Improving Delay in a Multi-hop Wireless Network with Receiver Diversity

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Joint Work with: Parul Gupta, M. Naghshvar, and H. Zhuang

(Acknowledgment: D. Teneketzis, C. Lott)

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single tx-type, single commodity, with orthogonal channels

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- Node i's tx successfully rcved and acked by subset S of neighbors with probability $P(S|i)$ independent of other tx (orthogonal tx)

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Objective:

Deliver the packets to the destination with small expected delay

- (per packet) delay ≡ interval between arrival time to delivery time

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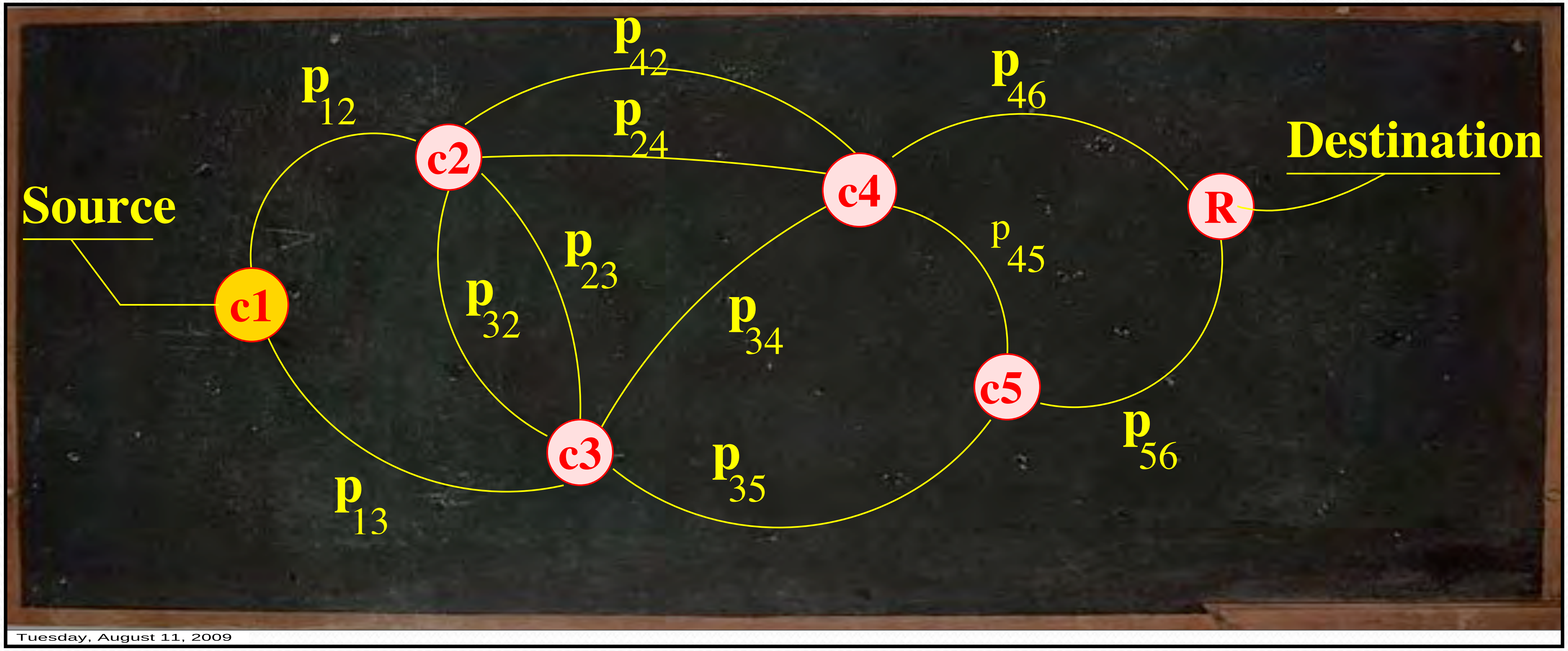

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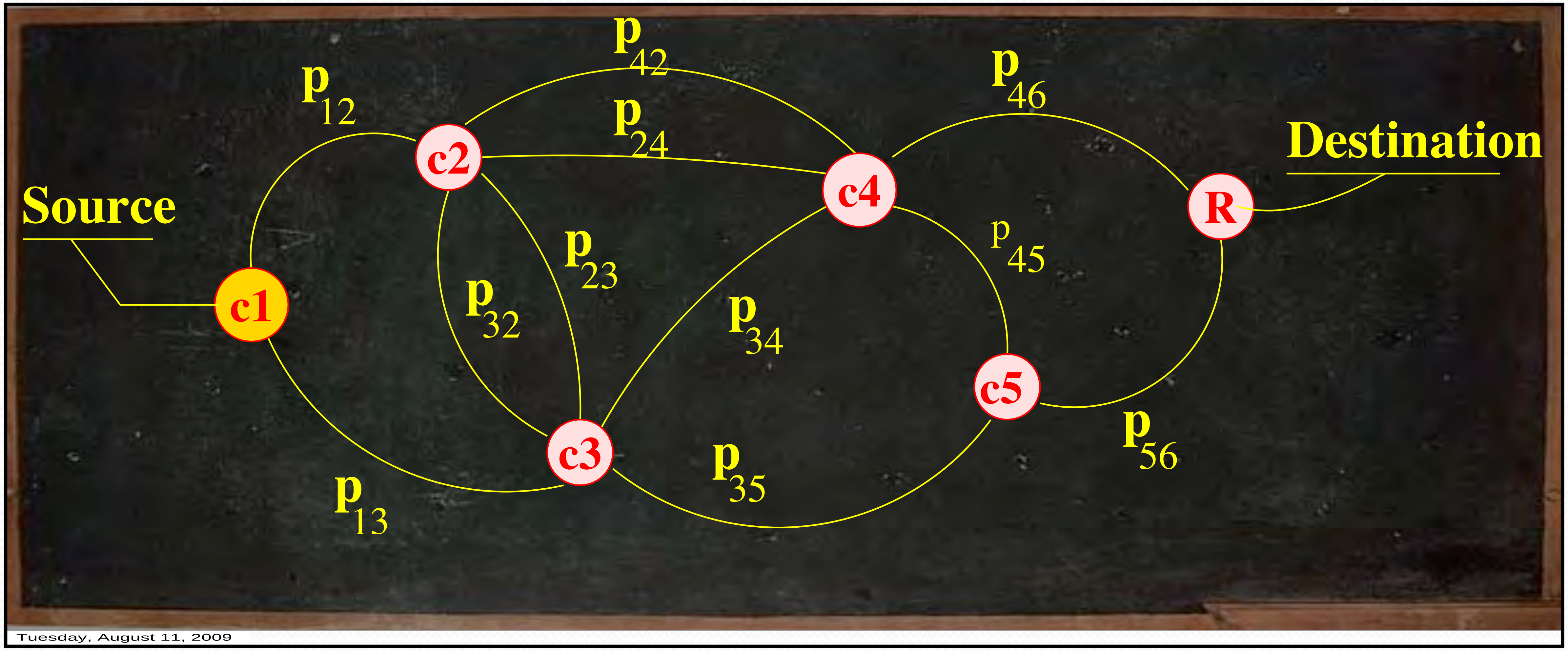

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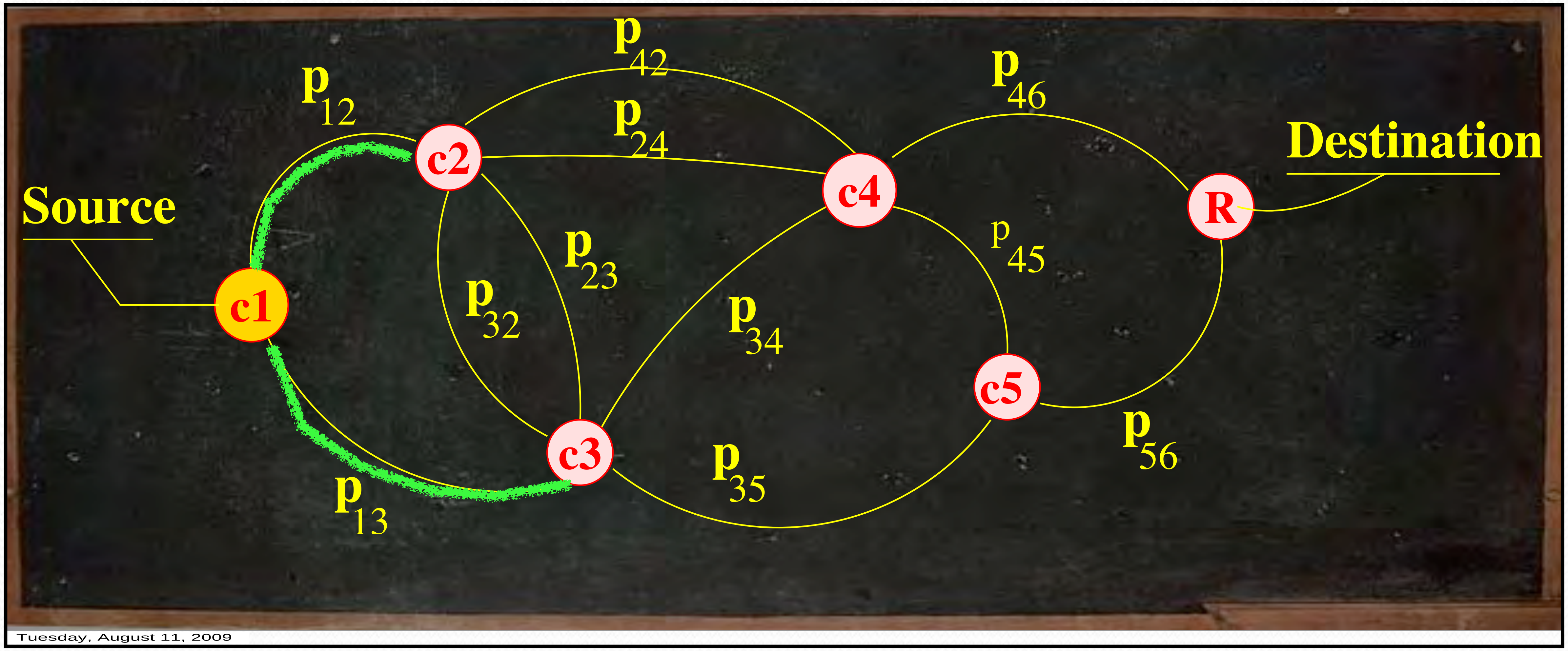

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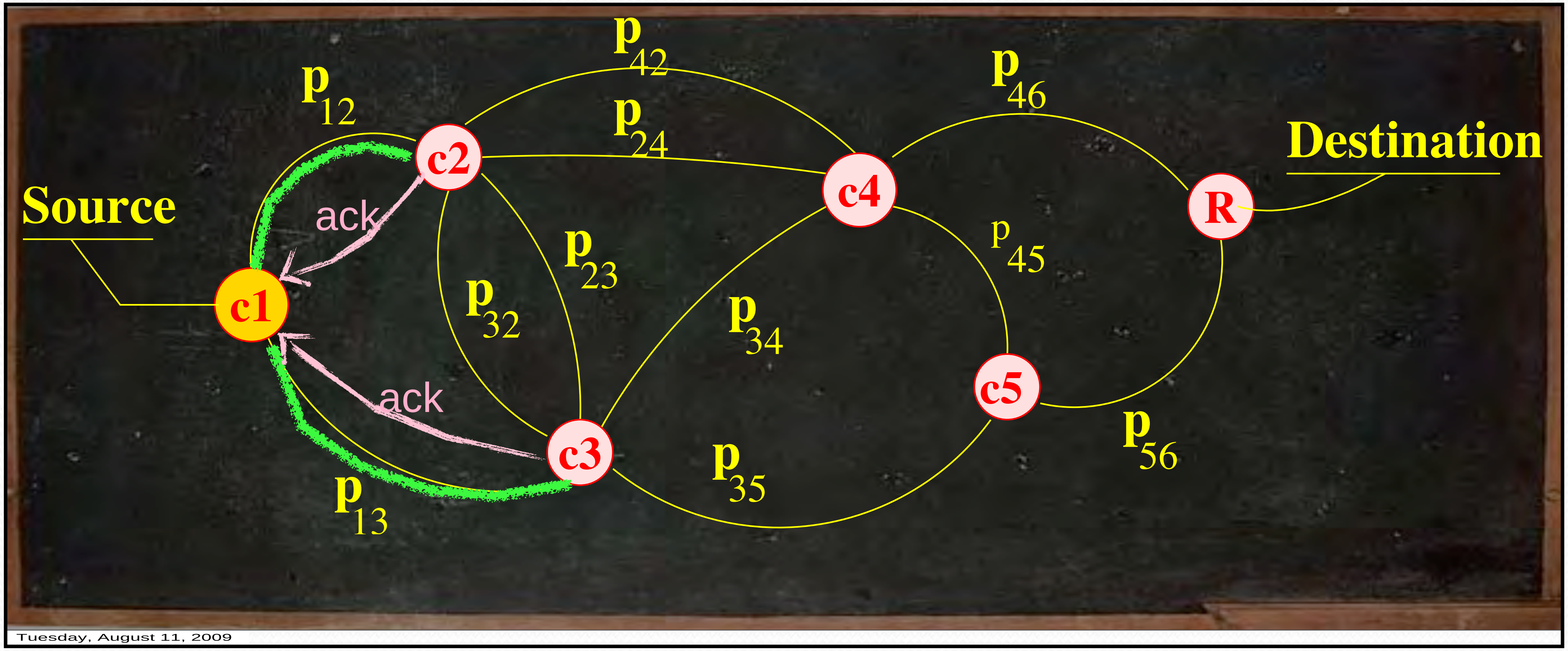

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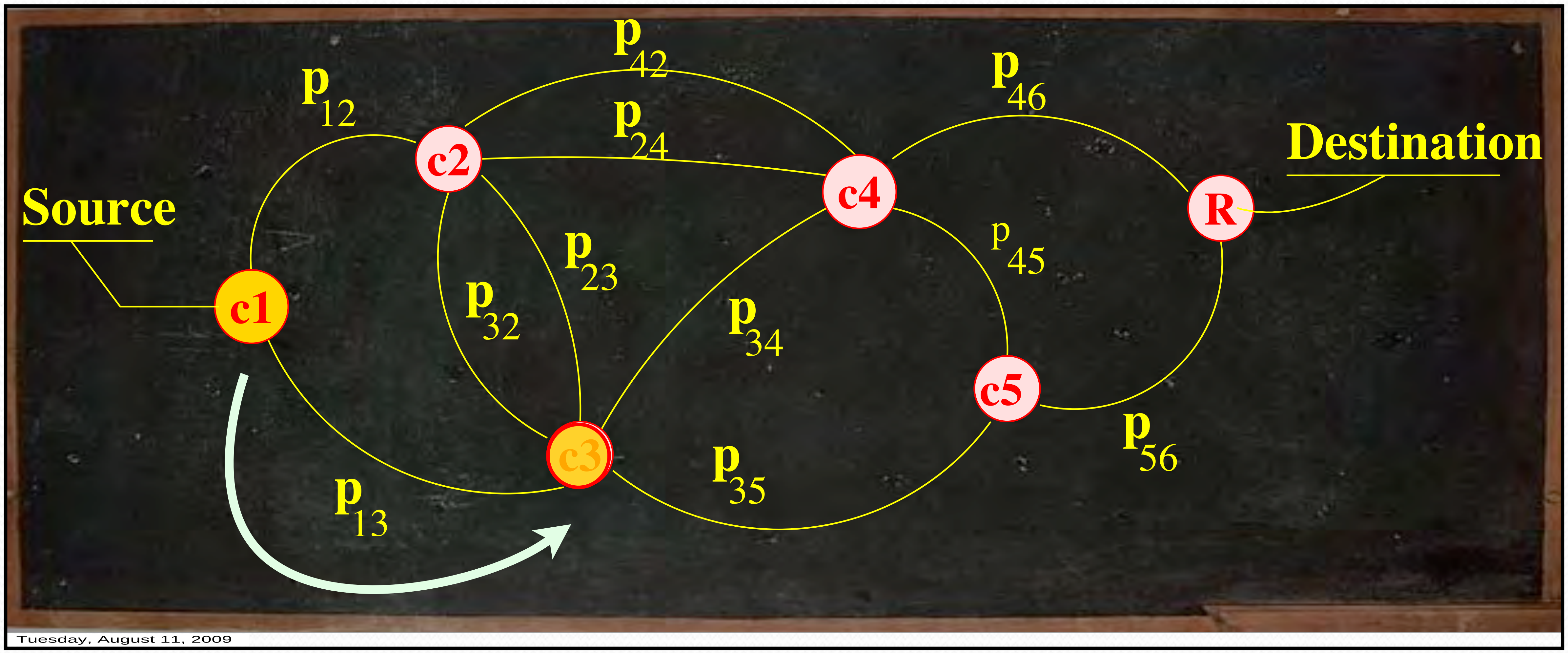

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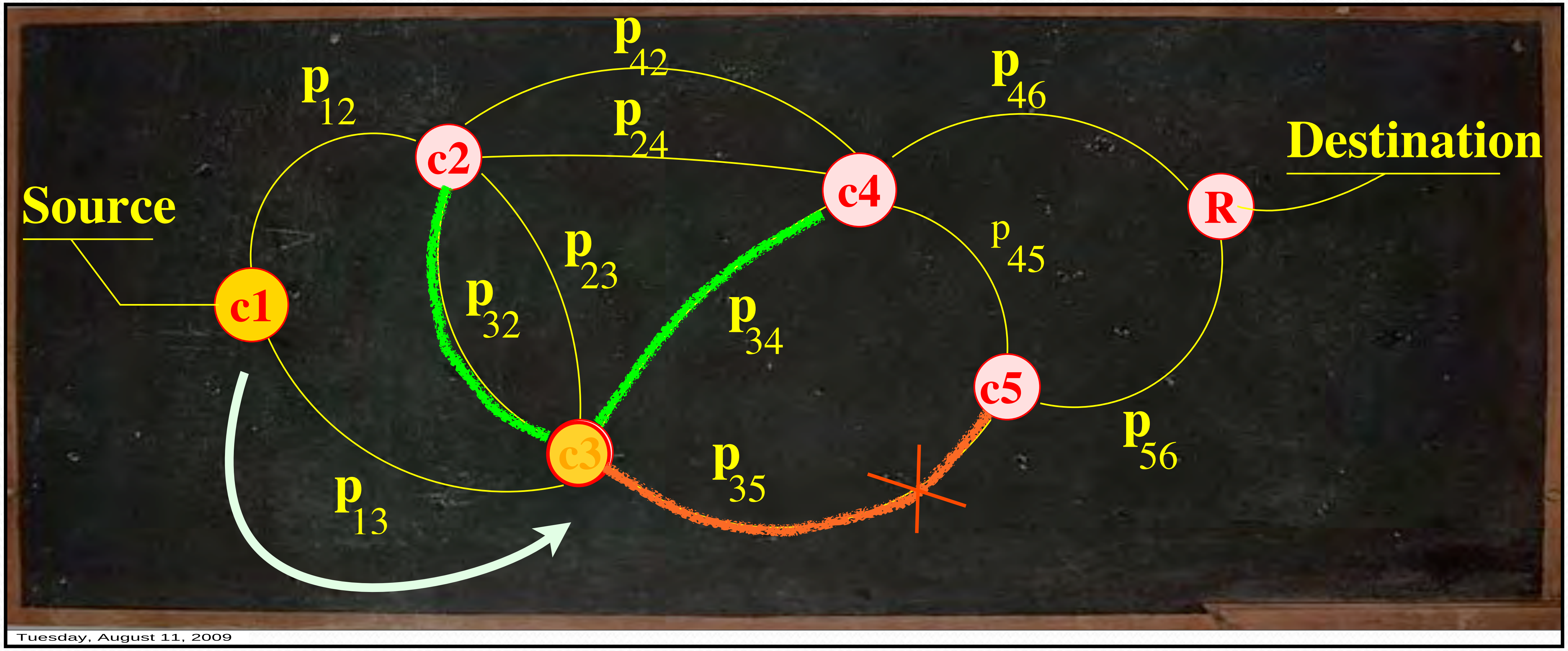

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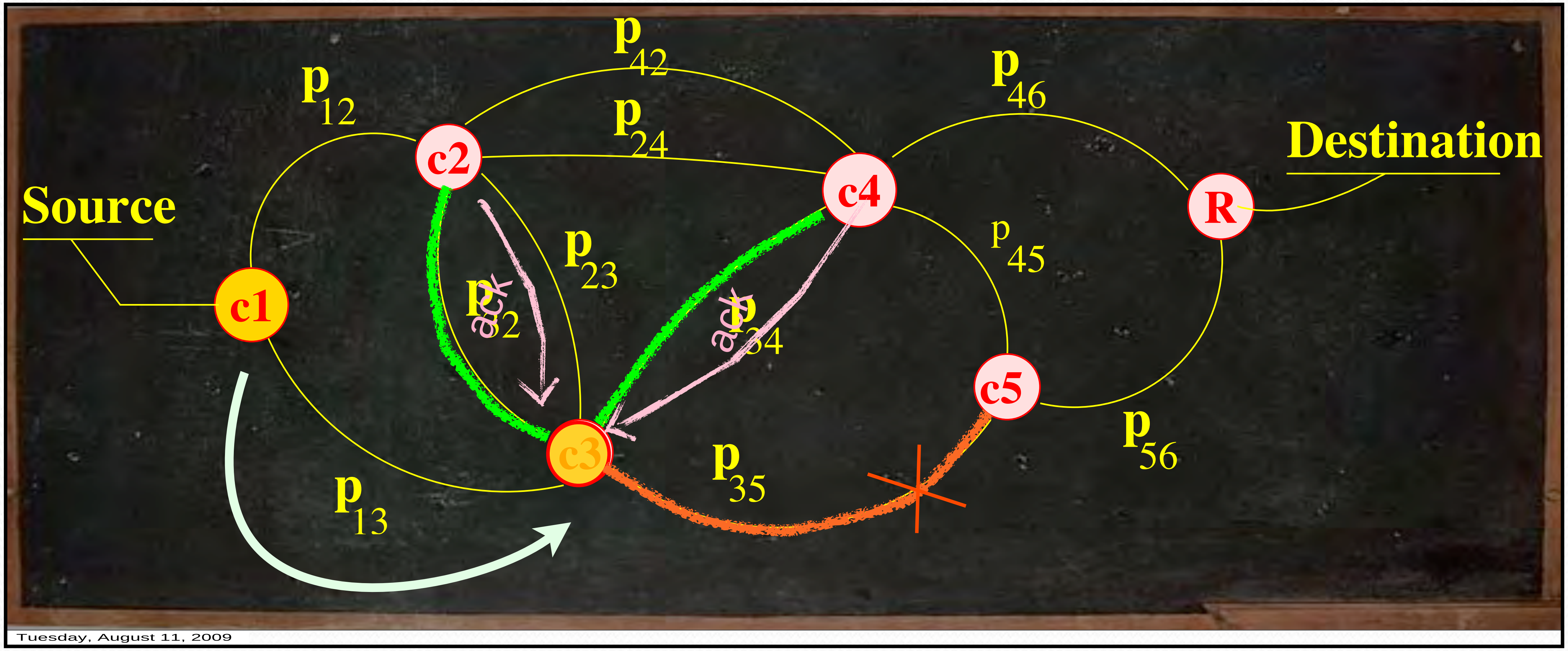

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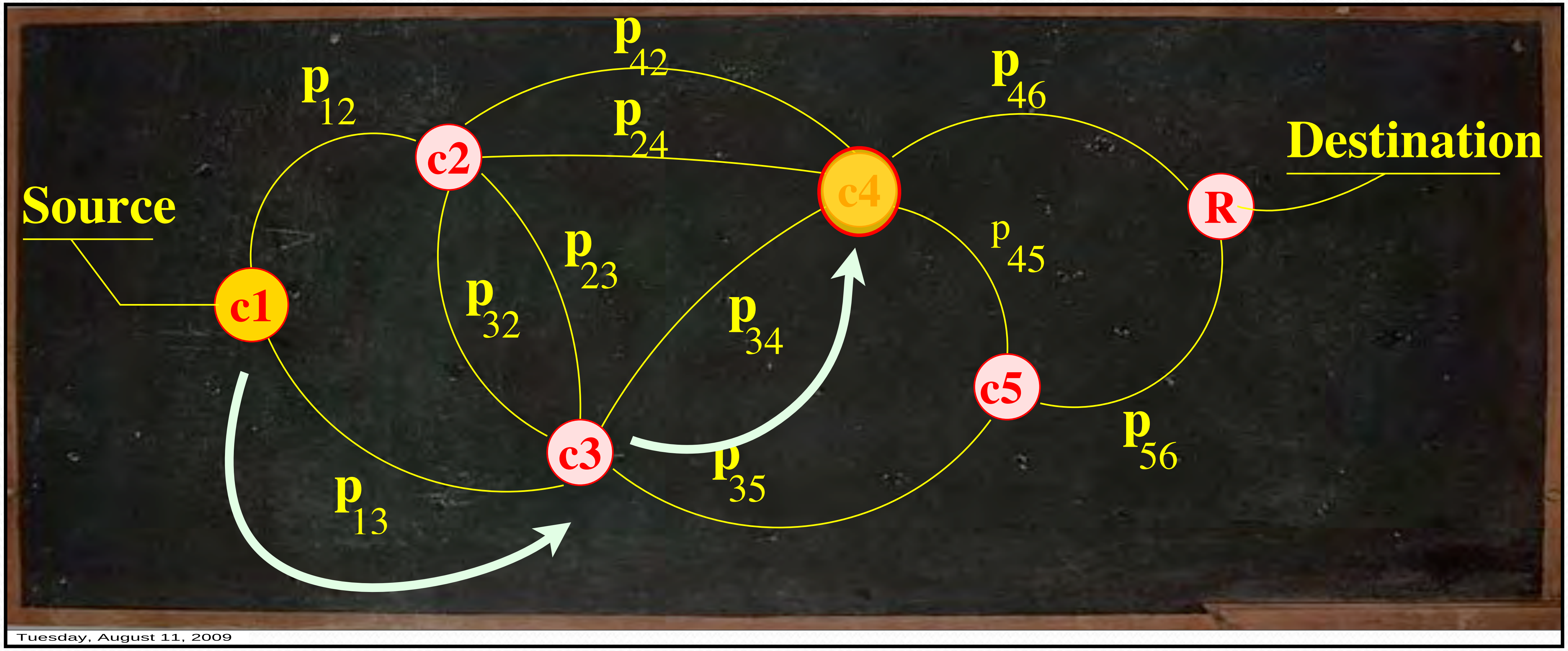

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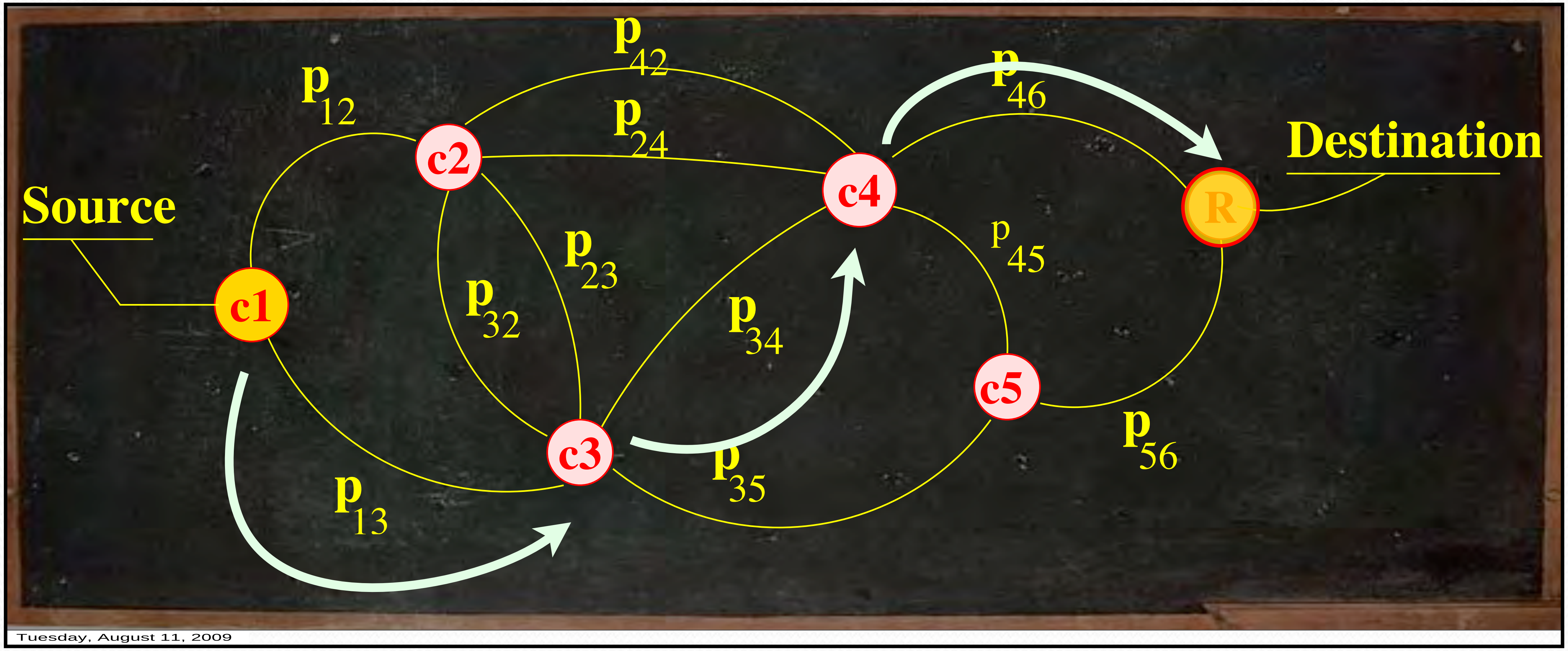

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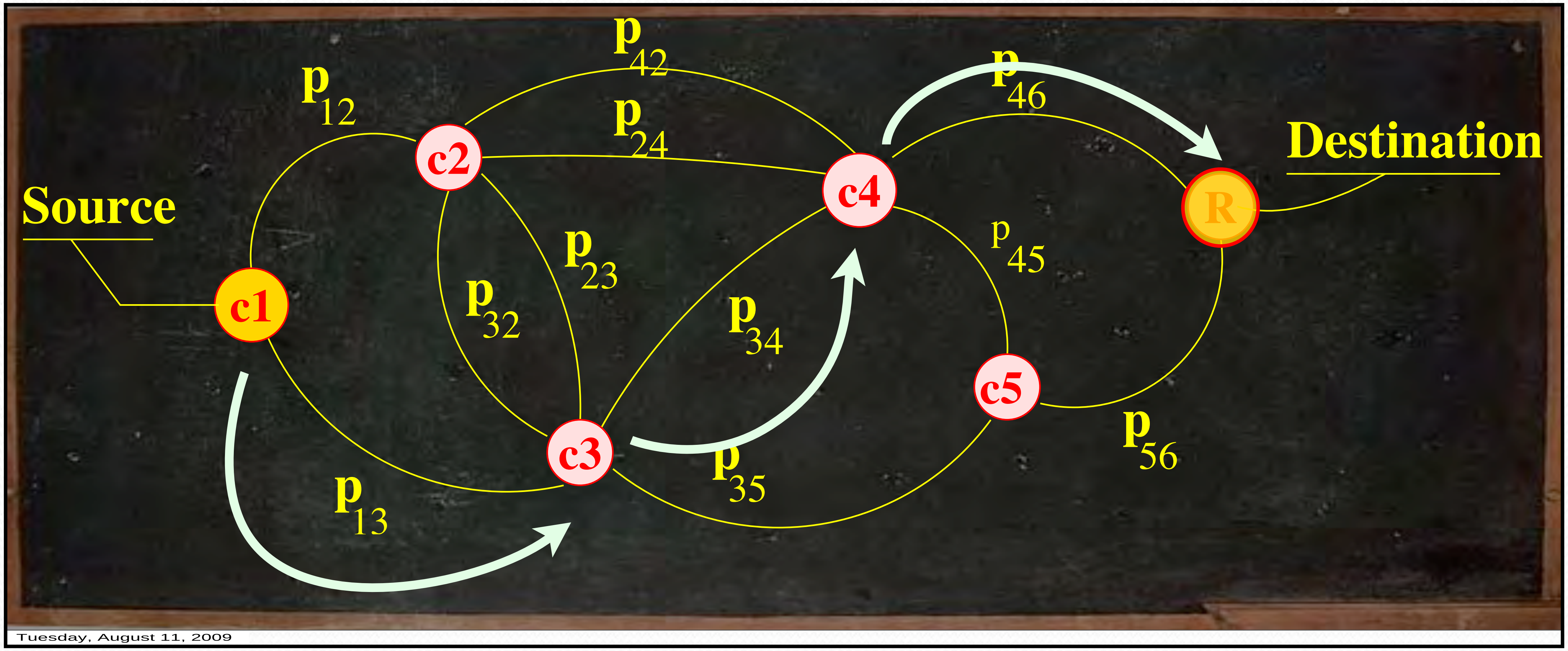

Monday, May 17, 2010

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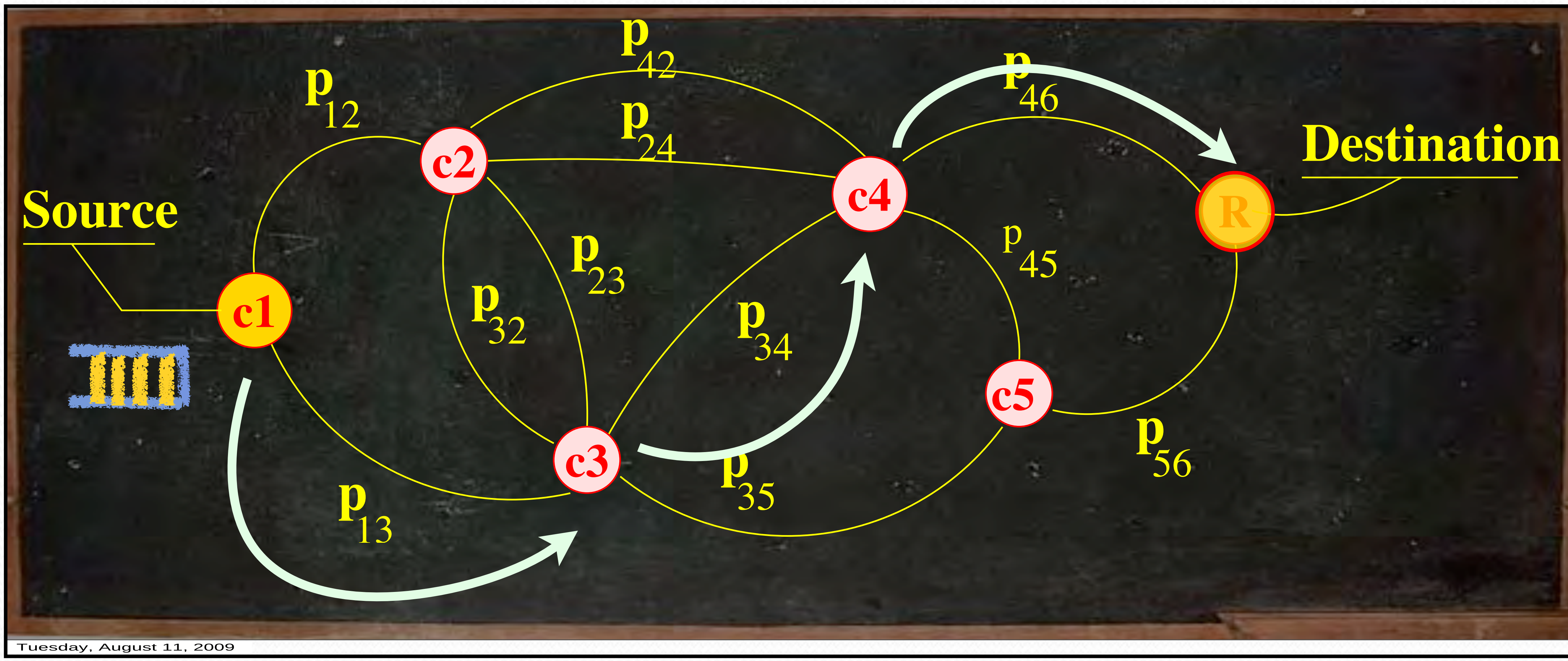

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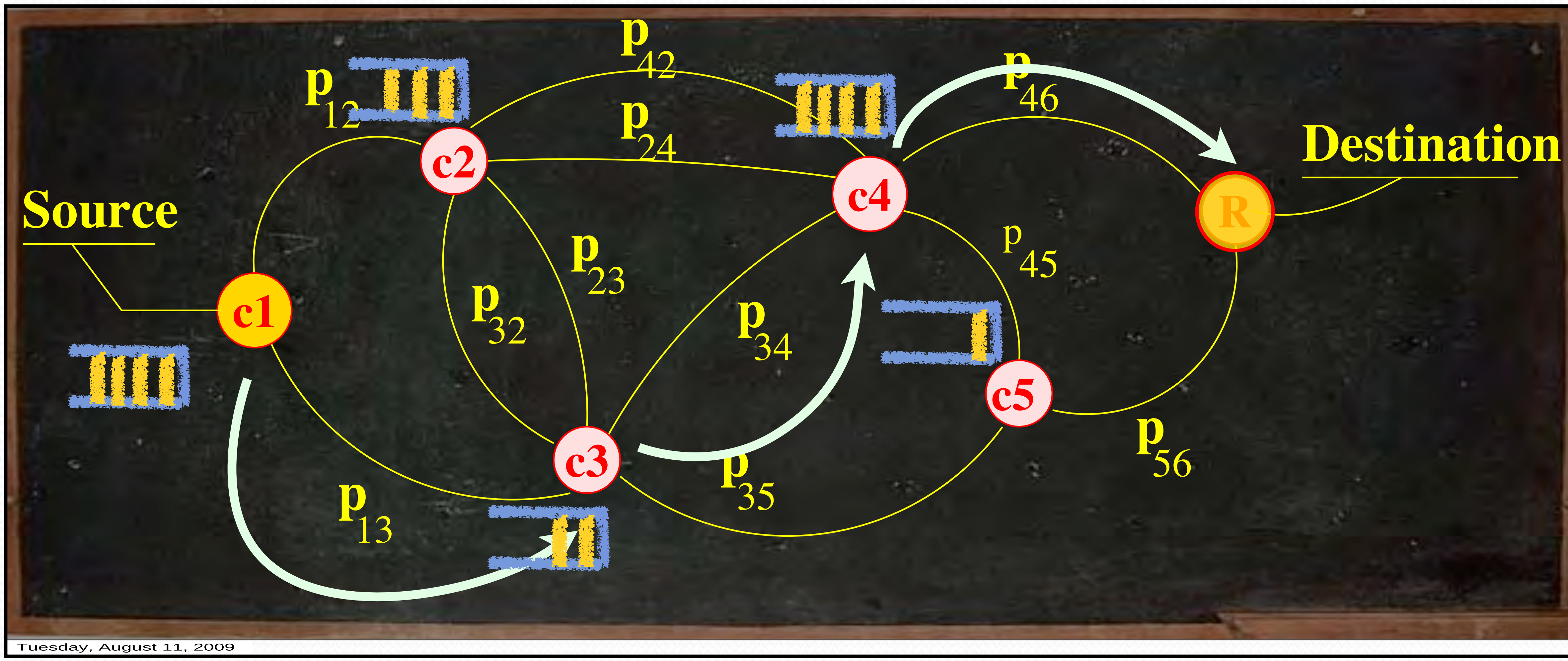

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e.g. rank ordering based on the sum of ETX and backlog

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  - Modifications of ORCD with lower overhead
  - Performance evaluation using simulations

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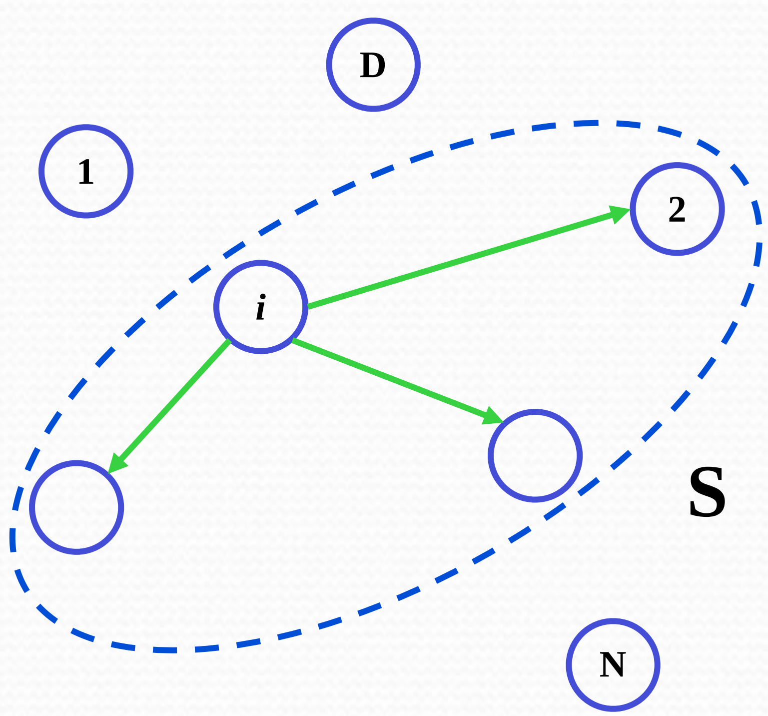

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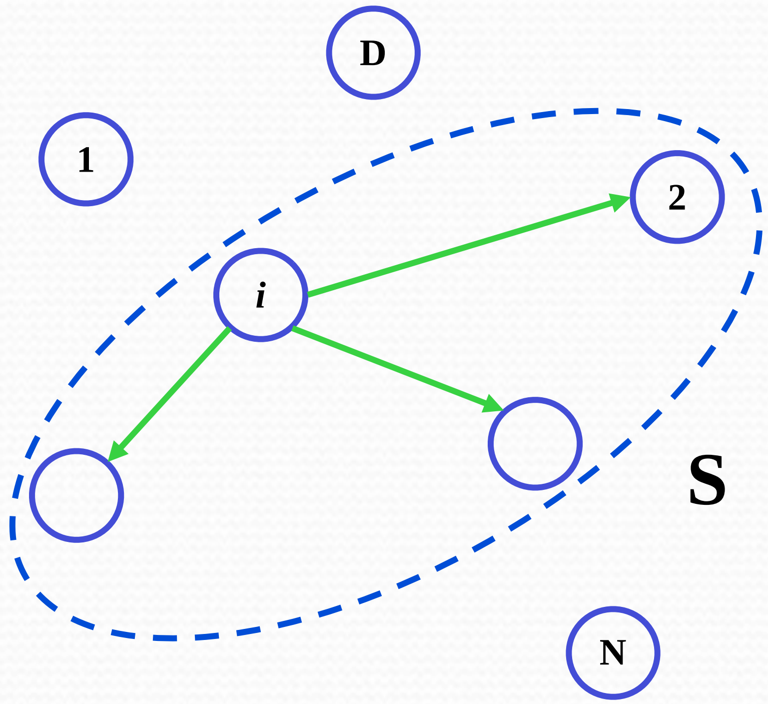

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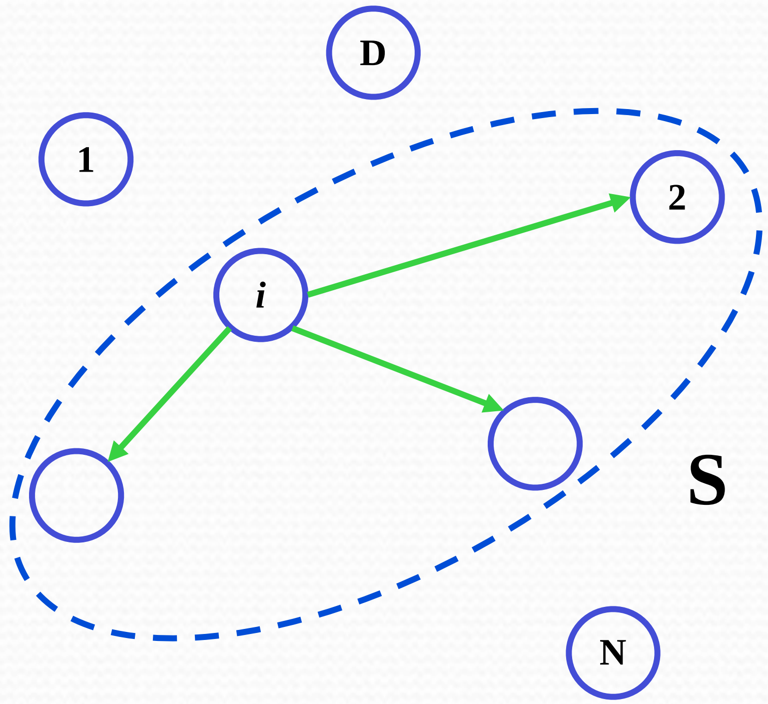

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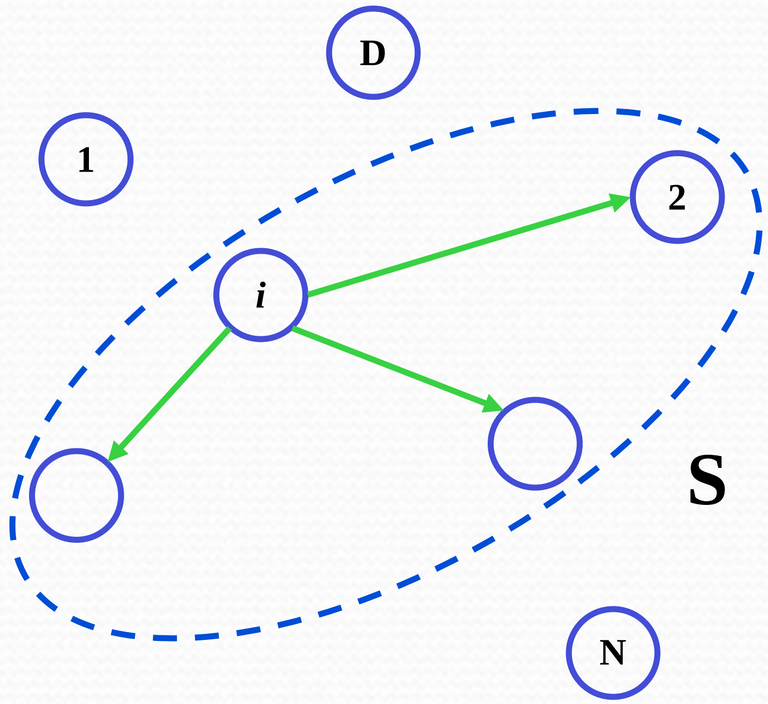

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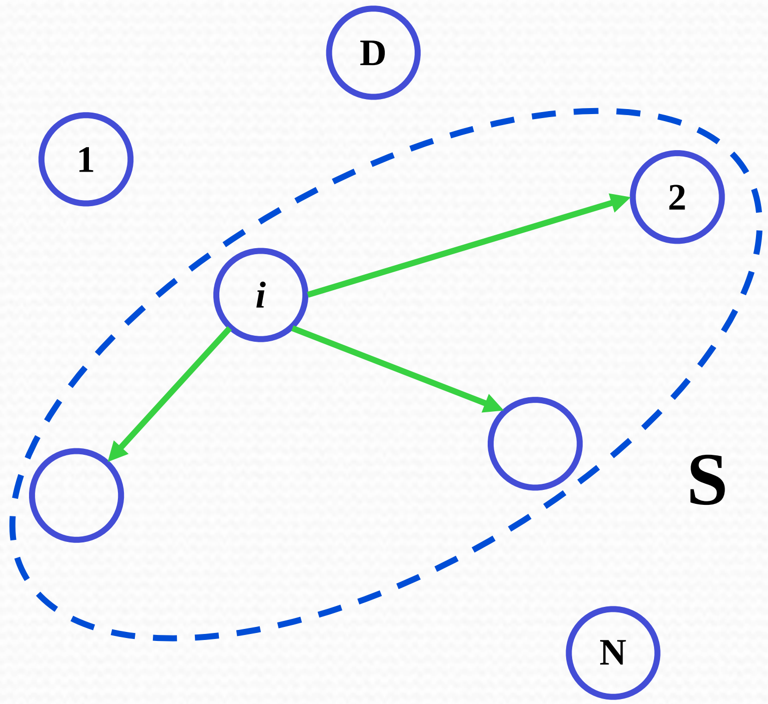
- $P(\mathrm{S}|i)$: probability that **S** be the set of nodes that receive the packet transmitted by node i
- $V_j(t)$: delivery time of node j
- $\min_{j \in S} V_j(t)$: delivery time when **S** reached



Computation of $V_i(t)$'s

Congestion measures $V_i(t)$ are solutions to the following fixed point equation:

$$\begin{cases} V_D(t) = 0, \\ V_i(t) = \mathrm{Q}_i(t) + \sum_{\mathrm{S} \subseteq \Omega} P(\mathrm{S} \mid i) \min_{j \in \mathrm{S}} V_j(t) \end{cases}$$

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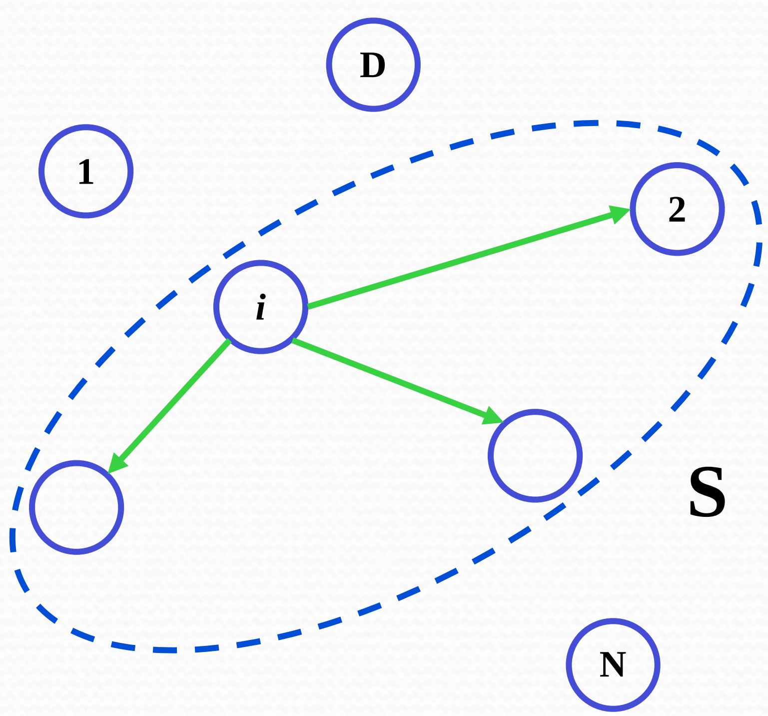

Computation of $V_i(t)$'s

Congestion measures $V_i(t)$ are solutions to the following fixed point equation:

$$\begin{cases} V_D(t) = 0, \\ V_i(t) = \underbrace{Q_i(t)}_{\text{Local congestion at node } i} + \underbrace{\sum_{S \subseteq \Omega} P(S \mid i) \min_{j \in S} V_j(t)}_{\text{average delivery time of the neighbors}} \end{cases}$$

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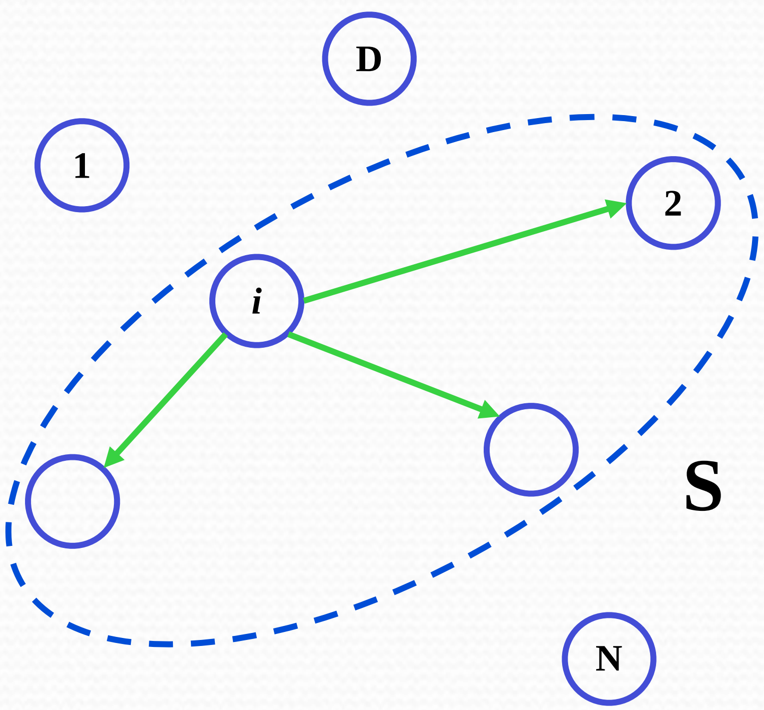

Computation of $V_i(t)$'s (Cont.)

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Centralized Computation:

Computation of $V_i(t)$'s (Cont.)

Centralized Computation:

Stochastic generalization of Dijkstra algorithm

Computation of $V_i(t)$'s (Cont.)

Centralized Computation:

Stochastic generalization of Dijkstra algorithm

1. Initialization:

$$V_{\mathrm{D}}(t) = 0, V_i(t) = \infty \text{ for all } i \in \Omega, i \neq \mathrm{D}$$

$$A = \{\mathrm{D}\},\ A^c \text{ is the complement of } A \text{ with respect to } \Omega.$$

2. Computation:

$$J_i(t) = \frac{1}{P(i,A)}\left[\mathrm{Q}_i(t) + \sum_{S:S\cap A\neq\phi} P(S\,|\,i)\min_{j\in S\cap A} V_j(t)\right], \qquad i \in A^c,$$

where, $P(i,A) = \sum_{S:S\cap A\neq\phi} P(S\,|\,i).$

3. Updtae:

$$i^* = \arg\min_{i\in A^c} J_i(t),\ V_{i*}(t) = J_{i*}(t),\ A = A \cup \{i^*\}.$$

4. Repeat steps 2 and 3 until $A=\Omega$

Computation of $V_i(t)$'s (Cont.)

Centralized Computation:

Stochastic generalization of Dijkstra algorithm

- Centralized controller is responsible for:
  - Collecting backlog information of all nodes in the network
  - Computing congestion measures $V_i(t)$ (worst-case run time $O(N^2)$)
  - Providing all nodes with the results of the computations

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It is not practical to compute $V_i(t)$ on every time slot.

Computation of $V_i(t)$'s (Cont.)

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- ORCD with infrequent computations (**Infreq-ORCD**)
  - Computation of congestion measures V_i is done every T slots
  - Routing decisions at time $nT \le t < (n+1)T$ are based on $V_i(nT)$

Computation of $V_i(t)$'s (Cont.)

- ORCD with infrequent computations (**Infreq-ORCD**)
  - Computation of congestion measures V_i is done every T slots
  - Routing decisions at time $nT \leq t < (n+1)T$ are based on $V_i(nT)$

- For sufficiently large T, the centralized controller has enough time to collect information and flood its decisions to the nodes in the network
- As expected, this lower overhead sacrifices the performance of ORCD

Computation of $V_i(t)$'s (Cont.)

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Iterative and Decentralized Computation:

Computation of $V_i(t)$'s (Cont.)

Iterative and Decentralized Computation:

Stochastic generalization of distributed Bellman-Ford algorithm

Computation of $V_i(t)$'s (Cont.)

Iterative and Decentralized Computation:

Stochastic generalization of distributed Bellman-Ford algorithm

$$\widetilde{V}_i^{\,k}(t) = \mathrm{Q}_i(t) + \sum_{S \subseteq \Omega} P(S \mid i) \min_{j \in S} \widetilde{V}_j^{\,k-1}(t), \quad \text{for } k = 1, 2, \ldots$$

Computation of $V_i(t)$'s (Cont.)

Iterative and Decentralized Computation:

Stochastic generalization of distributed Bellman-Ford algorithm

$$\tilde{V}_i^k(t) = Q_i(t) + \sum_{S \subseteq \Omega} P(S \mid i) \min_{j \in S} \tilde{V}_j^{k-1}(t), \quad \text{for } k = 1, 2, \ldots$$

- In each iteration k, all nodes are responsible for:
  - Exchanging $\tilde{V}_i^{k-1}(t)$ with their neighbors
  - Computing $\tilde{V}_i^k(t)$ using equation above

Computation of $V_i(t)$'s (Cont.)

Iterative and Decentralized Computation:

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Computation of $V_i(t)$'s (Cont.)

Iterative and Decentralized Computation:

Stochastic generalization of distributed Bellman-Ford algorithm

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High overhead for each time slot *t*

Computation of $V_i(t)$'s (Cont.)

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Stochastic generalization of distributed Bellman-Ford algorithm

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High overhead for each time slot *t*

It is not practical to compute $V_i(t)$ using this algorithm.

Computation of $V_i(t)$'s (Cont.)

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- Iterative ORCD with finite-round computations
  - Number of iterations is limited to some K rounds :

$$\tilde{V}_i^k(t) = \mathrm{Q}_i(t) + \sum_{S \subseteq \Omega} P(S \mid i) \min_{j \in S} \tilde{V}_j^{k-1}(t), \quad \text{for} \quad 1 \le k \le \mathrm{K},$$

$$\tilde{V}_i^0(t) = \tilde{V}_i^{\mathrm{K}}(t-1).$$

Computation of $V_i(t)$'s (Cont.)

- Iterative ORCD with finite-round computations
  - Number of iterations is limited to some K rounds :

$$\widetilde{V}_i^k(t) = \mathrm{Q}_i(t) + \sum_{S \subseteq \Omega} P(S \mid i) \min_{j \in S} \widetilde{V}_j^{k-1}(t), \quad \text{for} \quad 1 \le k \le \mathrm{K},$$

$$\widetilde{V}_i^0(t) = \widetilde{V}_i^{\mathrm{K}}(t-1).$$

- Distributed ORCD (**D-ORCD**)
  - Special case when K=1:

$$\widetilde{V}_i(t) = \mathrm{Q}_i(t) + \sum_{S \subseteq \Omega} P(S \mid i) \min_{j \in S} \widetilde{V}_j(t-1).$$

Simulations

Simulations

- Comparing the delay performance of:
  - **ExOR**, **SR** (expected hop-counts to the destination)
  - **DIVBAR** (queue backlog)
  - **E-DIVBAR** (queue backlog + expected hop-counts)
  - **ORCD**, **Infreq-ORCD**, and **D-ORCD** (expected delivery time)

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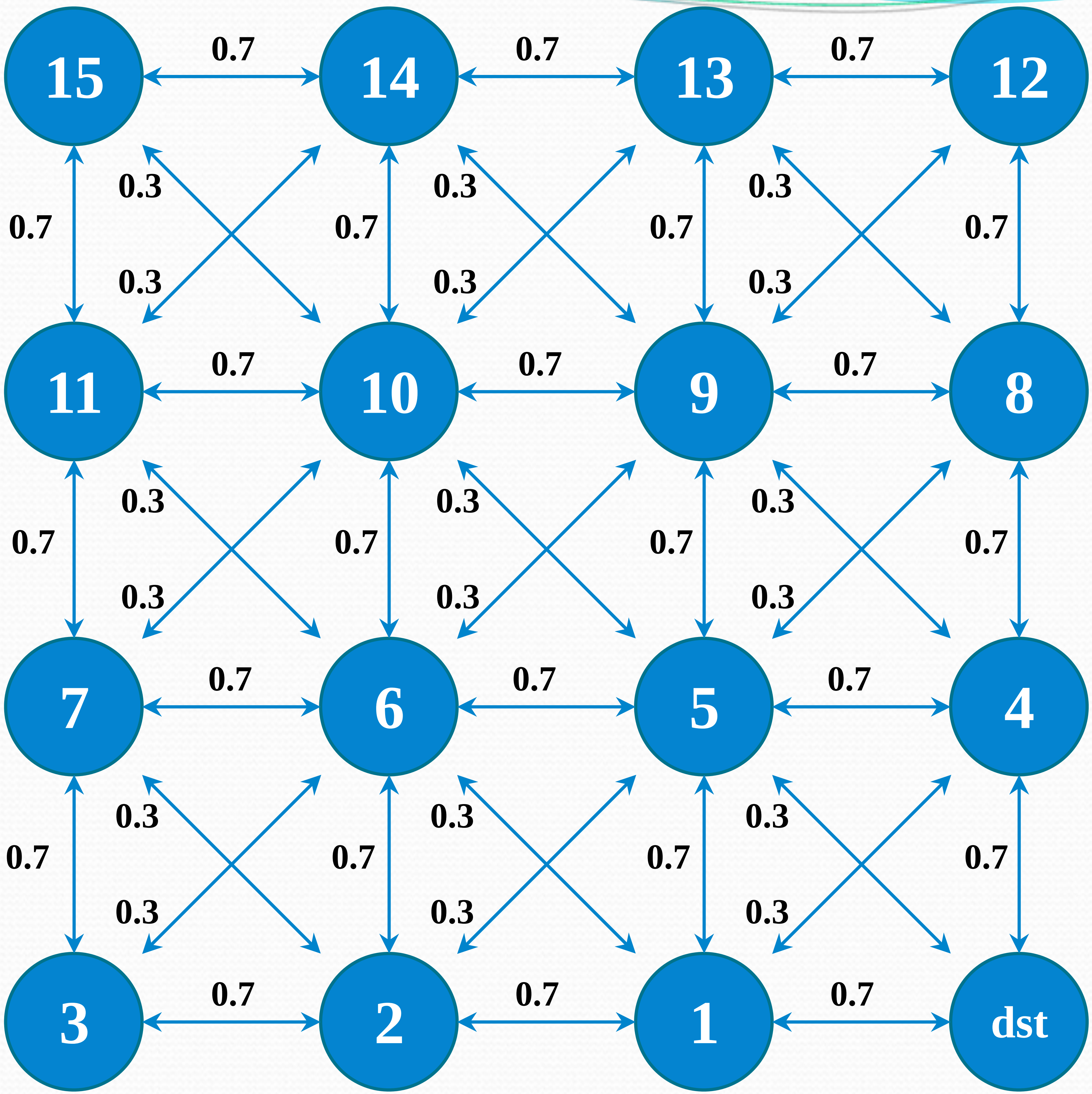
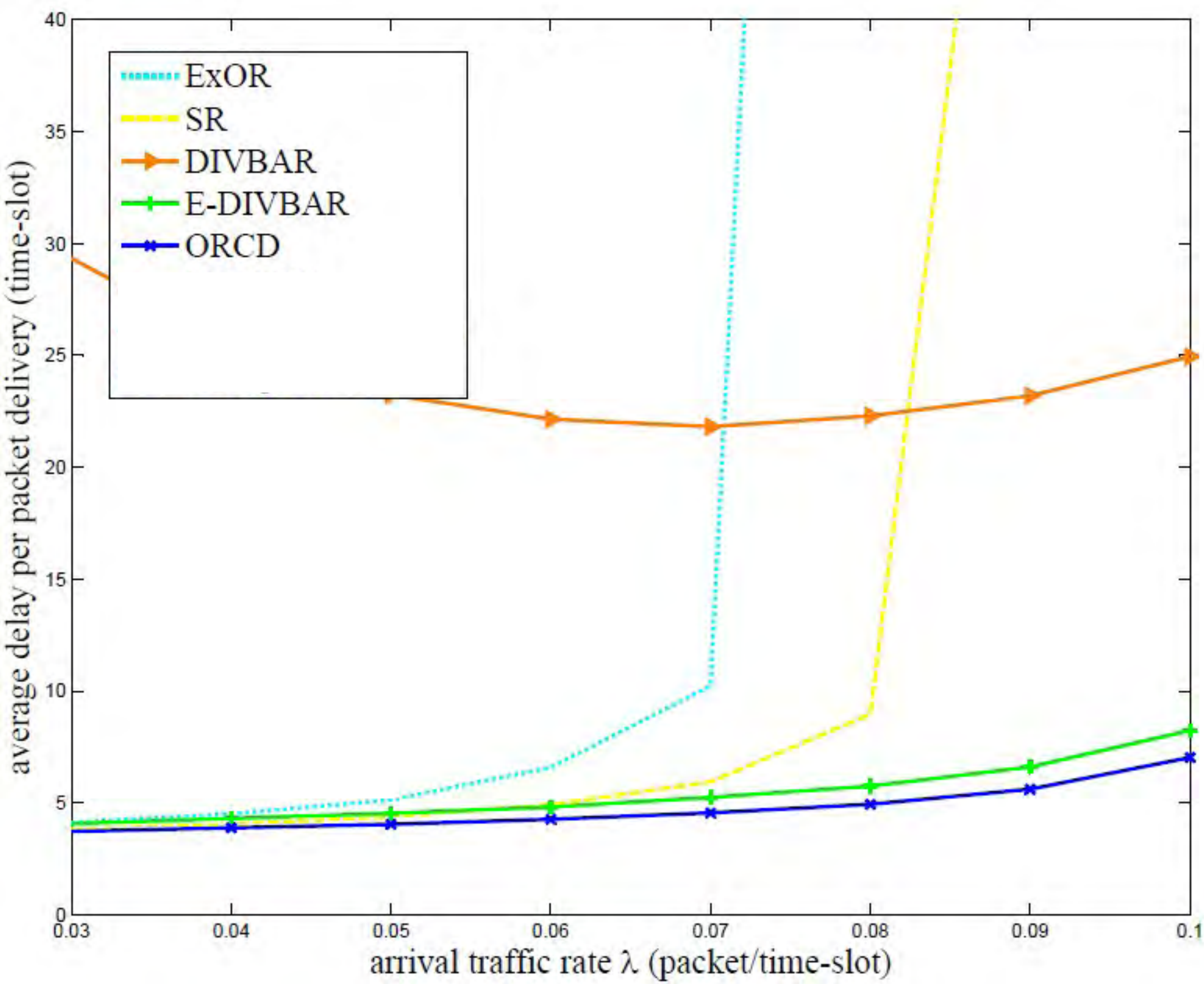
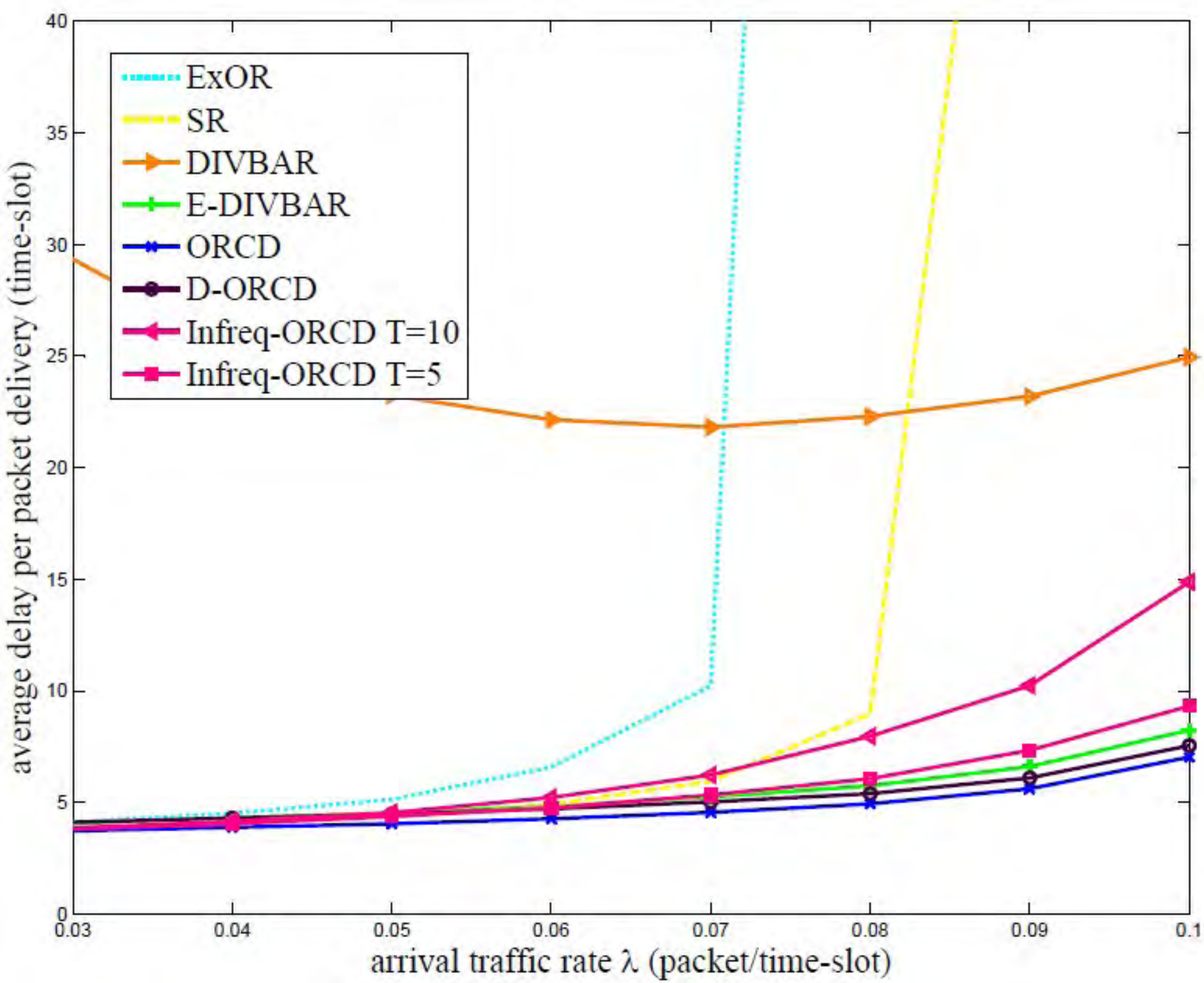
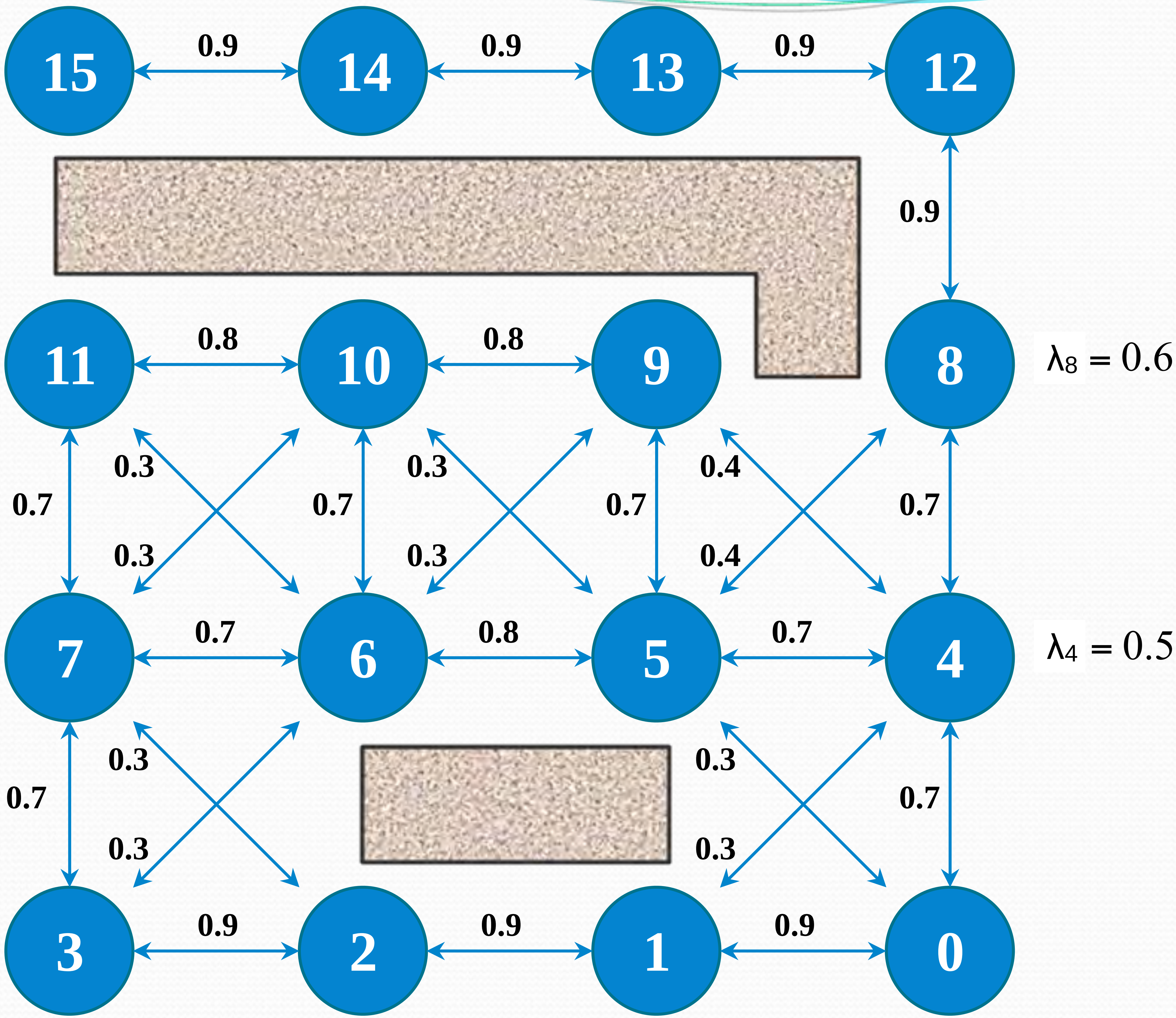
  - **ORCD**, **Infreq-ORCD**, and **D-ORCD** (expected delivery time)

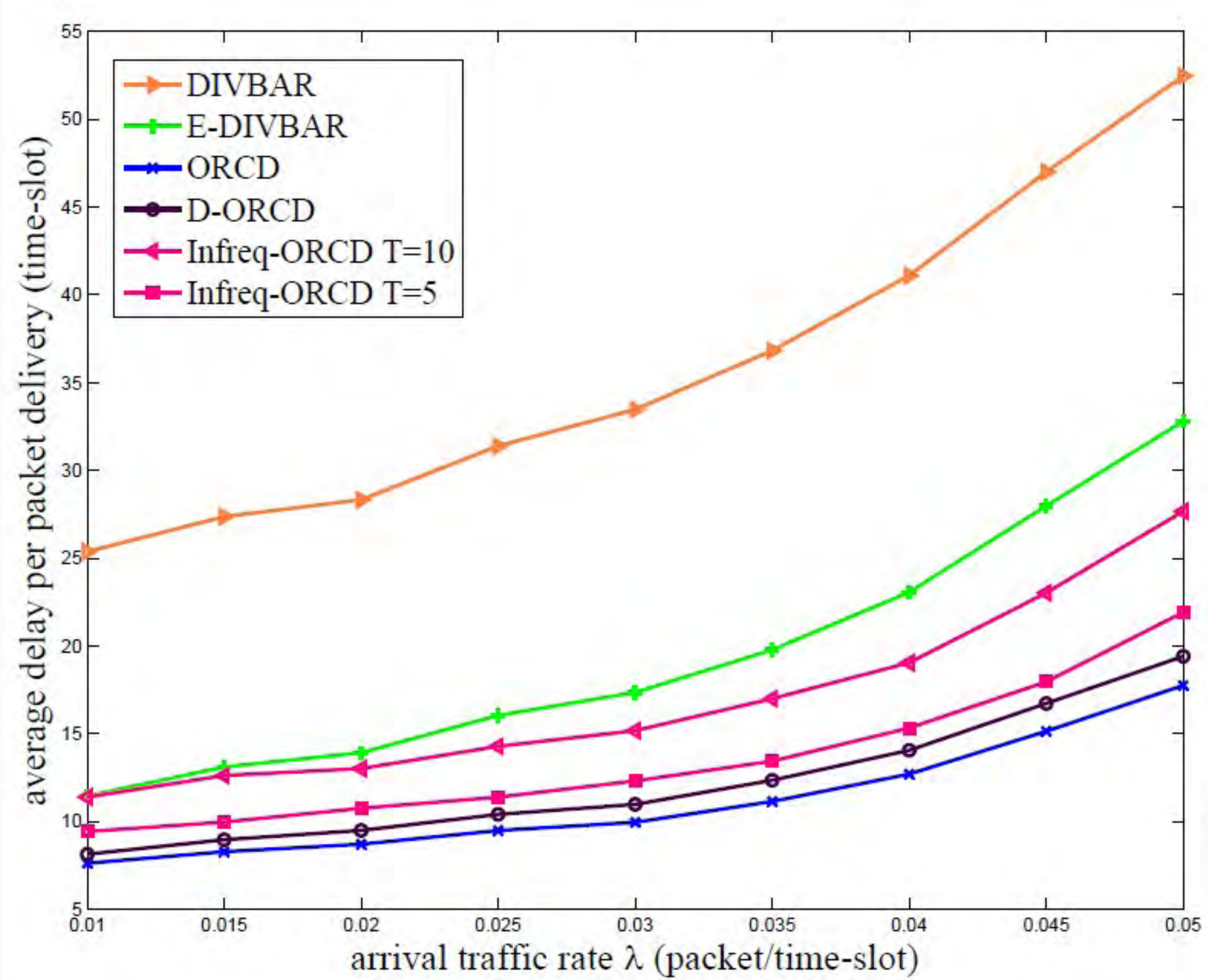
Routing Policy	Throughput Optimal	Delay Performance
ExOR, SR	✘	Poor delay in high traffic
DIVBAR	✓	Poor delay in low traffic
E-DIVBAR	✓	?
ORCD & its variants	✓	?


15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
dst
0.7
0.3


ExOR
SR
DIVBAR
E-DIVBAR
ORCD
average delay per packet delivery (time-slot)
arrival traffic rate λ (packet/time-slot)
0
5
10
15
20
25
30
35
40
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1


ExOR
SR
DIVBAR
E-DIVBAR
ORCD
D-ORCD
Infreq-ORCD T=10
Infreq-ORCD T=5
average delay per packet delivery (time-slot)
arrival traffic rate λ (packet/time-slot)
0
5
10
15
20
25
30
35
40
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1


15
14
13
12
0.9
0.9
0.9
0.9
11
10
9
8
0.8
0.8
$\lambda_8 = 0.6$
0.7
0.3
0.3
0.7
0.3
0.3
0.7
0.4
0.4
0.7
7
6
5
4
0.7
0.8
0.7
$\lambda_4 = 0.5$
0.7
0.3
0.3
0.3
0.3
0.7
3
2
1
0
0.9
0.9
0.9



DIVBAR
E-DIVBAR
ORCD
D-ORCD
Infreq-ORCD T=10
Infreq-ORCD T=5
average delay per packet delivery (time-slot)
arrival traffic rate λ (packet/time-slot)
55
50
45
40
35
30
25
20
15
10
5
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05

Summary

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Routing Policy	Throughput Optimal	Delay Performance
ExOR, SR	✘	Poor delay in high traffic
DIVBAR	✓	Poor delay in low traffic
E-DIVBAR	✓	Depends on topology & traffic
ORCD	✓	Good delay performance in all traffic conditions
Infreq-ORCD	✓	Depends on network & traffic
D-ORCD	?	Good delay performance in all traffic conditions

Future and On-going Research

- Extensions:
  - multi-rate and multi-commodity
  - Ack explosion: limiting neighbor set
- Interference: scheduled MAC vs. random access
- Multi-user detection, cooperation, fancy PHY
- Network coding