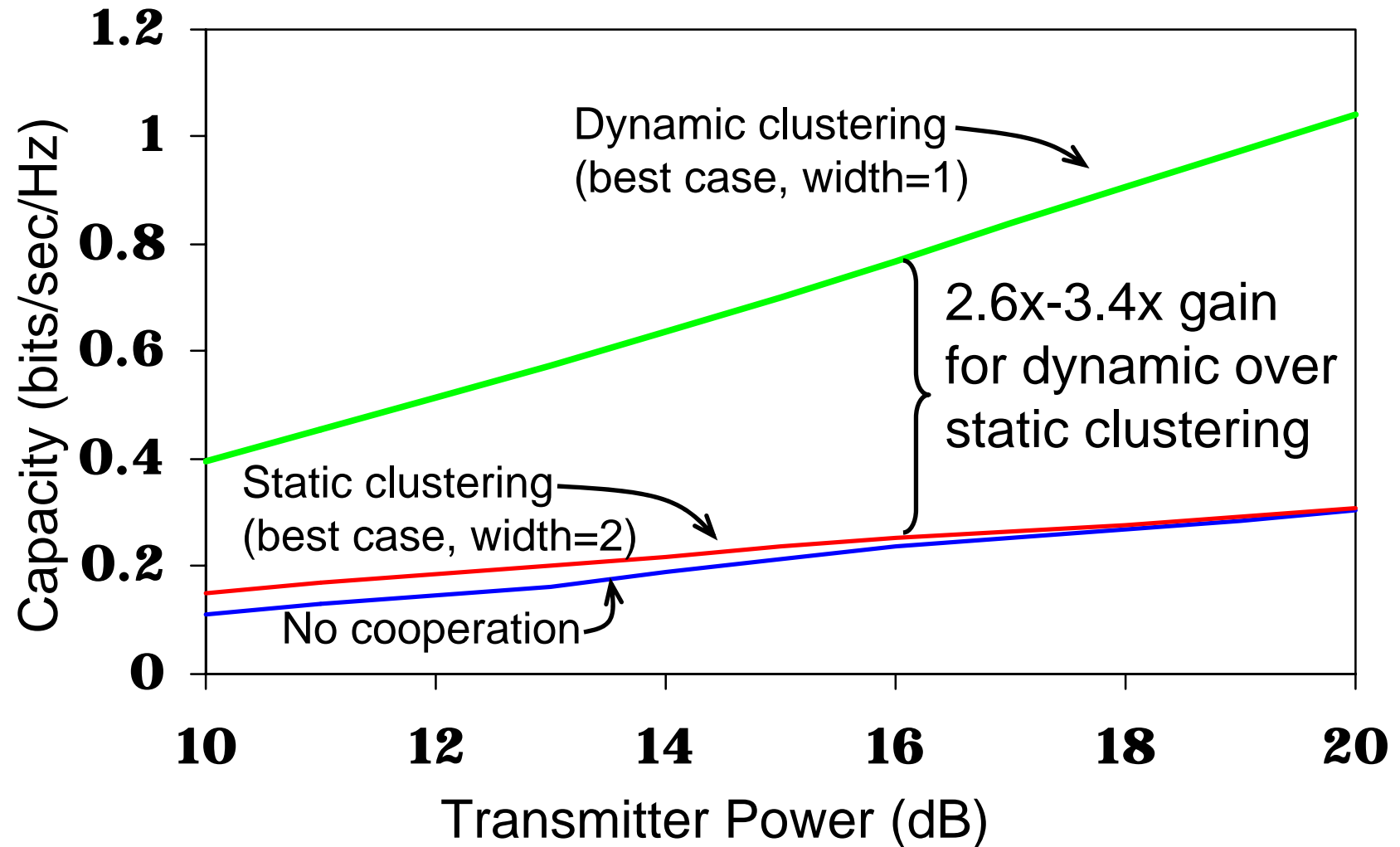
- Constraints
 - Packet size
 - Peak power (same for every node in the network)

- Performance metric: **network capacity**, or maximum throughput between source and destination under power constraint
 - Variables:
 - Packet injection rate at the source
 - Transmission time per node per packet
 - Normalize capacity by network resources used
 - Single-flow: divide by strip width
 - Multi-flow: divide by strip width + additional separation

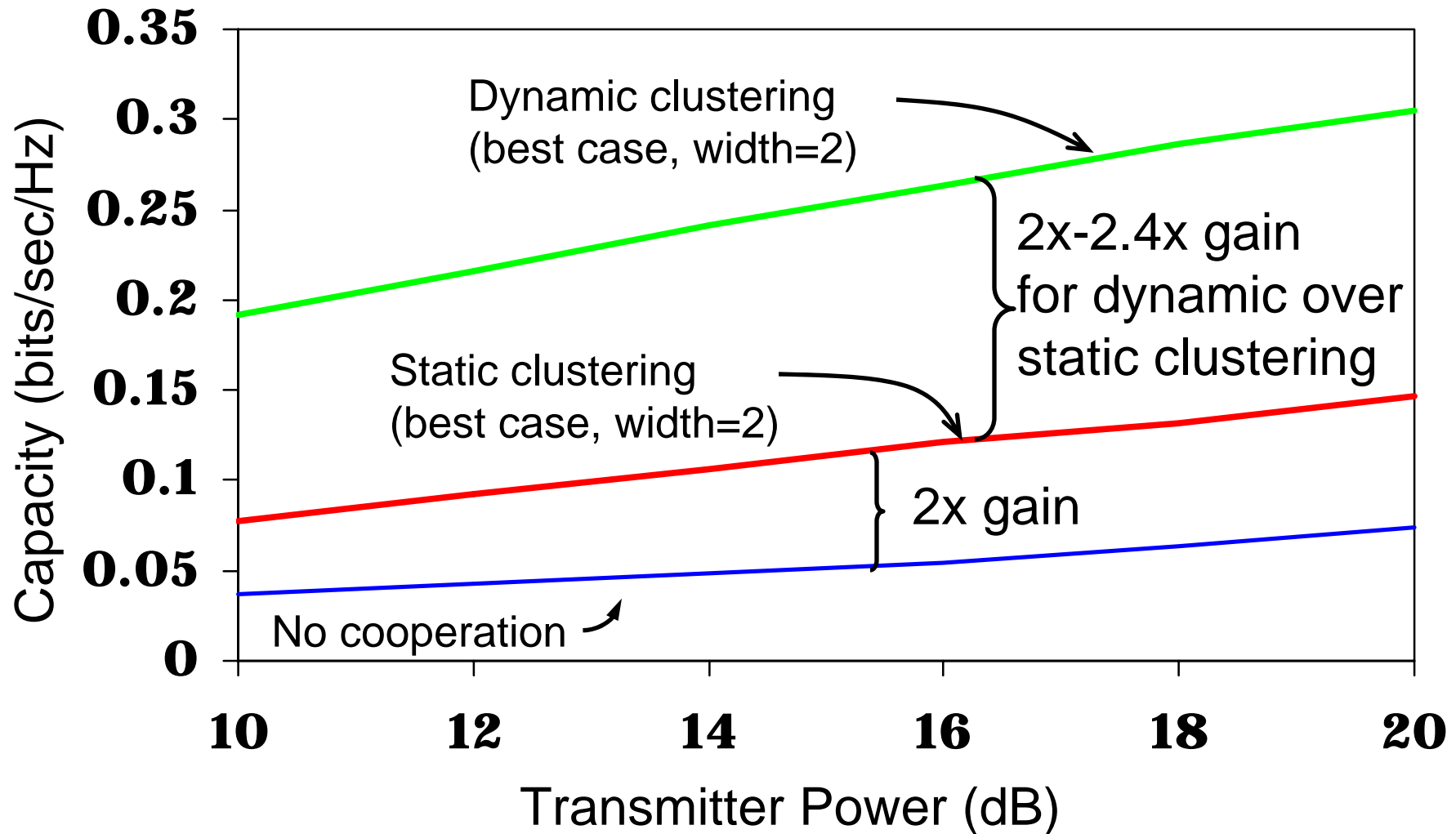
Outline

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Single flow network



Multiple flow network



Conclusions

- Dynamic clustering outperforms static in both single-flow and multi-flow cooperative networks
- Bit level simulations are comprehensive but computationally costly
 - Have analytical models that approximate (see tech report)
- Future work: adapting to changing network and workload conditions

Thank you!