Engineering a new loop-free shortest paths routing algorithm

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Outline

1. Motivation
2. The new algorithm
3. Experimental evaluation
4. Conclusion and future research

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The problem

Distributed minimum cost paths computation

- Crucial problem in today's practical applications
- Most important approach to solve the problem: **distributed all-pairs shortest paths problem**

Dynamic version

- Highly relevant in practice
- Widely studied in the literature, many solutions have been developed over the years

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Known solutions

Link-State

- Each node stores the whole graph topology and computes locally the SPs
- Each topology change needs to be notified to all the nodes
- High space/computational complexity
- OSPF protocol used in the Internet

Distance-Vector

- Each node computes the SPs by interacting with neighbors
- Broadcast a topology change only to affected nodes
- High message complexity but store very little information
- Classical Bellman-Ford method used in RIP protocol

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Recent developments

Recently

- Renewed interest in devising new **efficient light-weight** distributed SP solutions for **Large Scale Ethernet Networks**
- Focus on Distance-vector algorithms as an attractive alternative to link-state solutions when:
  - **scalability** is mandatory
  - routing devices have **limited** storage/computation capabilities

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State-of-the-art Distance-Vector algorithm

DUAL

- Part of CISCOs widely used EIGRP protocol
- Free of looping phenomena + fully dynamic
- Uses **SNC** (Source Node Condition) and Diffuse-Computation
- Good message complexity but high space complexity
- Requires $O(\Phi \cdot \Delta)$ messages and $\Theta(n \cdot \Delta)$ space where:
  - Φ: total number of nodes *affected* by a set of updates
  - Δ: maximum node degree

Our motivation

Develop a loop-free algorithm with a smaller space complexity than **DUAL**, able to send less messages at least in practically interesting scenarios

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Our contribution

Loop Free Routing

New distributed shortest paths routing algorithm which:

- is loop-free and fully dynamic
- combines **SNC** with a two phases distributed computation
- has the same message complexity of **DUAL**
- requires less memory: $O(n + \phi \cdot \Delta)$, where ϕ is the maximum number of destinations for which a node is *affected*

Basic Idea

Nodes:

- do not permanently store neighborhood data
- interact with neighbors when such information are needed

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What **SNC** (**S**ource **N**ode **C**ondition) is?

Sufficient condition for loop-freedom

- When a node has to choose a new via, if **SNC** is used, the graph induced by the vias is free of loops
- For a generic node v, a neighbor $u \in N(v)$ satisfies **SNC**, at a certain time t, if and only if
  - $u = \arg\min_{k \in N(v)} \{\mathtt{D}_k[s](t) + w^t(v,k)\}$
  - $\mathtt{D}_u[s](t) < \mathtt{D}_v[s](t)$

If no neighbors that satisfy **SNC** exist

$\Rightarrow$ Other methods to compute loop-free paths are required

- **DUAL** – Diffuse-Computation + Finite State Machine
- **LFR** – Local-Computation + Global-Computation + Queue

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LFR Data structures

Each node v stores, for each destination $s \in V$:

- $\mathtt{D}_v[s]$ and $\mathtt{VIA}_v[s]$: estimated distance and via
- $\mathtt{STATE}_v[s]$: the state of node v wrt s
  - $\mathtt{STATE}_v[s] = \mathit{true} \Rightarrow v$ is processing a weight increase operation wrt s
- $\mathtt{UD}_v[s]$: the upper bound distance to s, that is the distance to s through $\mathtt{VIA}_v[s]$
  - $\mathtt{UD}_v[s]$ is always greater or equal than $\mathtt{D}_v[s]$; if v is passive, they coincide

Plus, a temporary data structure, to implement **SNC**

- $\mathtt{tempD}_v$: allocated for a certain s only when v is active wrt s, deallocated when v turns passive wrt s
  - entry $\mathtt{tempD}_v[u][s]$ contains $\mathtt{UD}_u[s]$, for each $u \in N(v)$

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Messages

Three kinds of messages

- *update*: notifies that the distance to a node is changed
- *get.dist*: asks for the current `UD[]`
- *get.feasible.dist*: asks for a loop-free distance if no neighbors satisfy **SNC** (induces the target node to activate, if needed)

Behaviour

We analyze the algorithm in the two possible cases:

- the weight of an edge $\{x_i, y_i\}$ increases
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If the weight of an edge $\{x_i, y_i\}$ changes

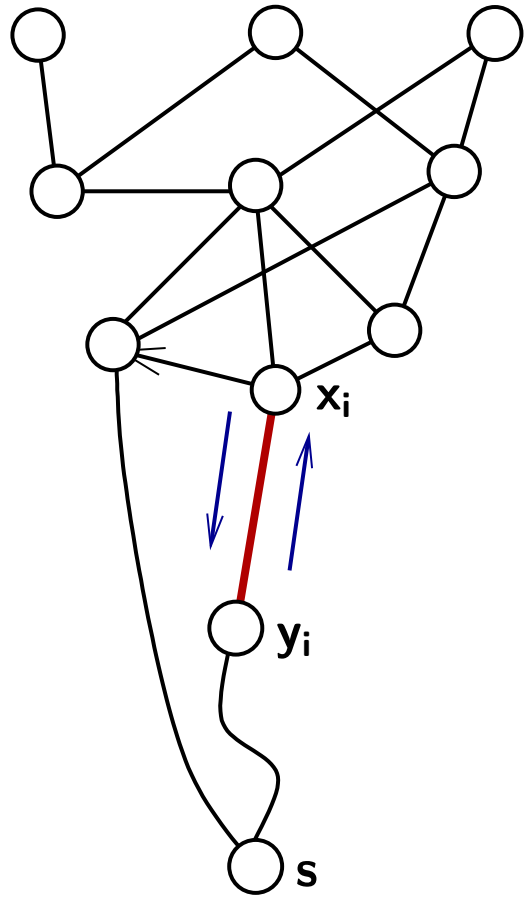
The algorithm starts

1: Node x_i sends, for each $s \in V$, a message $update(x_i, \mathtt{UD}_{x_i}[s])$ to y_i

2: Node y_i sends, for each $s \in V$, a message $update(y_i, \mathtt{UD}_{y_i}[s])$ to x_i

If the nodes are passive

- $\mathtt{UD}_{x_i}[s] \equiv \mathtt{D}_{x_i}[s]$
- $\mathtt{UD}_{y_i}[s] \equiv \mathtt{D}_{y_i}[s]$



If a node v receives an $update(u, \mathtt{UD}_u[s])$ from $u \in N(v)$

1: If $\mathtt{D}_v[s] \equiv \mathtt{UD}_u[s] + w(v,u)$: discard the message

2: If $\mathtt{D}_v[s] > \mathtt{UD}_u[s] + w(v,u)$
- 2.1: set $\mathtt{D}_v[s] = \mathtt{UD}_u[s] + w(v,u)$, $\mathtt{VIA}_v[s] = u$
- 2.2: forward the change by sending $update(v, \mathtt{UD}_v[s])$ to all the neighbors

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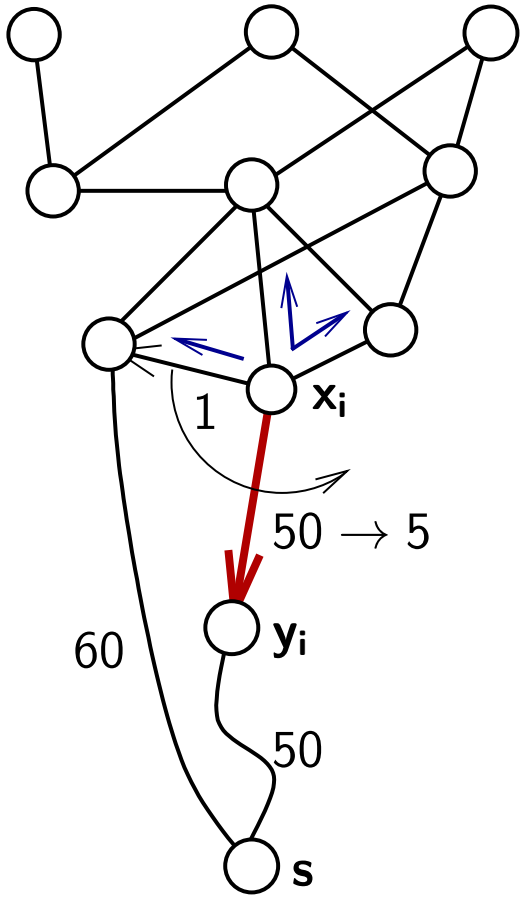

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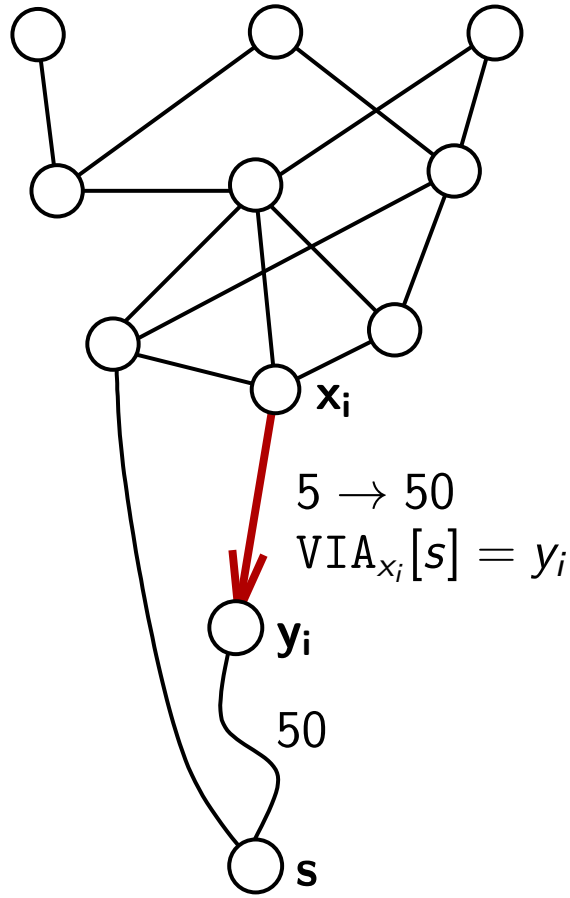
3: If $\mathtt{D}_v[s] < \mathtt{UD}_u[s] + w(v,u)$ and $\mathtt{VIA}_v[s] = u$
  3.1: Perform Local-Computation
  3.2: If Local-Computation fails, perform Global-Computation



If a generic node v performs Local-Computation wrt s

1: Node v turns active and sends *get.dist* to each $u \in N(v) : u \neq \mathtt{VIA}_v[s]$

2: Each neighbor immediately replies with $\mathtt{UD}_u[s]$

3: If a neighbor k that satisfies **SNC** exists, node v:

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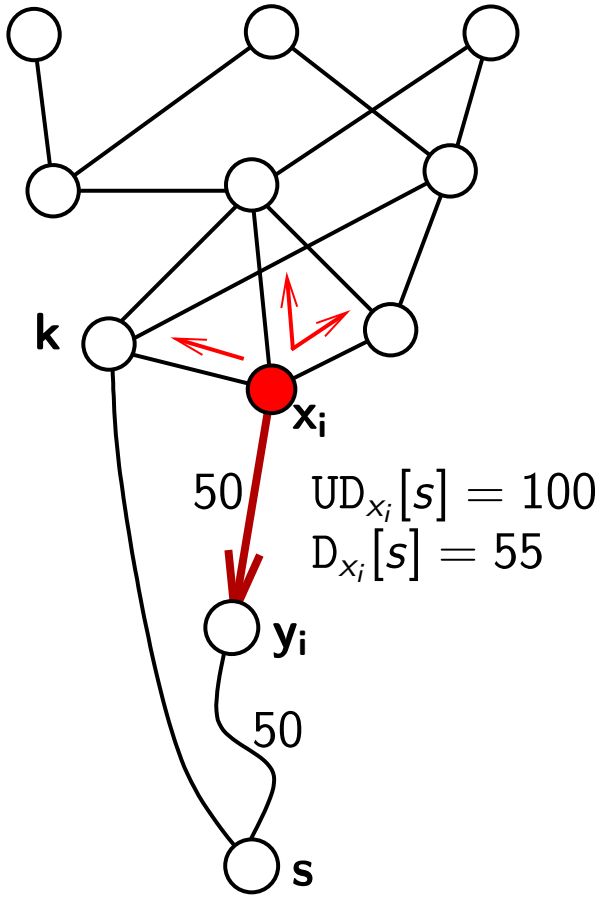
3.2: turns passive and forwards the change

4: Otherwise, v performs Global-Computation



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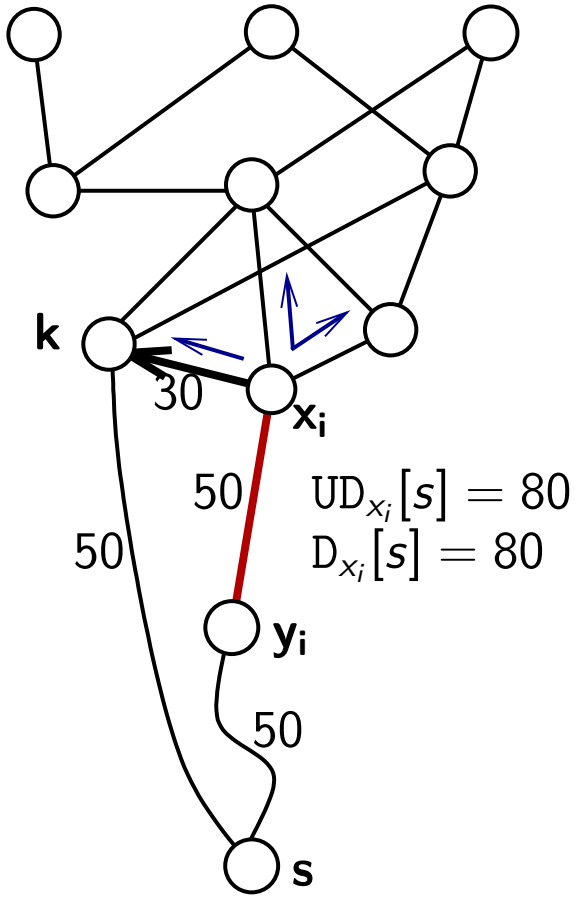

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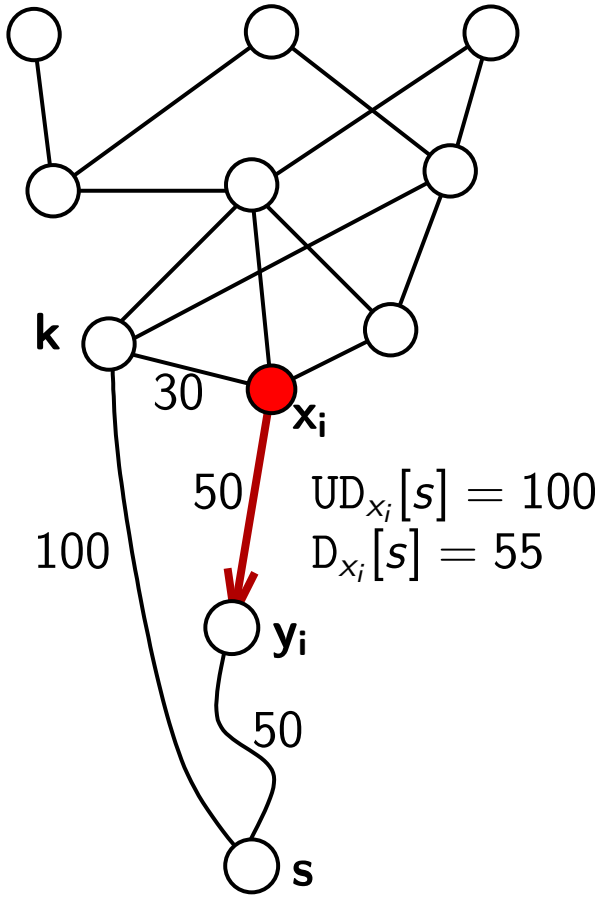
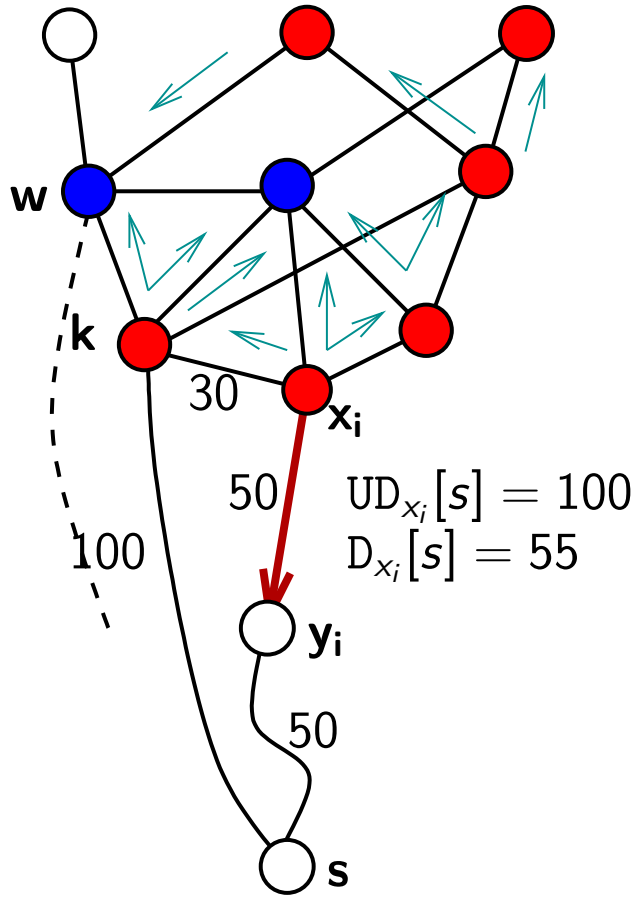


If a generic node v performs Global-Computation wrt s

Global-Computation

- Nodes of network communicate by *get.feasible.dist* messages in order to compute loop-free paths
- Always terminates
- When a node receives the replies to its *get.feasible.dist* messages it:
  - updates its data structures
  - turns passive
  - replies to possible pending *get.feasible.dist* and forwards the change



Handling special cases

- If multiple weight changes occur, each node running **LFR** uses a FIFO queue in order to guarantee:
  - mutual exclusion
  - properly ordered processing of the messages
- While a node is active wrt s, incoming *update* messages are enqueued
- When a node turns passive wrt s, enqueued *update* messages are dequeued in FIFO order

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Experimental evaluation

Simulation environment

- Extensive experimental evaluation within OmNet++, a well-known distributed systems simulation enviroment
- We measured the total number of message sent and the space requirements

Implemented algorithms

- We implemented, in C++, **LFR** and **DUAL**

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Input data

Graphs

- Real-world graphs (G_{IP}), provided by the Cooperative Association for Internet Data Analysis (CAIDA)
- Artificial random graphs (G_{ER}), generated by the Erdòs-Renyi algorithm

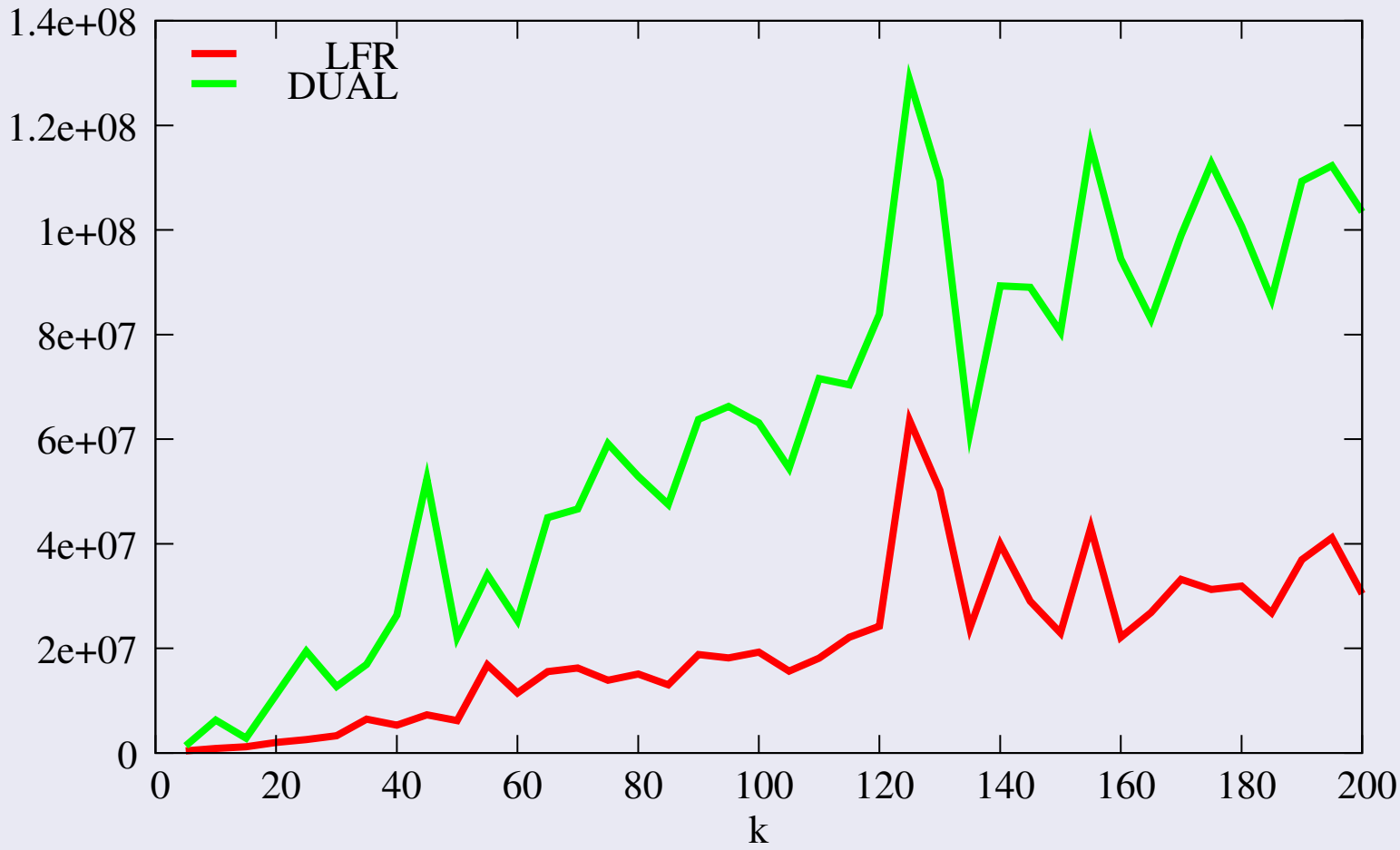
Executed tests

Executed tests

- We ran simulations in different dynamic **realistic** settings, where the weight of an edge represents the delay needed to a packet to traverse it
- Due to **DUAL**'s high memory requirements we used CAIDA and Erdòs-Renyi instances with maximum number of nodes equal to 8000 and 2000, respectively
- We show the results for:
  - a CAIDA graph with $n = 8000$, $m = 11141$ $(m/n \approx 1.4)$ and number of modifications $k \in \{5, 10, ..., 200\}$
  - artificial graphs with number of nodes $n = 2000$, *density* ranging from 0.01 to 0.61 and fixed number of modifications $k = 200$
- The other instances give similar results

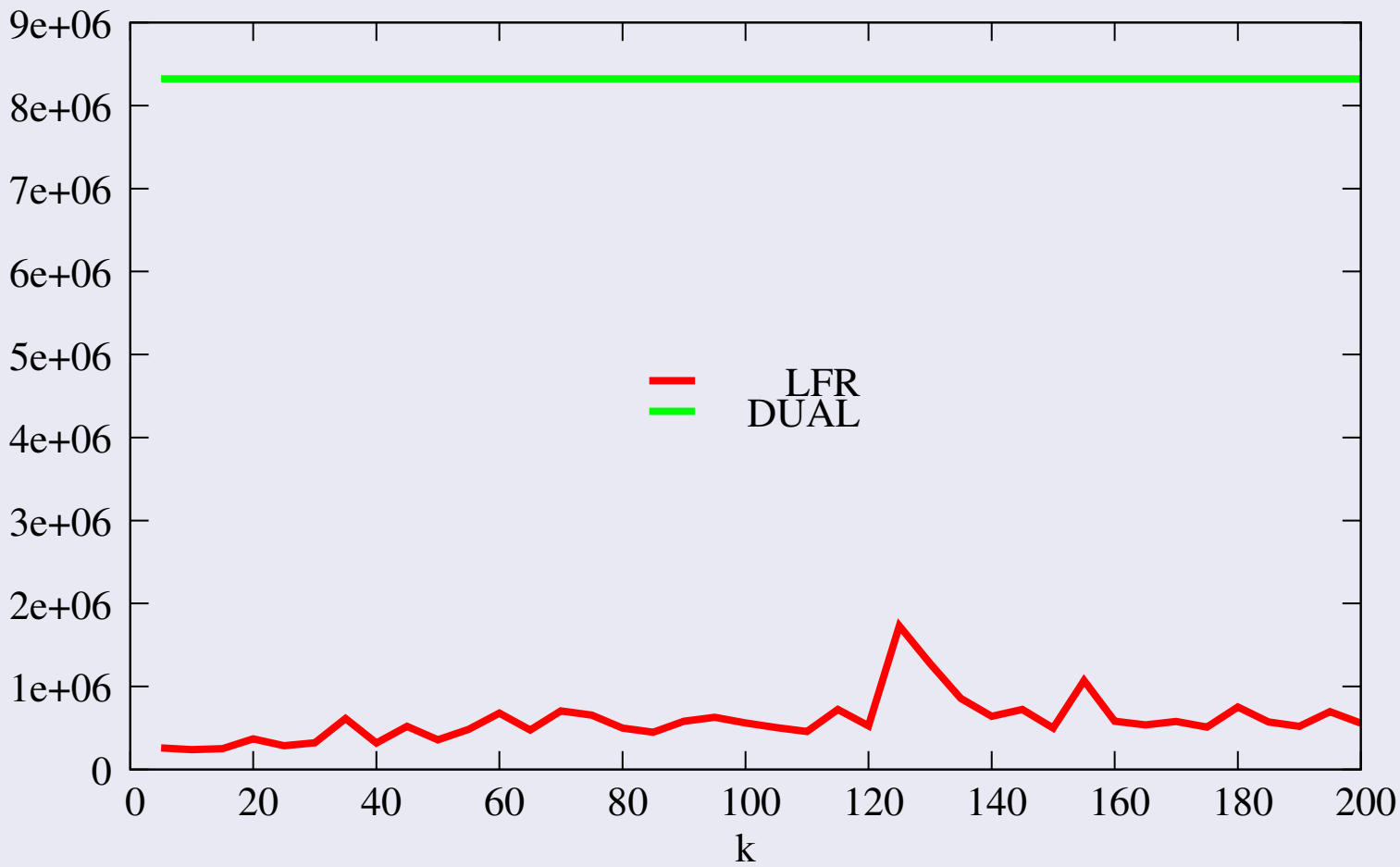
Results – Message complexity in real-world instances

Number of messages sent - G_{IP_8000}



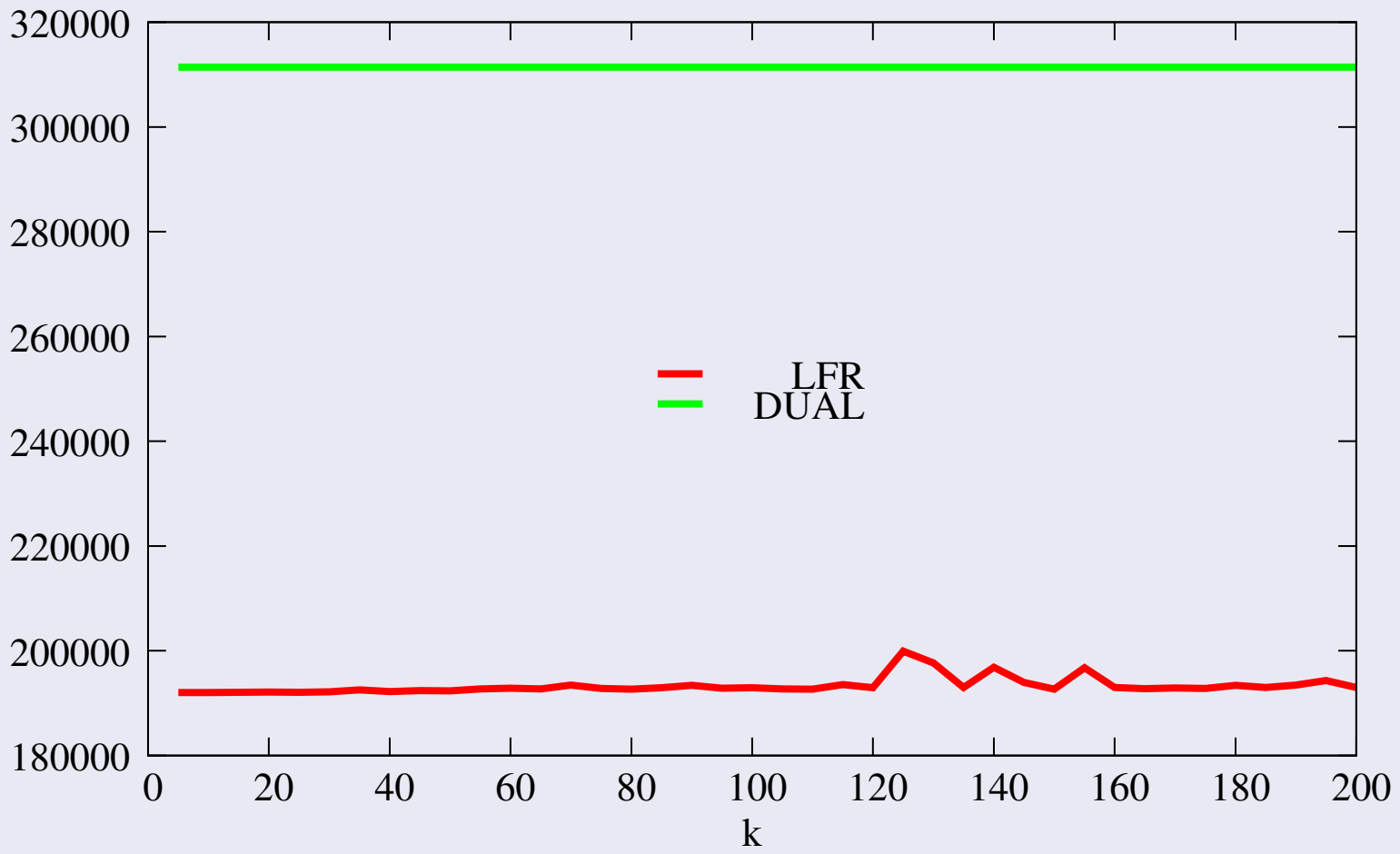
Results – Space complexity in real-world instances

Maximum space occupancy - $G_{IP-8000}$



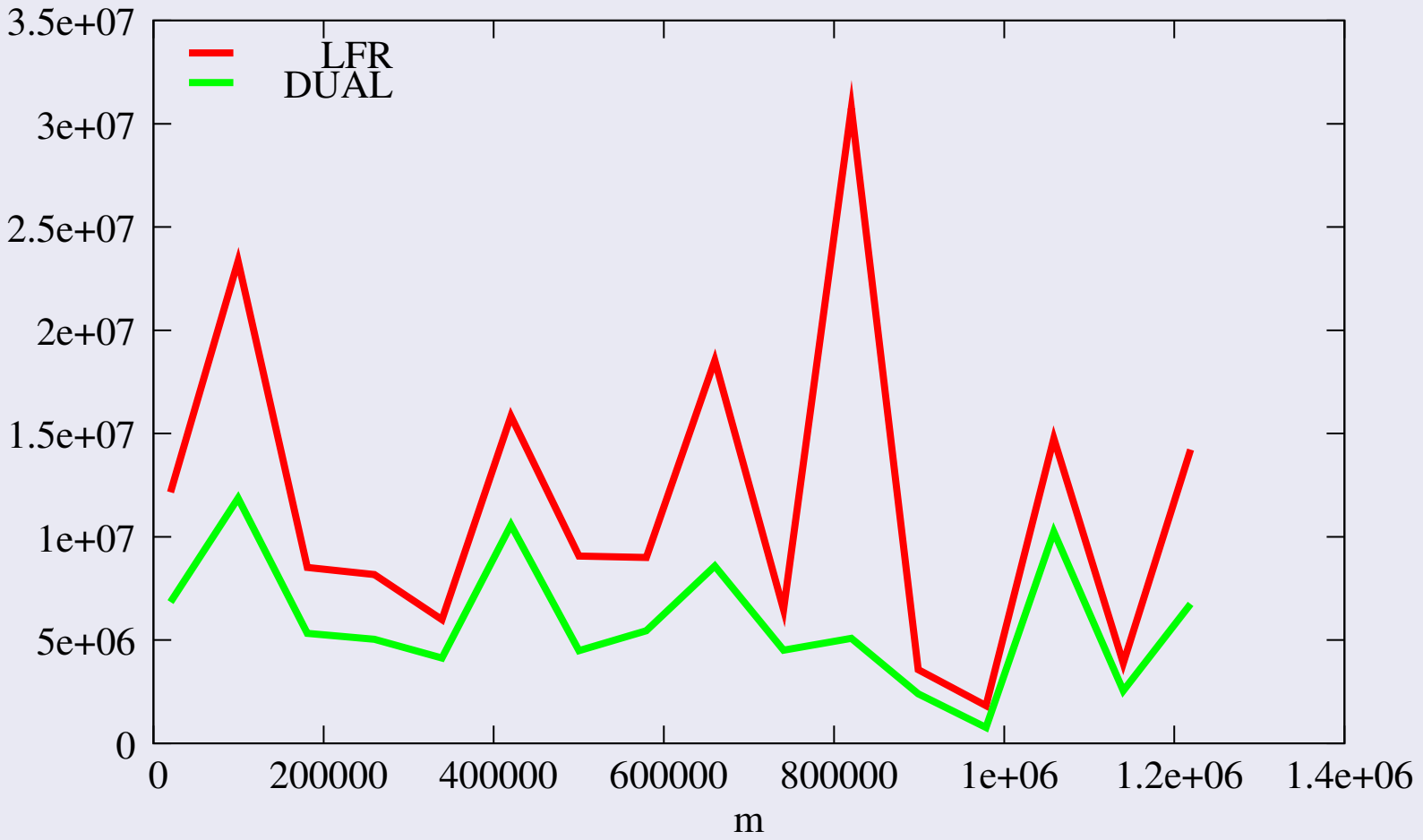
Results – Space complexity in real-world instances

Average space occupancy - $G_{IP-8000}$



Results – Message complexity in artificial instances

Number of messages sent - $G_{ER-2000}$



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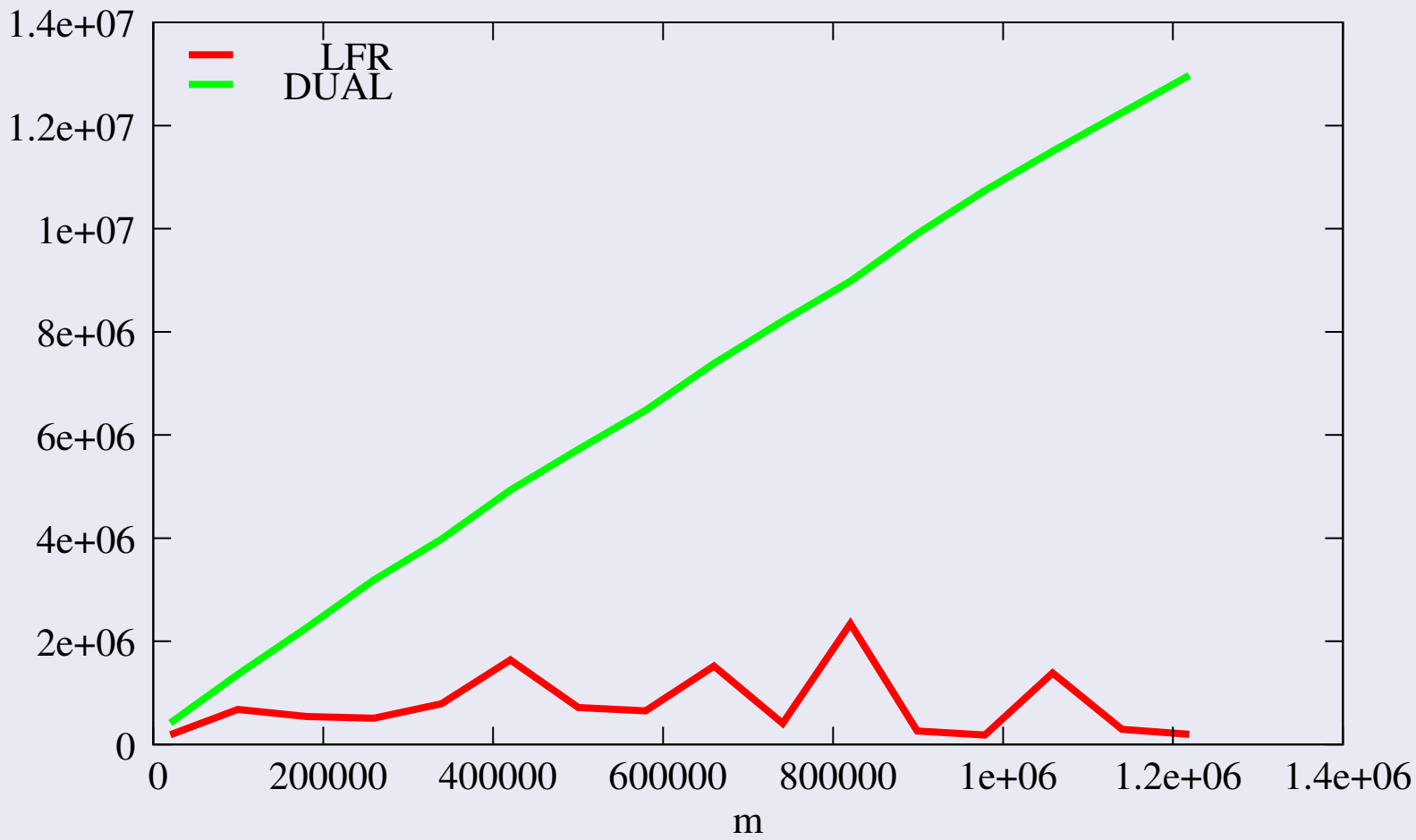

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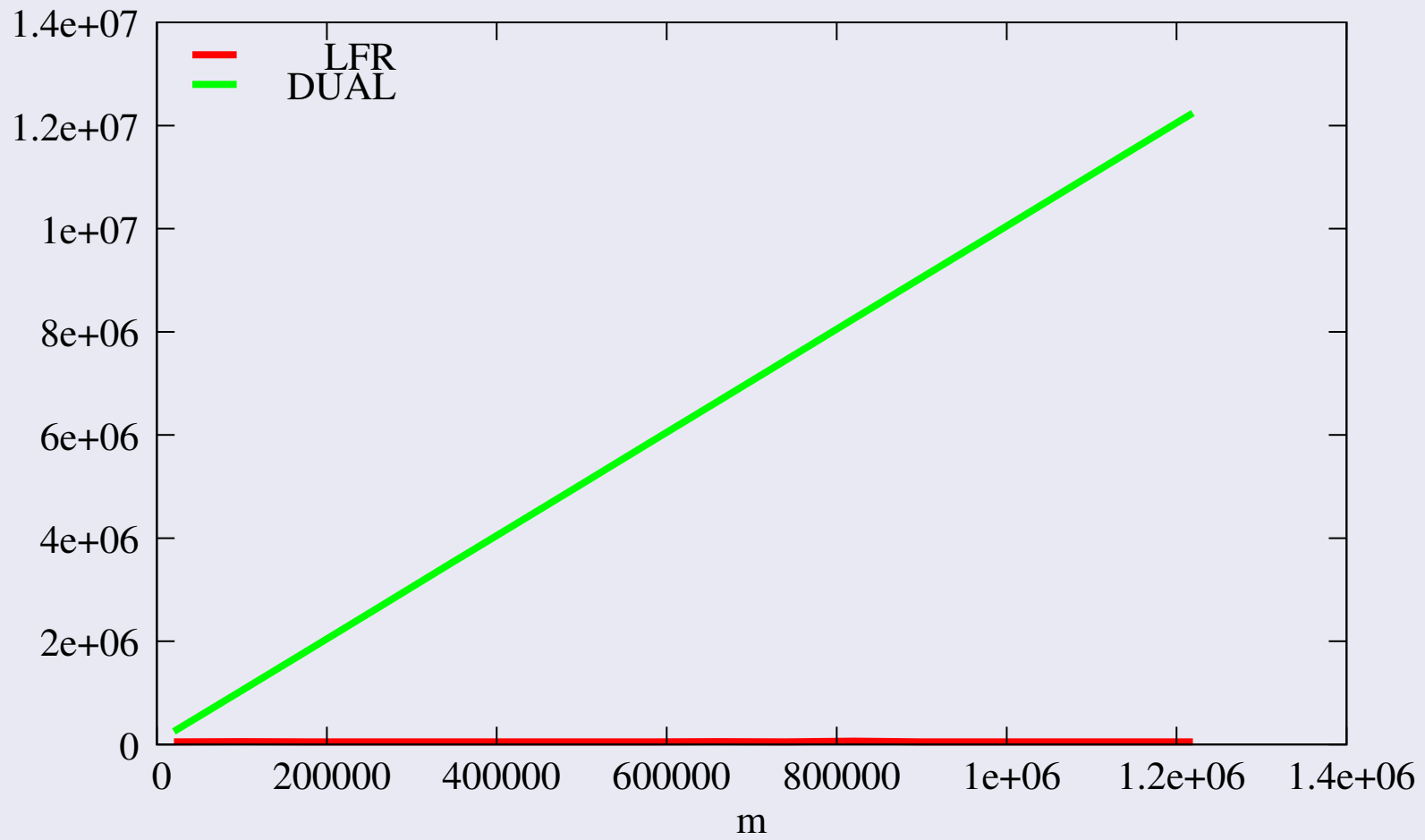

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- We proposed **LFR**, a new fully dynamic loop-free shortest paths routing algorithm which:
  - has the same message complexity of **DUAL**
  - has a better space complexity

Experimental contribution

- We implemented and tested **LFR** and **DUAL**
- We showed that:
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  - **LFR** is the best choice in terms of messages sent in the CAIDA real-world networks

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Future research

- Improve **LFR**, like e.g. by:
  - reducing the message/space complexity while preserving loop-freedom
- Design new algorithms tailored to be effective in other real world practically interesting scenarios
- Extend the experimental evaluation to other real-world/artificial instances

Thank you for your attention - Q&A