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École Mines-Télécom

Toward Reliable & Available Wireless Low-power Mesh Networking

École d'Été Temps Réel #ETR2021

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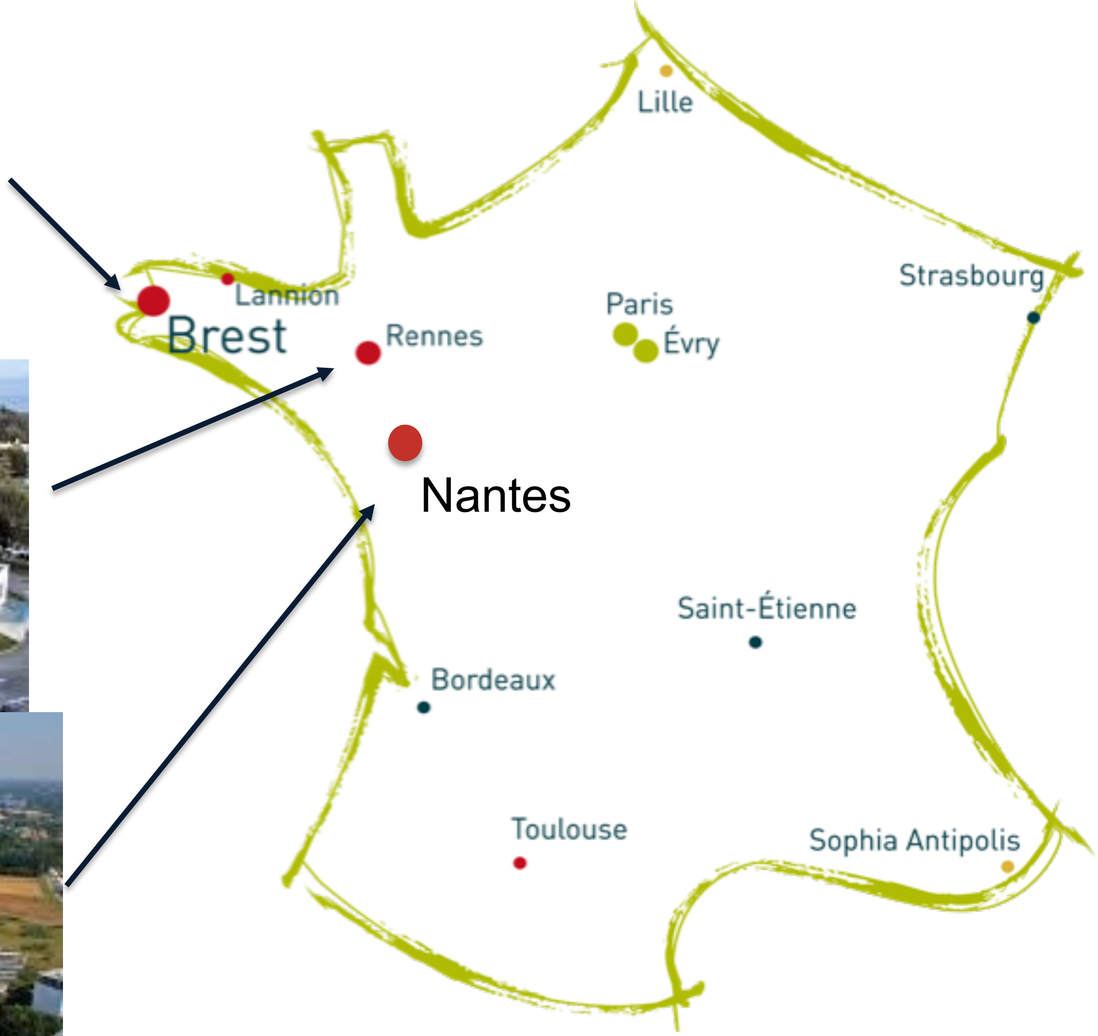
IMT Atlantique



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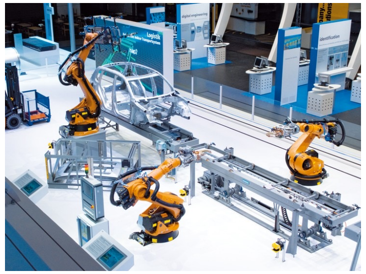
Research Overview

Security | **Scalability / Interoperability** | **Quality of Service**

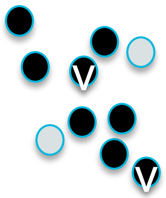


Smart Grid & EV

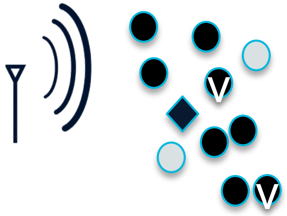
Smart city

Industry 4.0

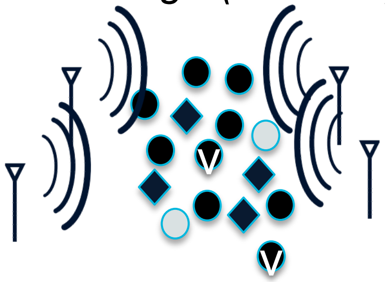
Wired (PLC)



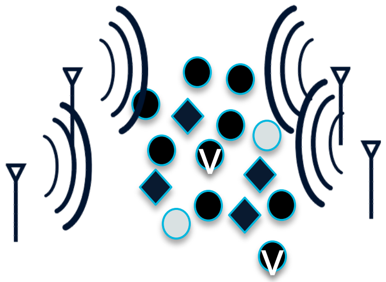
Wireless: long range (star)



Wireless: short range (multi-hop)



Research Overview



Application

Transport

Network

MAC

Physical

I E T F®

- Architectures
- Standards
- Protocols / Algorithms (MAC, Routing)
- Data (compression, fragmentation, representation)

Outline

1. Introduction
2. IETF RAW WG
   Standardization Efforts
3. Meet the PAREO Functions
4. Multi-path Strategies
   in RPL-based Networks

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Introduction

Toward Deterministic Networking

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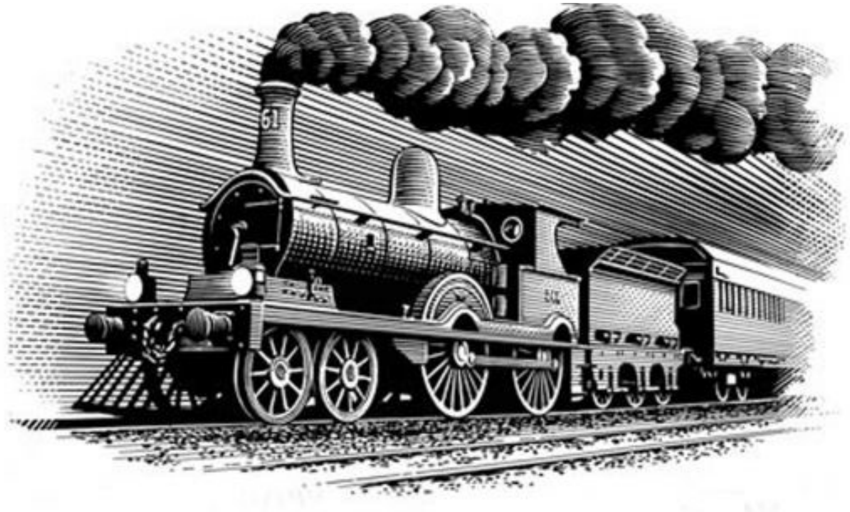
Toward Deterministic Networking

What is determinism?

- The information will be carried out in a pre-defined and constant delay;
  - Transparent to link quality, interference or node failure



Toward Deterministic Networking

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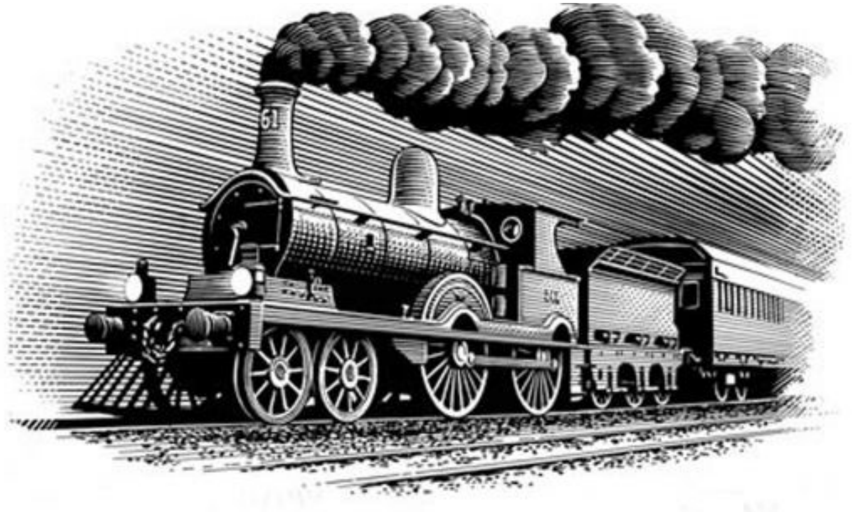
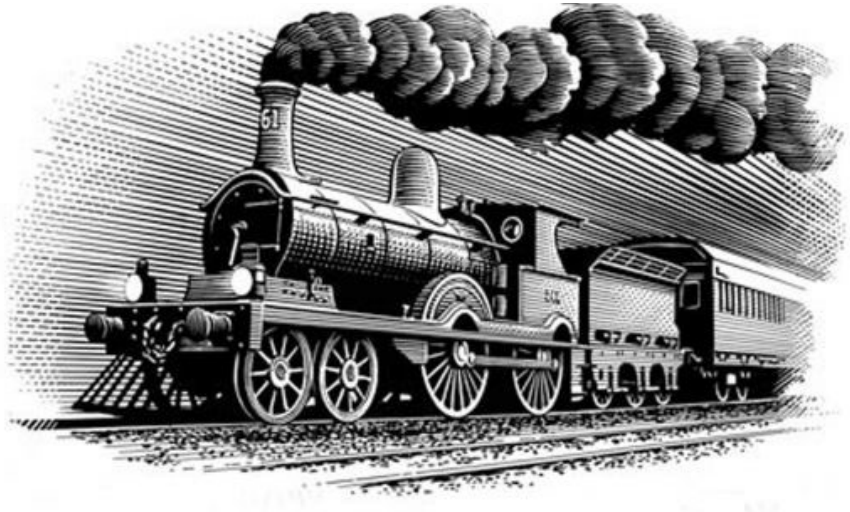


Toward Deterministic Networking

What is determinism?

- The information will be carried out in a pre-defined and constant delay.
  - Transparent to link quality, interference or node failure
- Deterministic networks should exhibit low jitter performance.
- However, the current technologies in IoT are based on best-effort.
  - Packets are subject to variable delay due to retransmissions & enqueuing



Analogies of Deterministic Behaviour from Real-world

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Analogies of Determinism from Real-world

Bus Analogy

- The reserved bus lanes are to avoid delays due to traffic jams

Analogies of Determinism from Real-world

Train Analogy

- The collision of two trains using the same rails at the same time, is avoided by fully scheduled operations that repeat, day after day.

Analogies of Determinism from Real-world

The Booking Analogy (time-sharing)

- The “collision” of two individual bookings of the same apartment at the same time, is avoided by fully scheduled operation.

Problem Formulation

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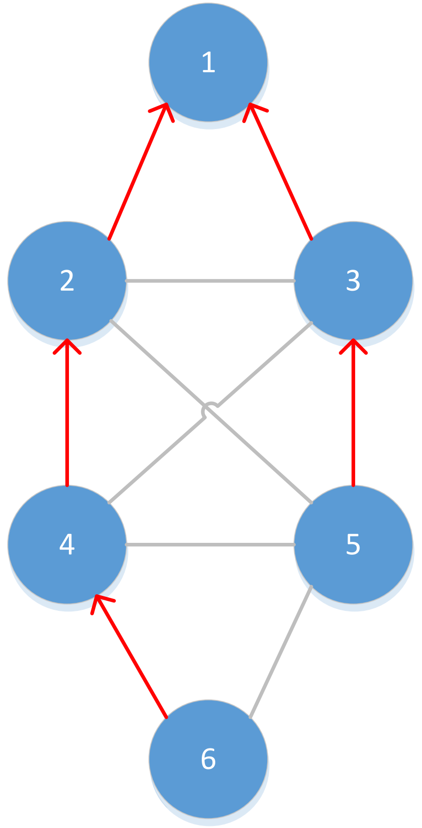
Problem Formulation

An example of a crashed node or bad link quality

Default TSCH + RPL operation



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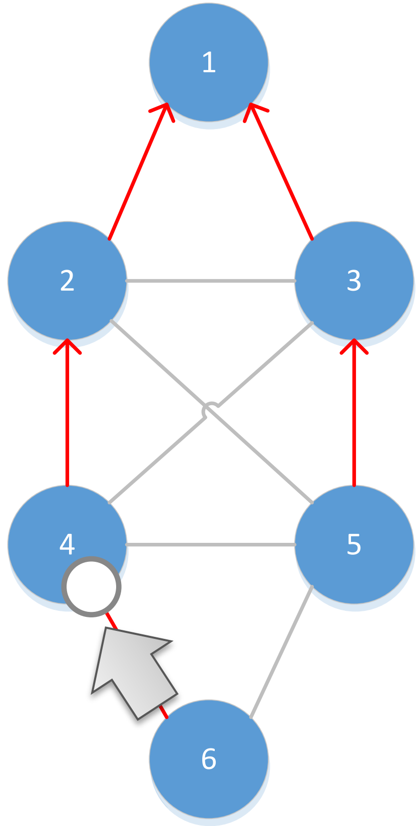


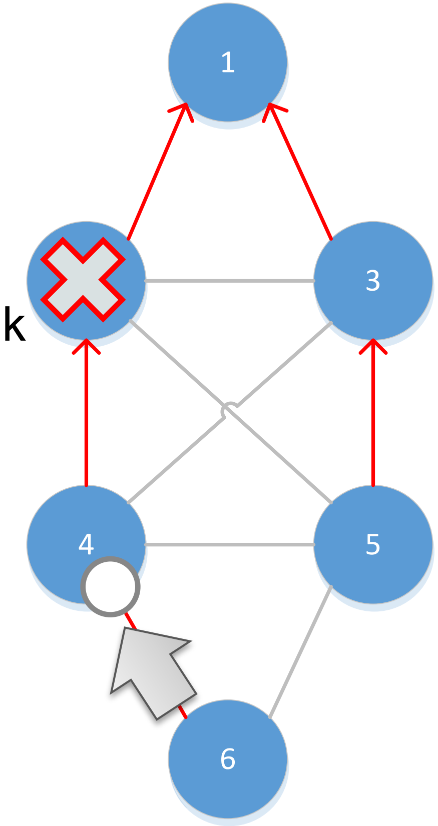
Problem Formulation

An example of a crashed node or bad link quality

- Crashed node or heavily interfered link:

Default TSCH + RPL operation

Node failure or bad link



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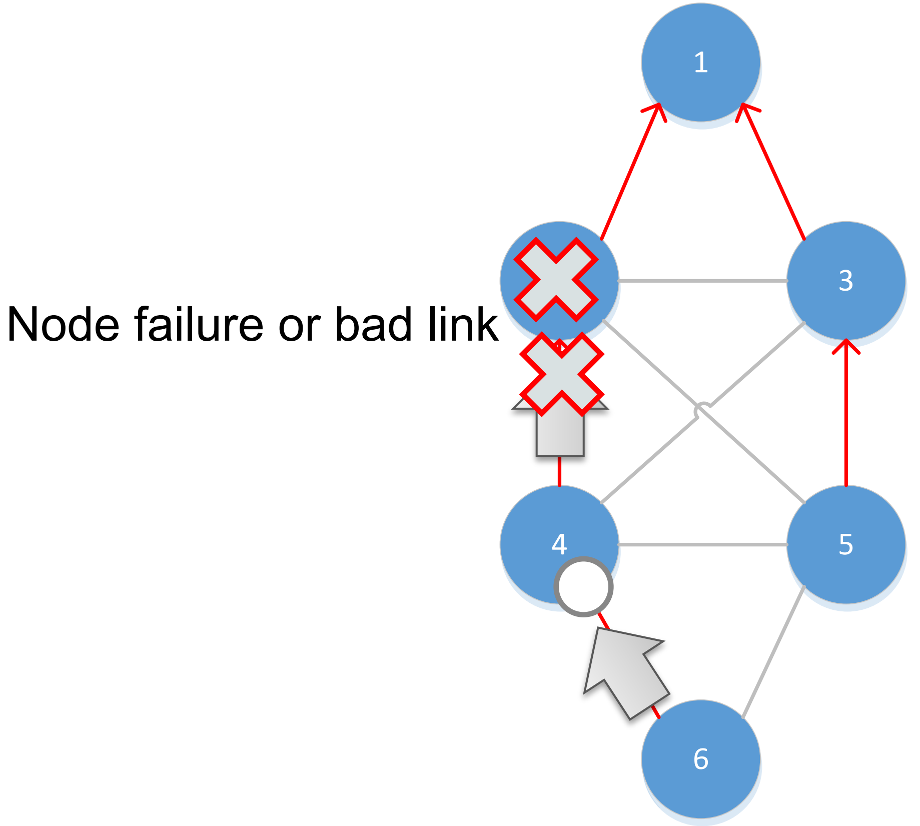
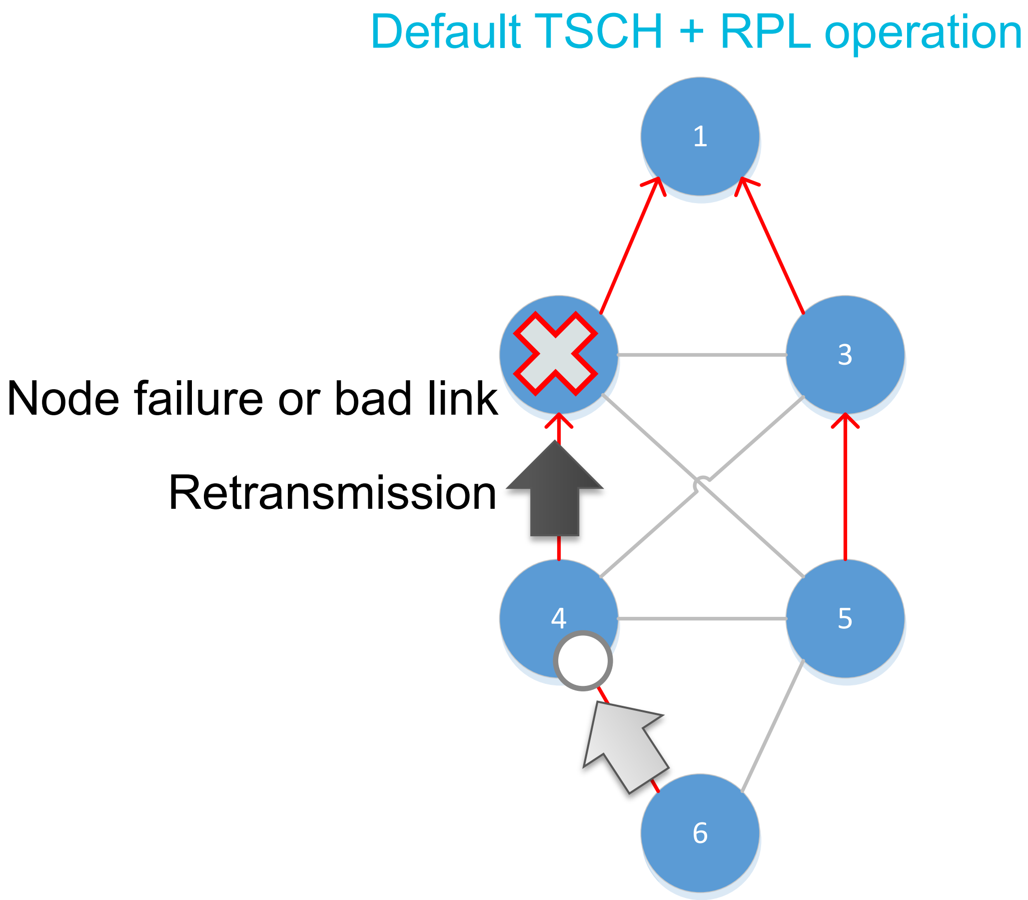


Problem Formulation

An example of a crashed node or bad link quality

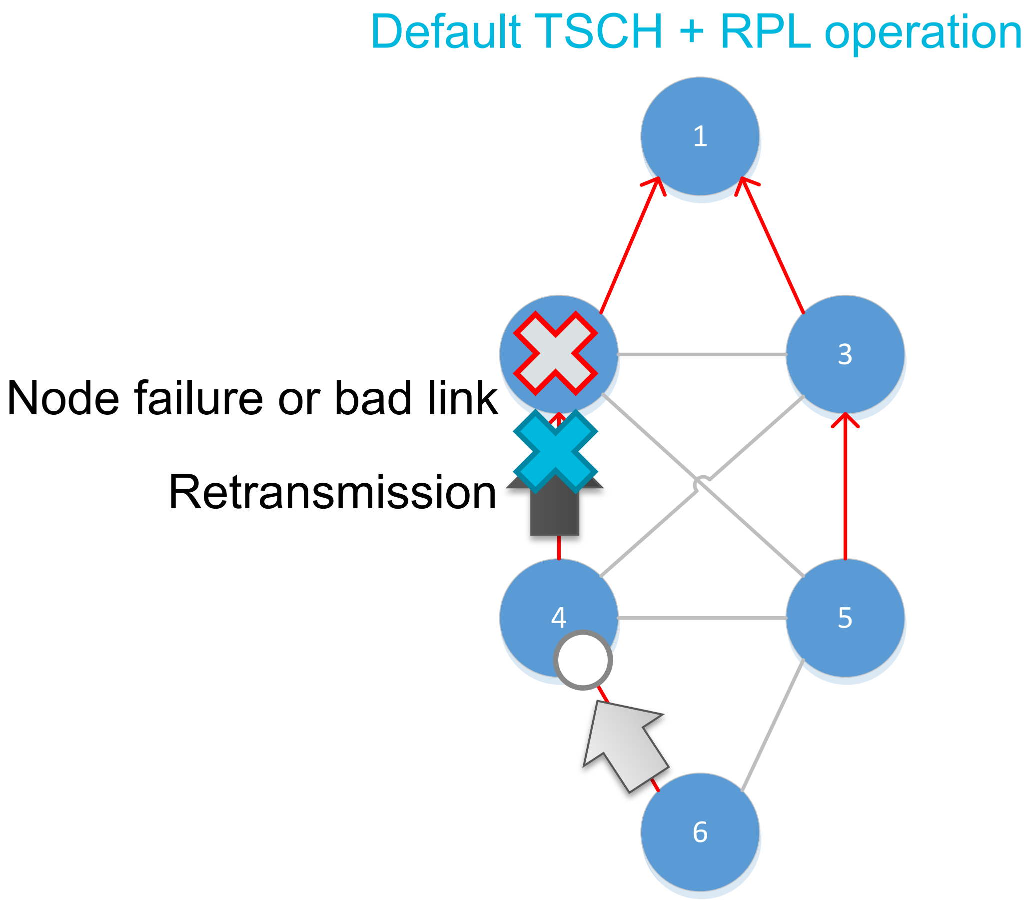
- Crashed node or heavily interfered link:
  - X retransmissions (over different frequencies)



Problem Formulation

An example of a crashed node or bad link quality

- Crashed node or heavily interfered link:
  - X retransmissions (over different frequencies)
  - **Local or Global repair → alternative path**



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- Cost:
  - Delay & Jitter
  - Reliability
  - Network overload

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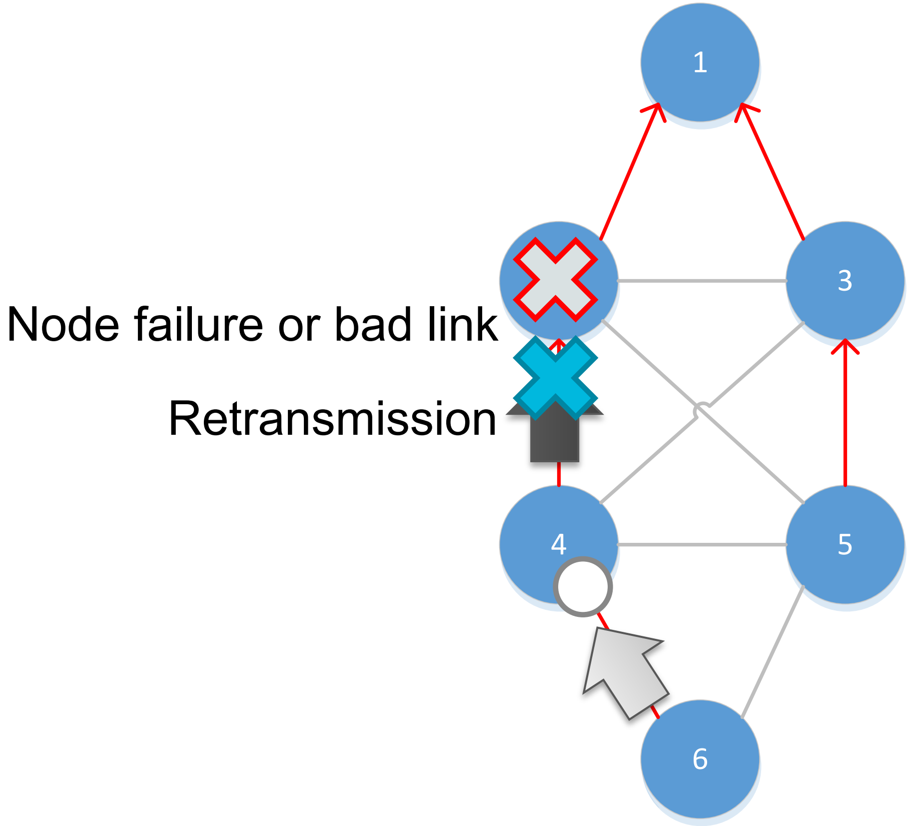

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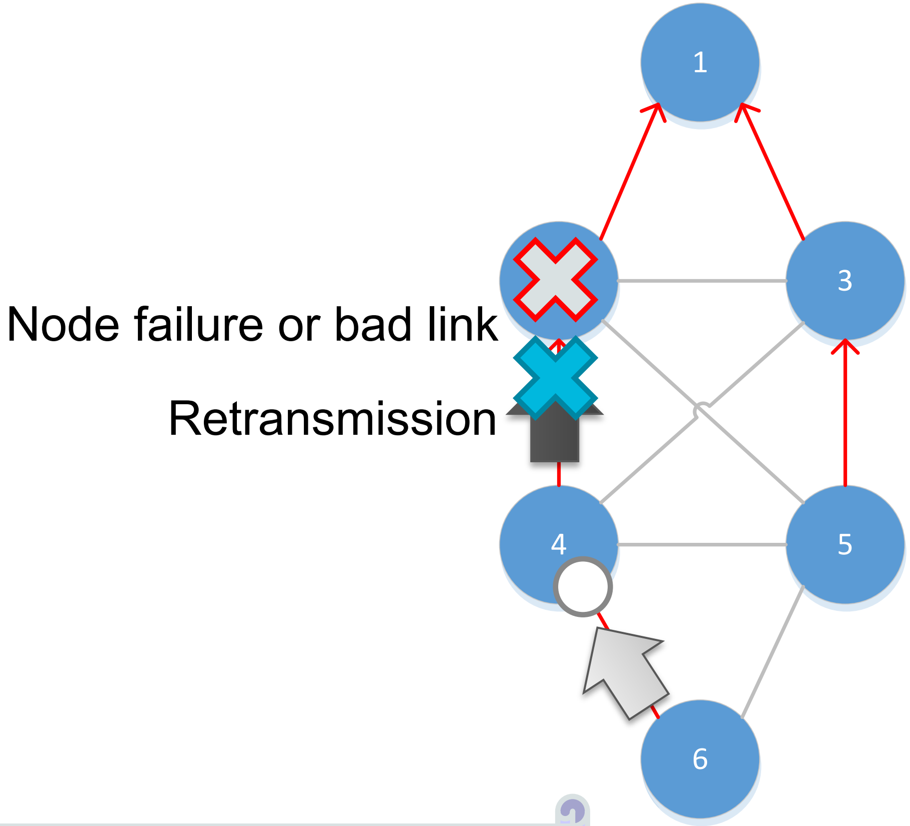

Even with IEEE 802.15.4-2015 TSCH (radio channel hoping scheme) can not be addressed!

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IETF RAW WG
Standardization Efforts

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IETF RAW WG

Reliable and Available Wireless (RAW)

- IETF 107: Vancouver (virtual), Mar. 23-27, **2020** : 1st official WG meeting
- IETF 106: Singapore, Nov. 16-22, **2019** : Birds of a Feather (BoF)
- IETF 103: Bangkok, Nov. 3-9, **2018** : 1st unofficial meeting

Overview

"Charter IETF RAW WG, Reliable and Available Wireless", July 2020

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IETF RAW WG

Specifics

- RAW extends the DetNet WG concepts :
  - Centrally scheduled operations, PCE/PSE.

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IETF RAW WG

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- RAW extends the DetNet WG concepts :
  - Centrally scheduled operations, PCE/PSE.
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  - Variable link conditions (even with low mobility).
- But how that is effectively achieved is different in wireless:

IETF RAW WG

Specifics

- RAW extends the DetNet WG concepts :
  - Centrally scheduled operations
- Heterogeneous technologies (mostly wireless).
  - Variable link conditions (even with low mobility).
- But how that is effectively achieve[illegible]less:

Diversity, Diversity, Diversity

- Routing over multipath
- Replication over parallel paths
- Frequency hopping (within and between frames)

IETF RAW WG

Main drafts

- Reliable and Available Wireless Architecture/Framework
  - draft-ietf-raw-architecture-01
- RAW use cases
  - draft-ietf-raw-use-cases-02
- Reliable and Available Wireless Technologies
  - draft-ietf-raw-technologies-04
- Operations, Administration and Maintenance (OAM) features for RAW
  - draft-ietf-raw-oam-support-02

IETF RAW WG

Differentiators between RAW and other IETF WGs

- DetNet: Mostly a focused Subset though
  - Radio specialists, different interests
  - Unstable links (bandwidth, flapping), not ‘deterministic’
  - Focus on forwarding optimizations rather routing.
- MANET: Non Congruent domains
  - Non-Mobile & not Ad-Hoc (antagonistic to DetNet)
  - Centralized routing

RAW Use Cases

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"*RAW use cases*"

G. Z. Papadopoulos, P. Thubert, F. Theoleyre and CJ. Bernardos

IETF **RAW WG**, **draft-ietf-raw-use-cases-02**, 12 July 2021

RAW Use Cases

Use cases defined in the draft

- Amusement Parks
- Wireless for Industrial Applications
- Pro Audio and Video
- Wireless gaming
- UAV platooning and control
- Edge Robotics control

- L-band Digital Aeronautical Communications System (LDACS) [1]

[1] Nils Mäurer, Thomas Gräupl, Corinna Schmitt,
L-band Digital Aeronautical Communications System (LDACS),
draft-ietf-raw-ldacs-08

Added Terminology

"*Reliable and Available Wireless Architecture/Framework*",
P. Thubert, G. Z. Papadopoulos and L. Berger
IETF **RAW WG**, **draft-ietf-raw-architecture-01**, 28 July 2021

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Terms

Reliability

Reliability: Reliability is a measure of the probability that an item will perform its intended function for a specified interval under stated conditions. **For RAW, the service that is expected is delivery within a bounded latency and a failure is when the packet is either lost or delivered too late**. RAW expresses reliability in terms of Mean Time Between Failure (MTBF) and Maximum Consecutive Failures (MCF).

Terms
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Availability: **Availability is a measure of the relative amount of time where a path operates in stated condition**, in other words (uptime)/(uptime+downtime). Because a serial wireless path may not be good enough to provide the required availability, and even 2 parallel paths may not be over a longer period of time, the RAW availability implies a path that is a lot more complex than what DetNet typically envisages (***a Track***).

Terms
PAREO

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PAREO: Packet (hybrid) ARQ, Replication, Elimination and Ordering. ***PAREO is a superset Of DetNet's PREOF*** that includes radio-specific techniques such as short range broadcast, MUMIMO, constructive interference and overhearing, which can be leveraged separately or combined to increase the reliability.

Terms

Flapping

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Flapping: In the context of RAW, a link flaps when the reliability of the wireless connectivity drops abruptly for a short period of time, typically of a subsecond to seconds duration.

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Meet the PAREO Functions

"Meet the PAREO Functions: Towards Reliable and Available Wireless Networks”
R.-A. Koutsiamanis, G. Z. Papadopoulos, T. Lagos Jenschke, P. Thubert and N. Montavont
In Proc. **IEEE ICC 2020** - Dublin, Ireland, June 2020

PAREO Functions

- Pool of functions :
  - Packet Transmission
  - Automatic Repeat reQuest (ARQ)
  - Replication
  - Overhearing
  - Elimination

- and more such as :
  - Forward Error Correction (FEC)
  - Constructive Interference
  - (Re)Ordering

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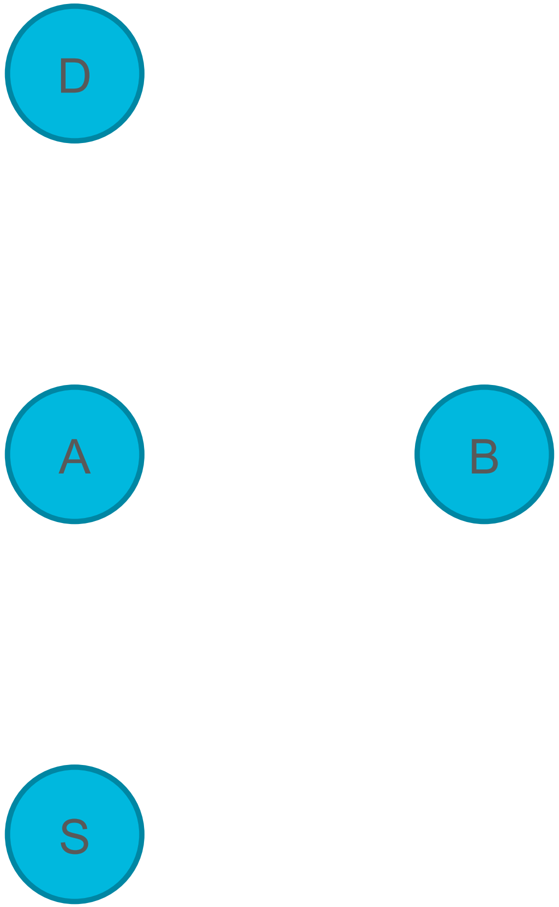
PAREO Functions

Example of a Wireless Topology

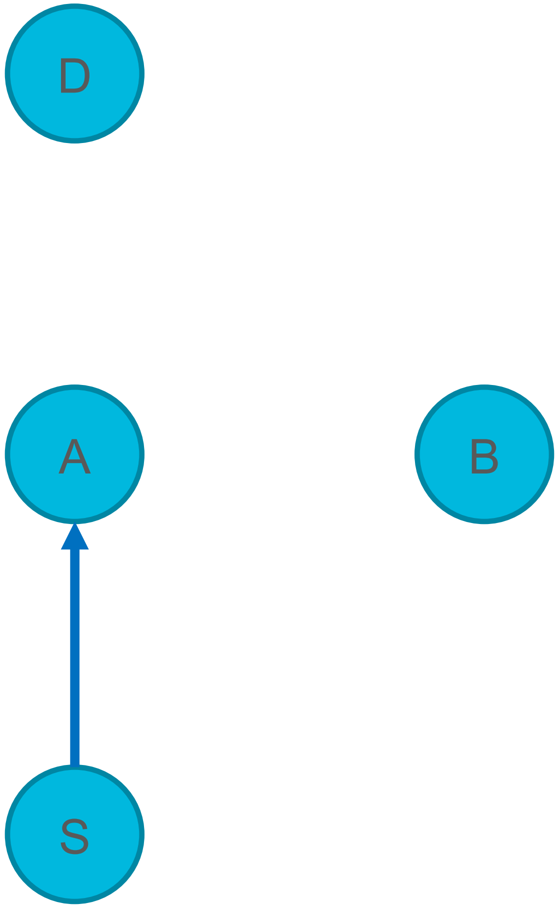
- S is the Source
- D is the Destination
- A and B are the Relay nodes



PAREO Functions

Packet Transmission from S to A

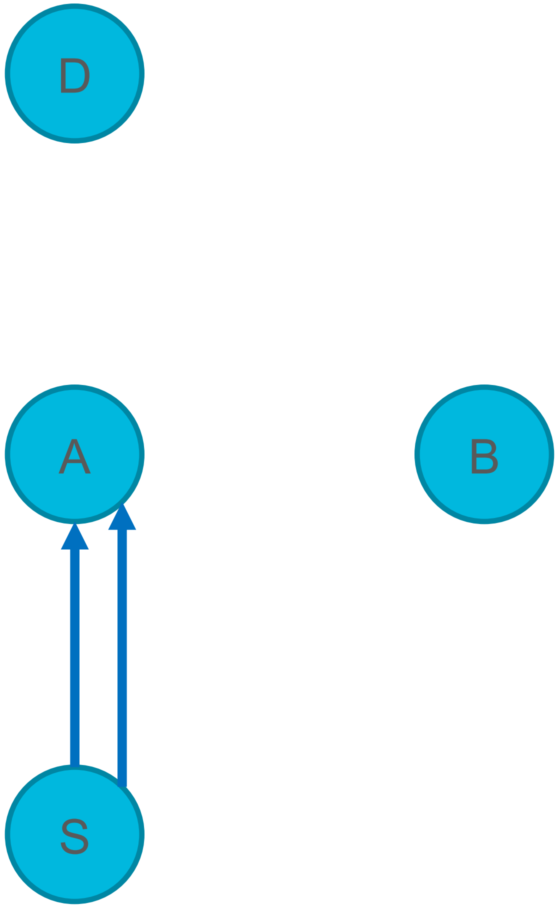
Channel Offset	3		S → A				
	2						
	1						
	0	EB					
		0	1	2	3	4	5
Slotframe							



PAREO Functions

Automatic Repeat reQuest (ARQ)

Channel Offset							
	3		S → A	S → A			
	2						
	1						
	0	EB					
		0	1	2	3	4	5
Slotframe							



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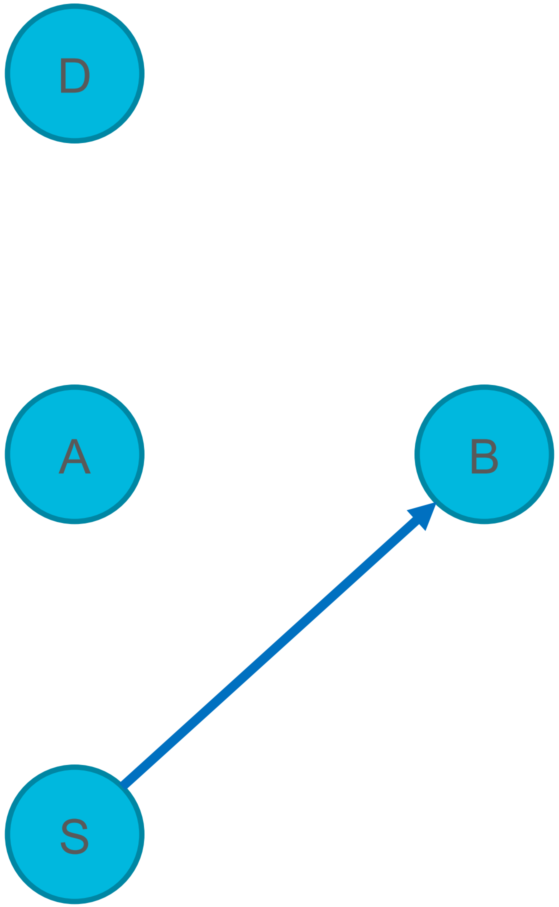
PAREO Functions

Replication

- Data packet is sent to both Preferred & “Alternative” Parent

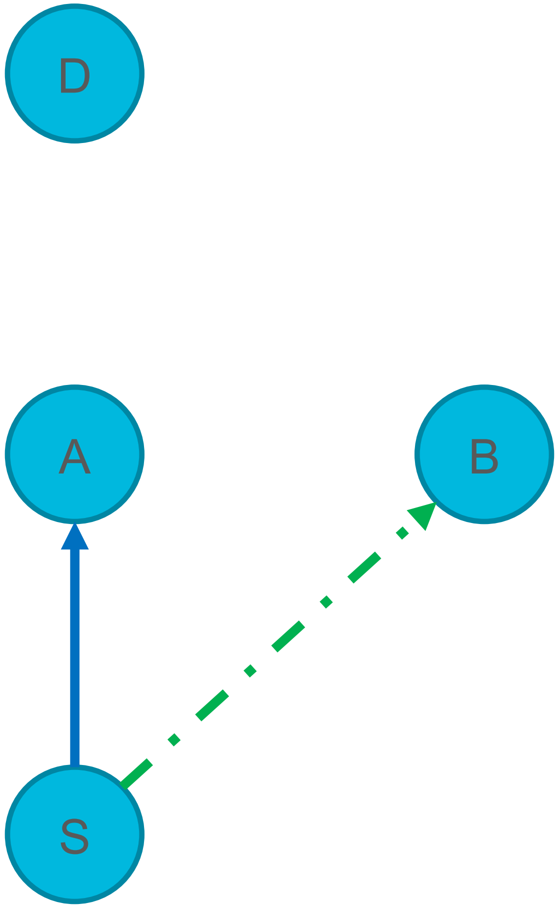
Channel Offset	3		S → A	S → A			
	2				S → B		
	1						
	0	EB					
		0	1	2	3	4	5
Slotframe							



PAREO Functions
Promiscuous Overhearing

- Wireless medium is broadcast by nature
- Any neighbor of a transmitter may overhear a transmission

Channel Offset							
	3		S → A, (B)	S → A, (B)			
	2				S → B, (A)		
	1						
	0	EB					
		0	1	2	3	4	5
Slotframe							

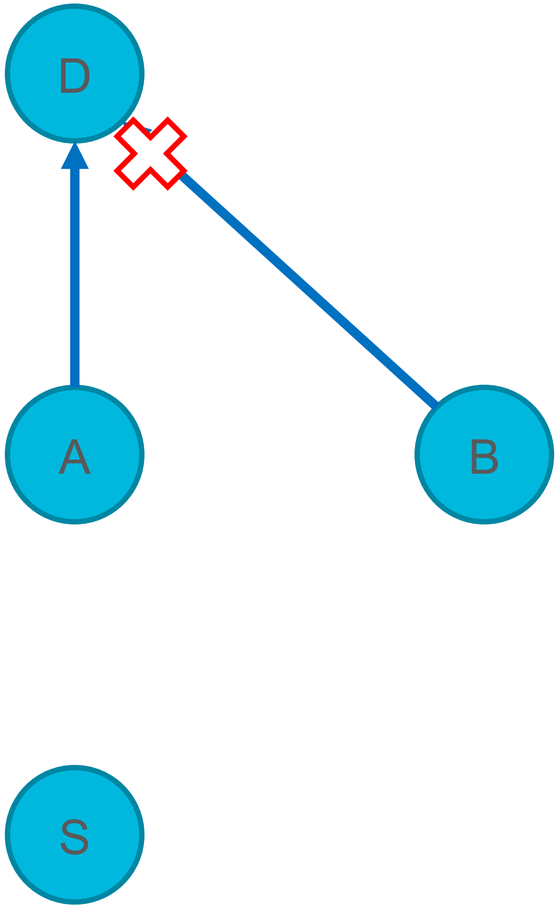


PAREO Functions

Elimination

- Discards the duplicated packet

Channel Offset						
3		S → A, (B)	S → A, (B)			
2				S → B, (A)		
1						B → D
0	EB				A → D	
	0	1	2	3	4	5
Slotframe						



Alternative Parent Selection

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"*RPL DAG Metric Container (MC) Node State and Attribute (NSA) object type extension*",
R. A. Koutsiamanis, G. Z. Papadopoulos, N. Montavont and P. Thubert,
IETF **ROLL WG**, **draft-ietf-roll-nsa-extension-10**, 29 October 2020, *Submitted to IESG for Publication*.

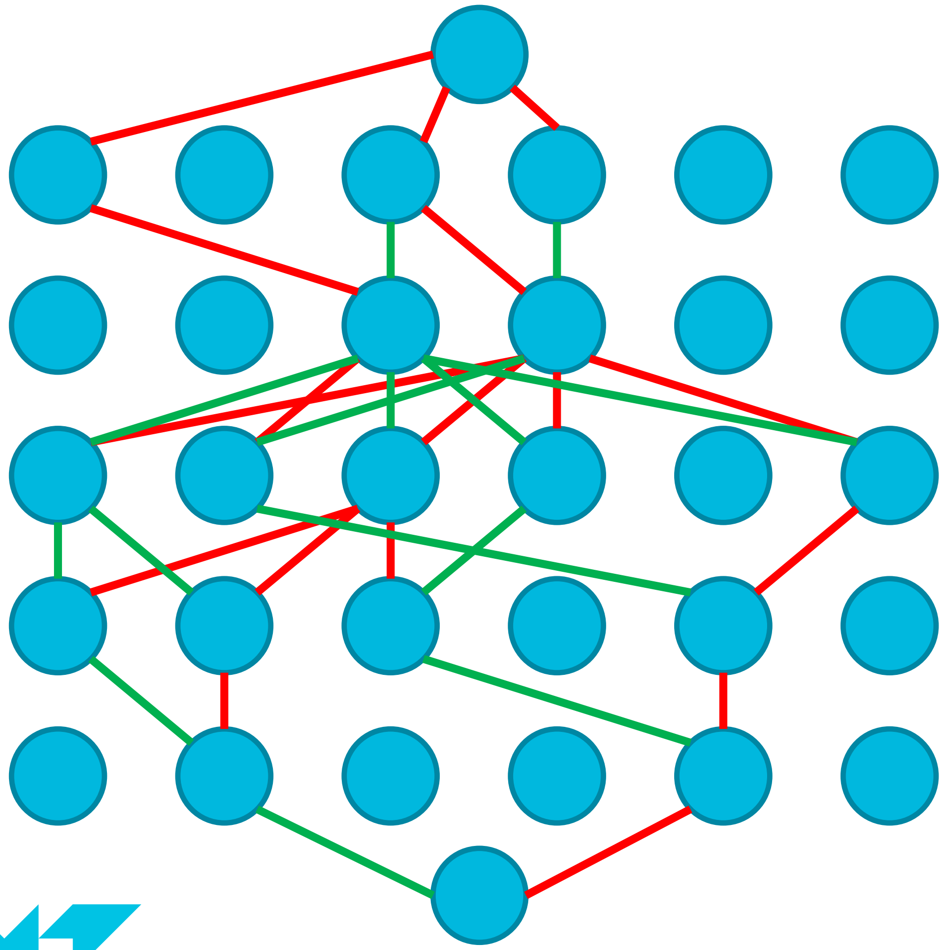
Alternative Parent Selection

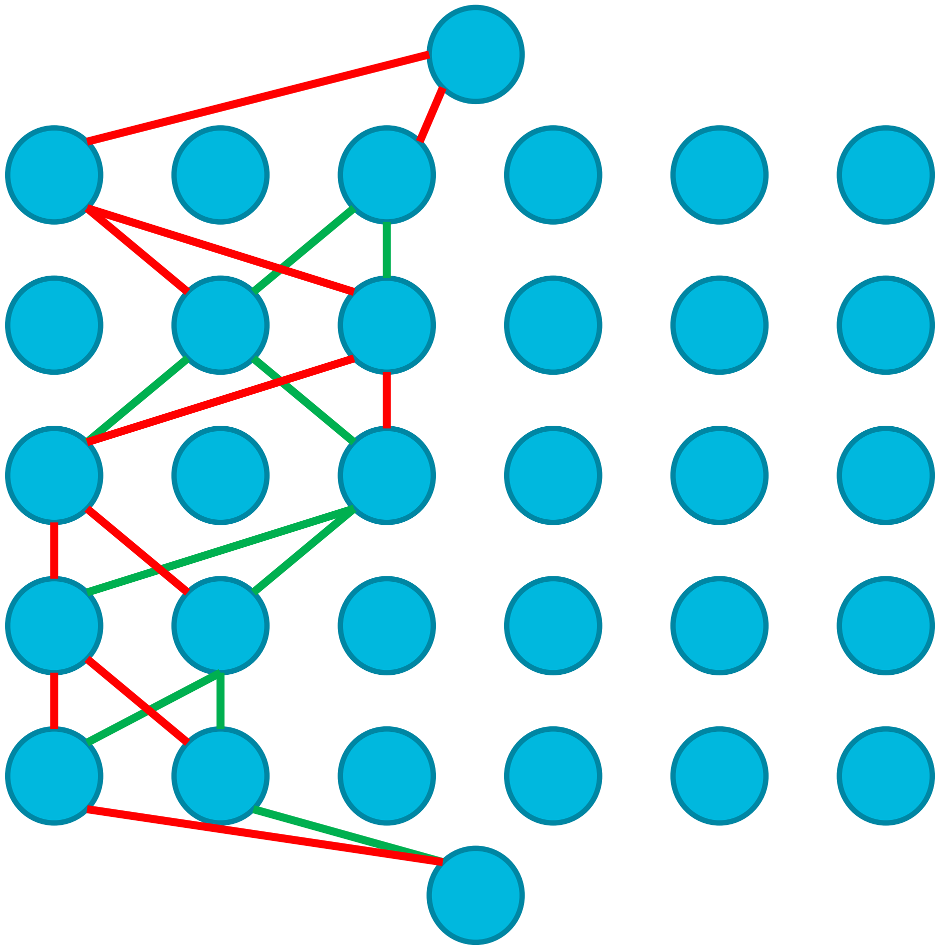
Definition

One possible option is to select the Alternative Parent as the one having common ancestor

Alternative Parent Selection

Why Common Ancestor pattern?





Alternative Parent Selection: Terminology

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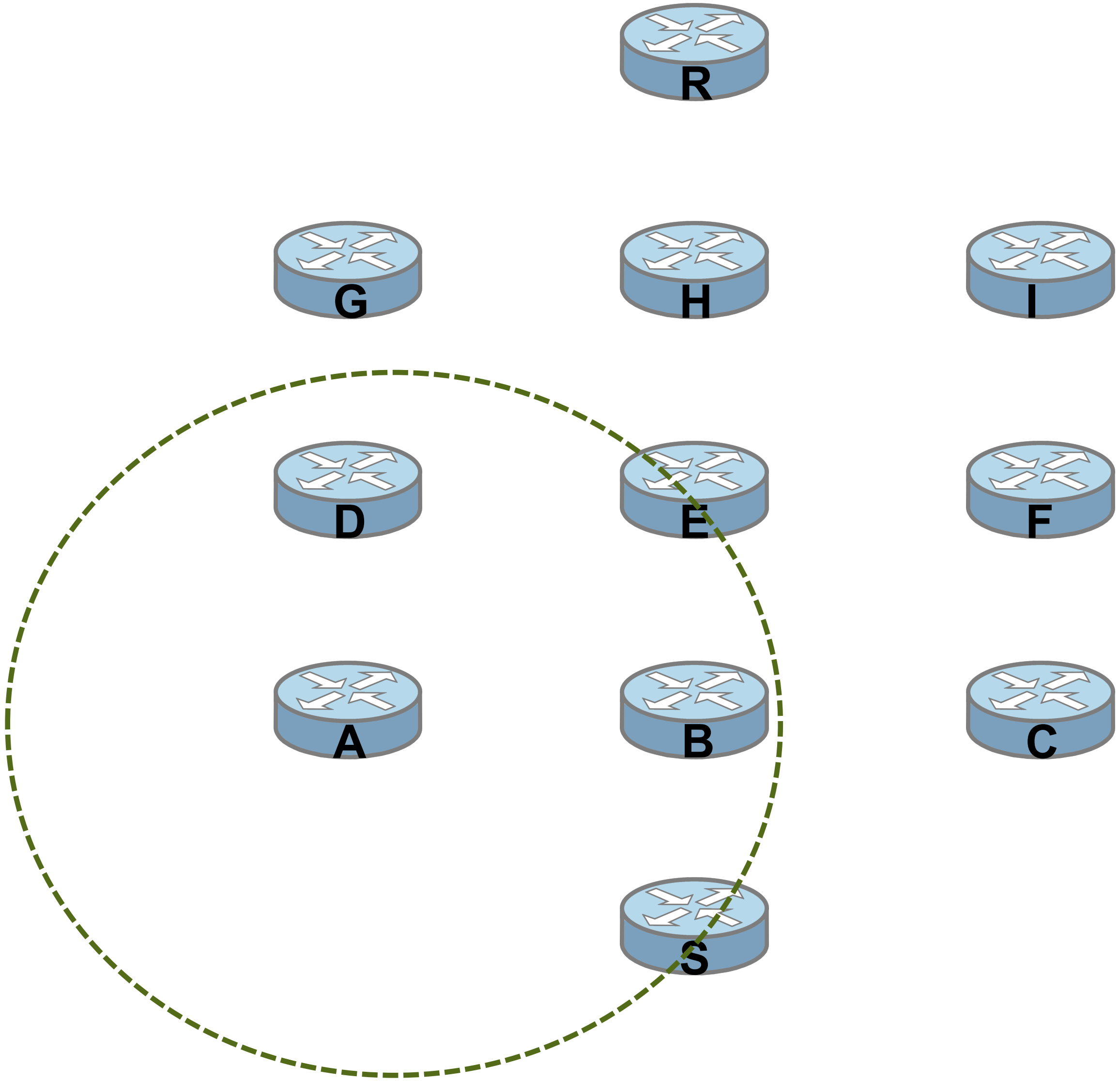
Terminology
Neighbor Set

- Neighbor Set A:
  - {D, E, B, S}



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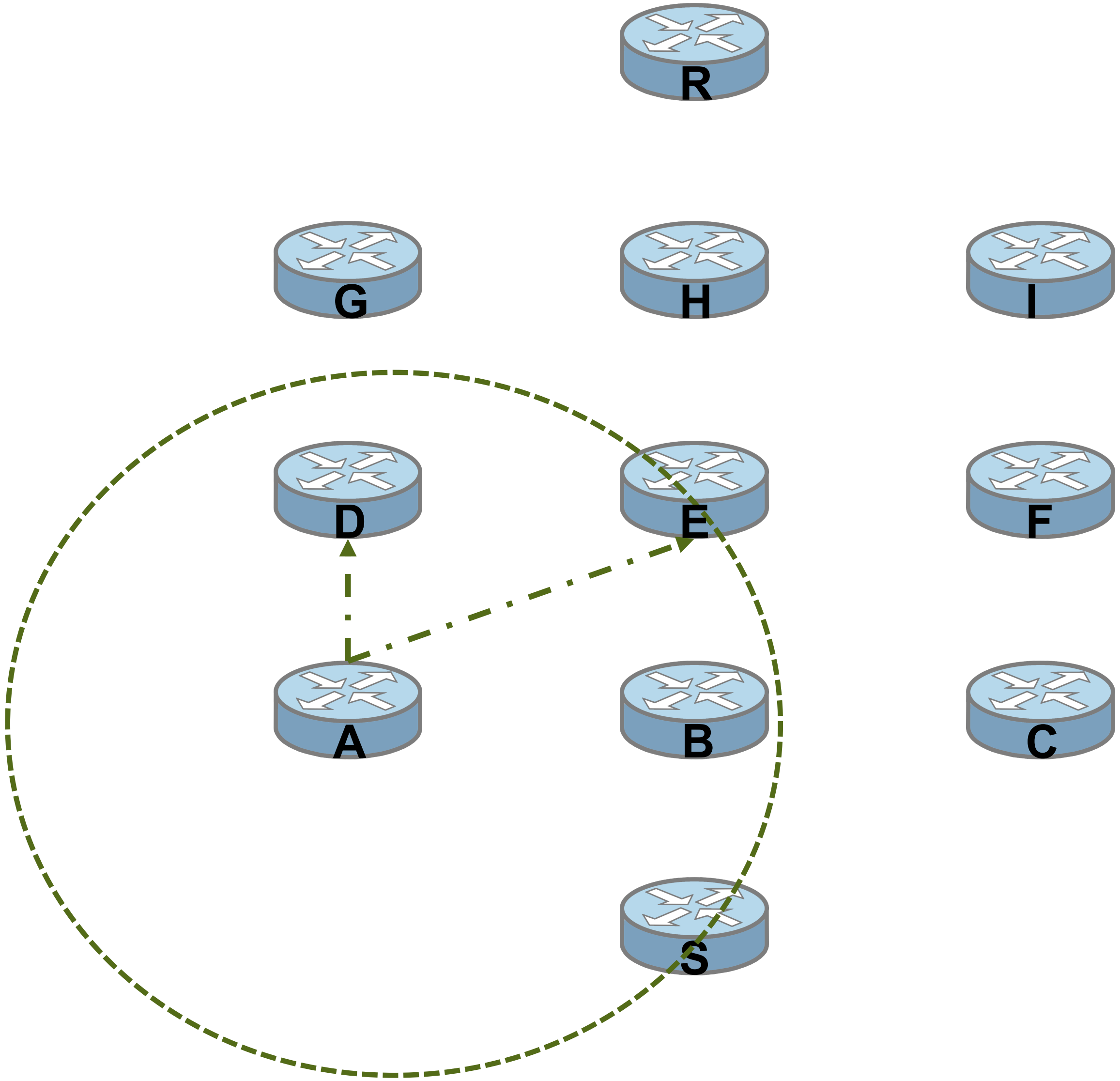
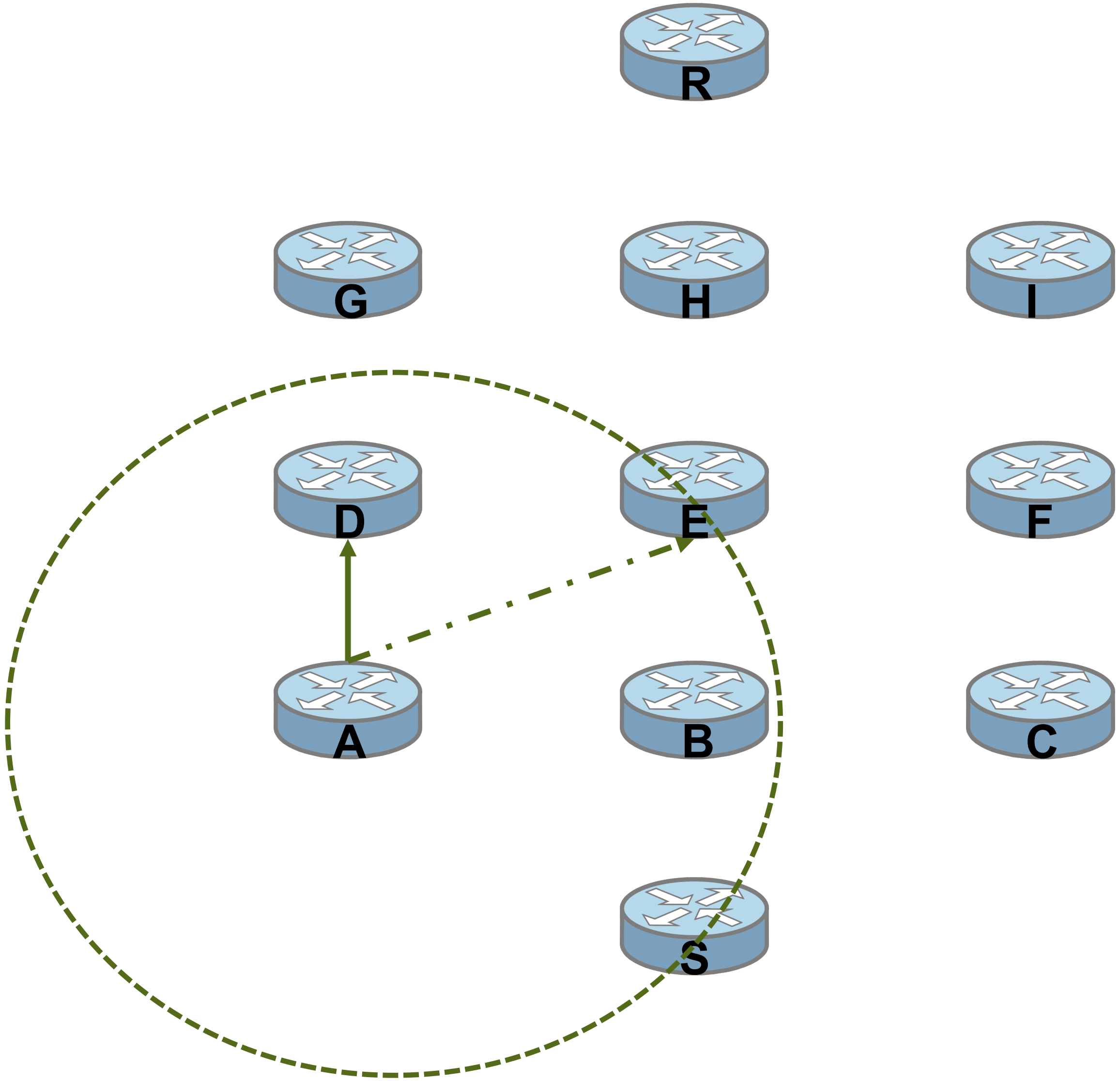
- Parent Set (PS) A:
  - {D, E}



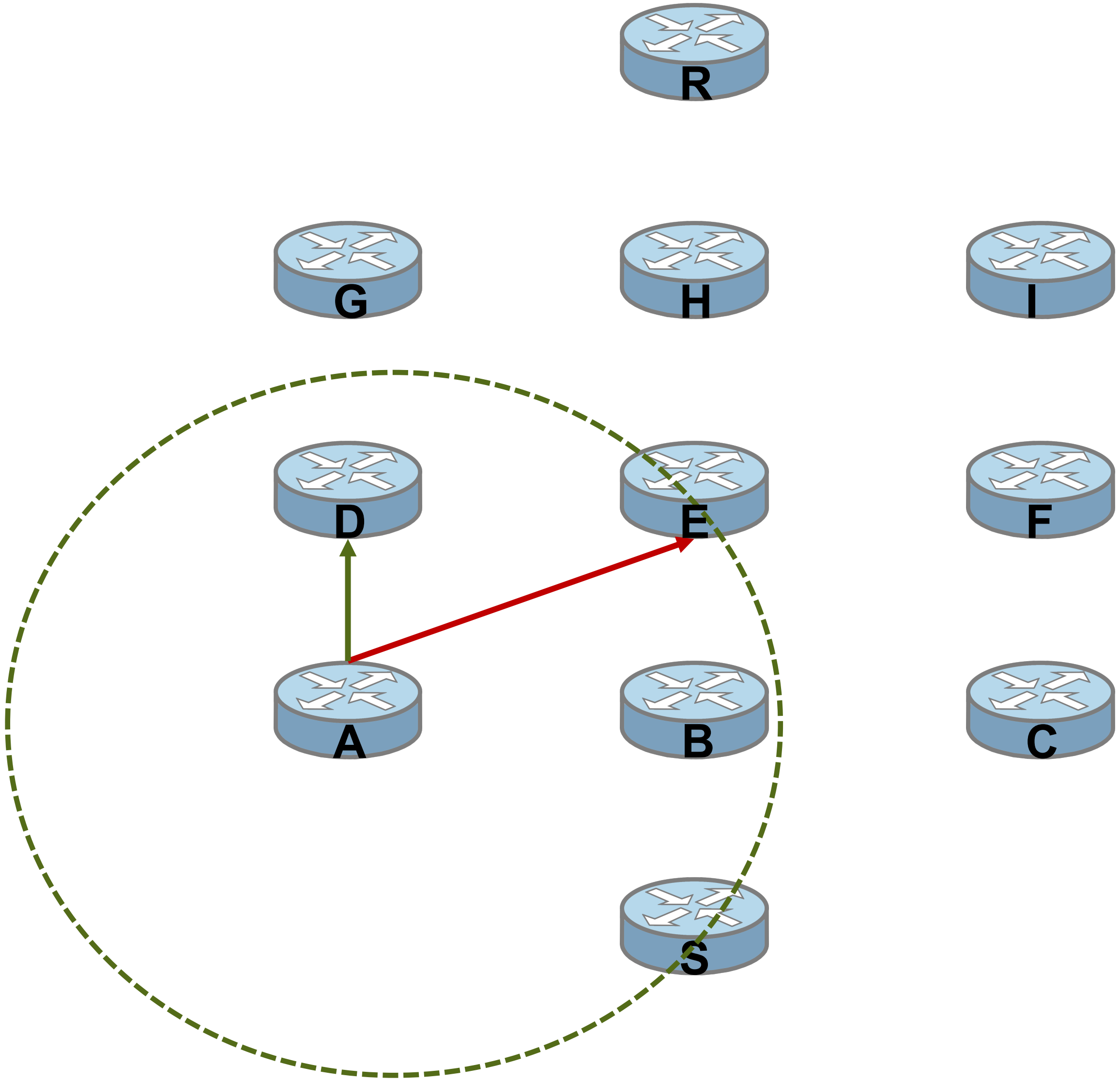
Terminology

Preferred Parent (PP)

- Preferred Parent (PP) A:
  - {D, E}



- Alternative Parent (AP) A:
  - {D, E}



Alternative Parent Selection: Example

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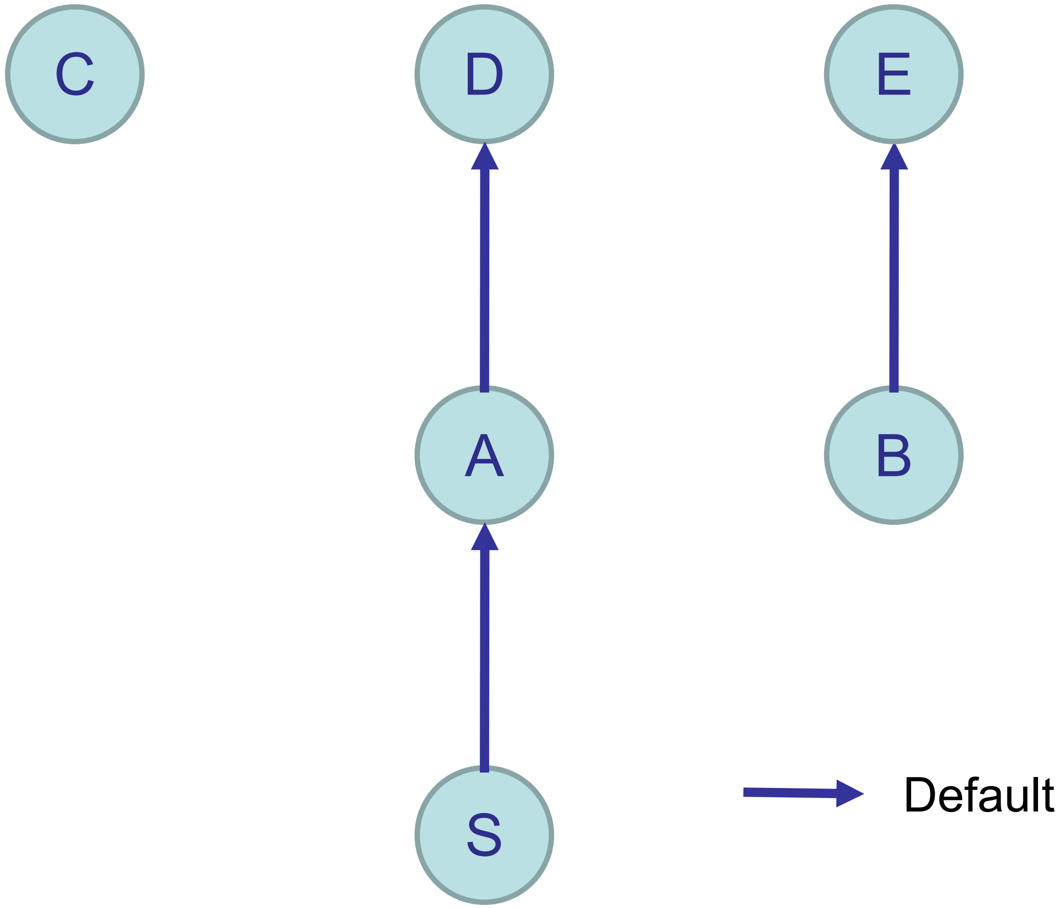
Alternative Parent Selection

Example

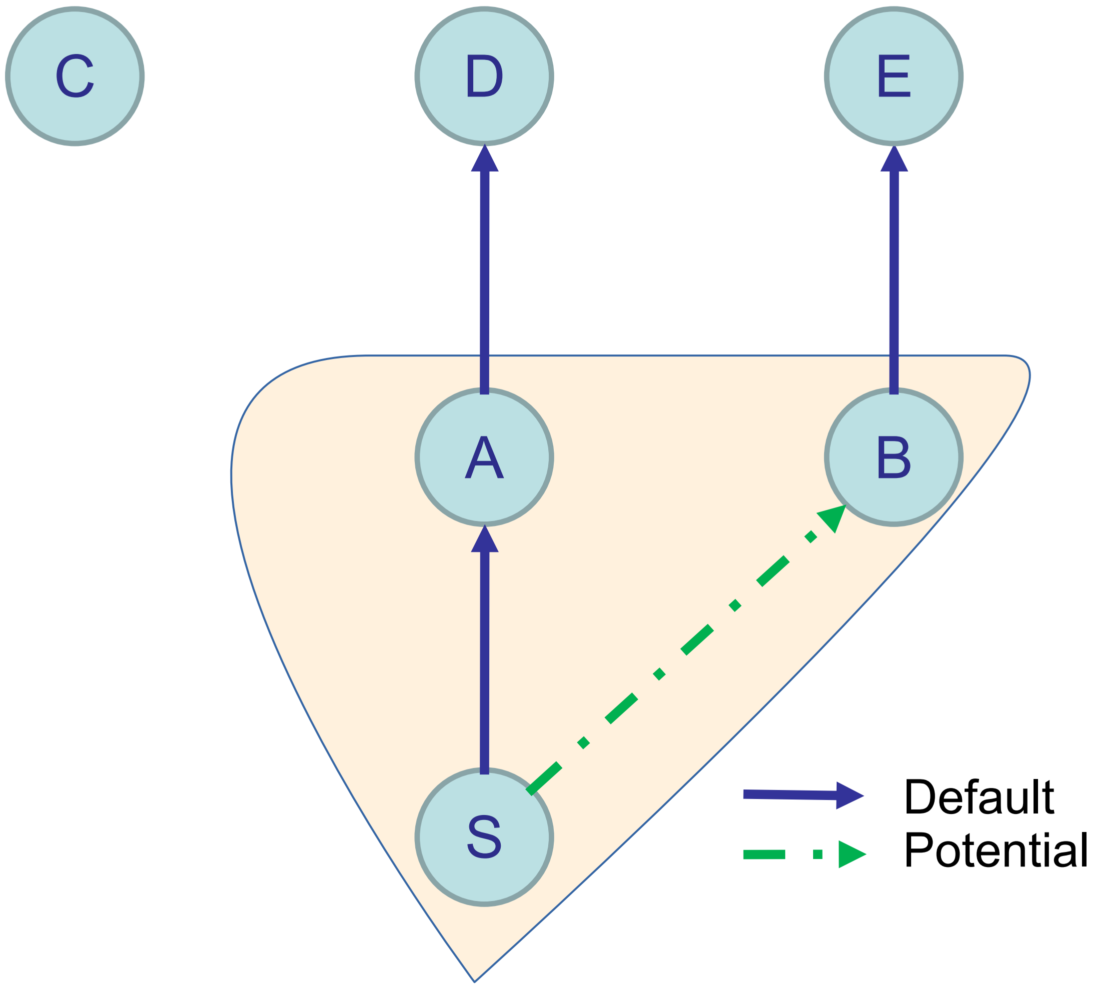
- RPL DODAG
  - S→A→D
  - B→E



Alternative Parent Selection

Example

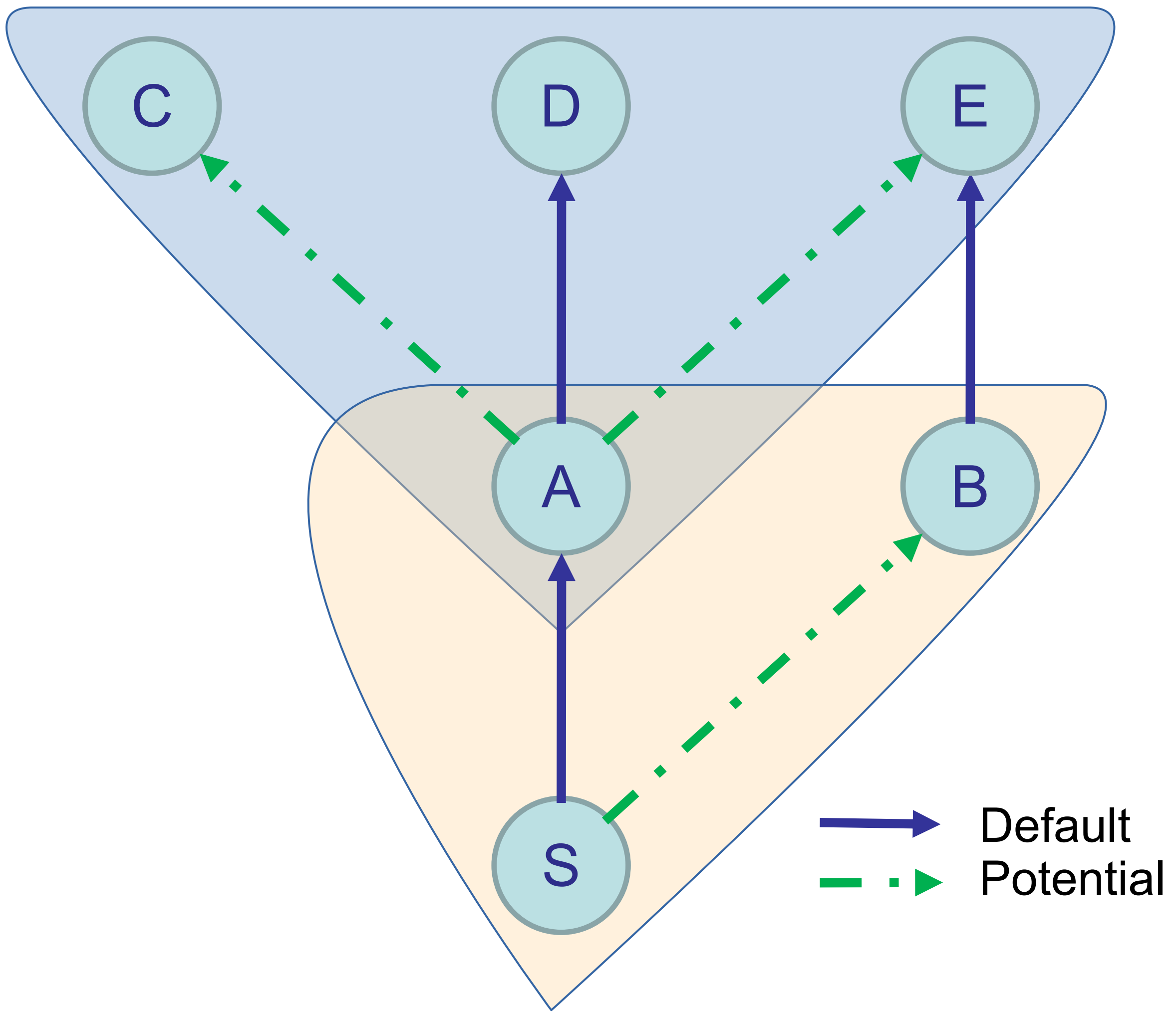
- Parent set S:
  - {A, B}



Alternative Parent Selection

Example

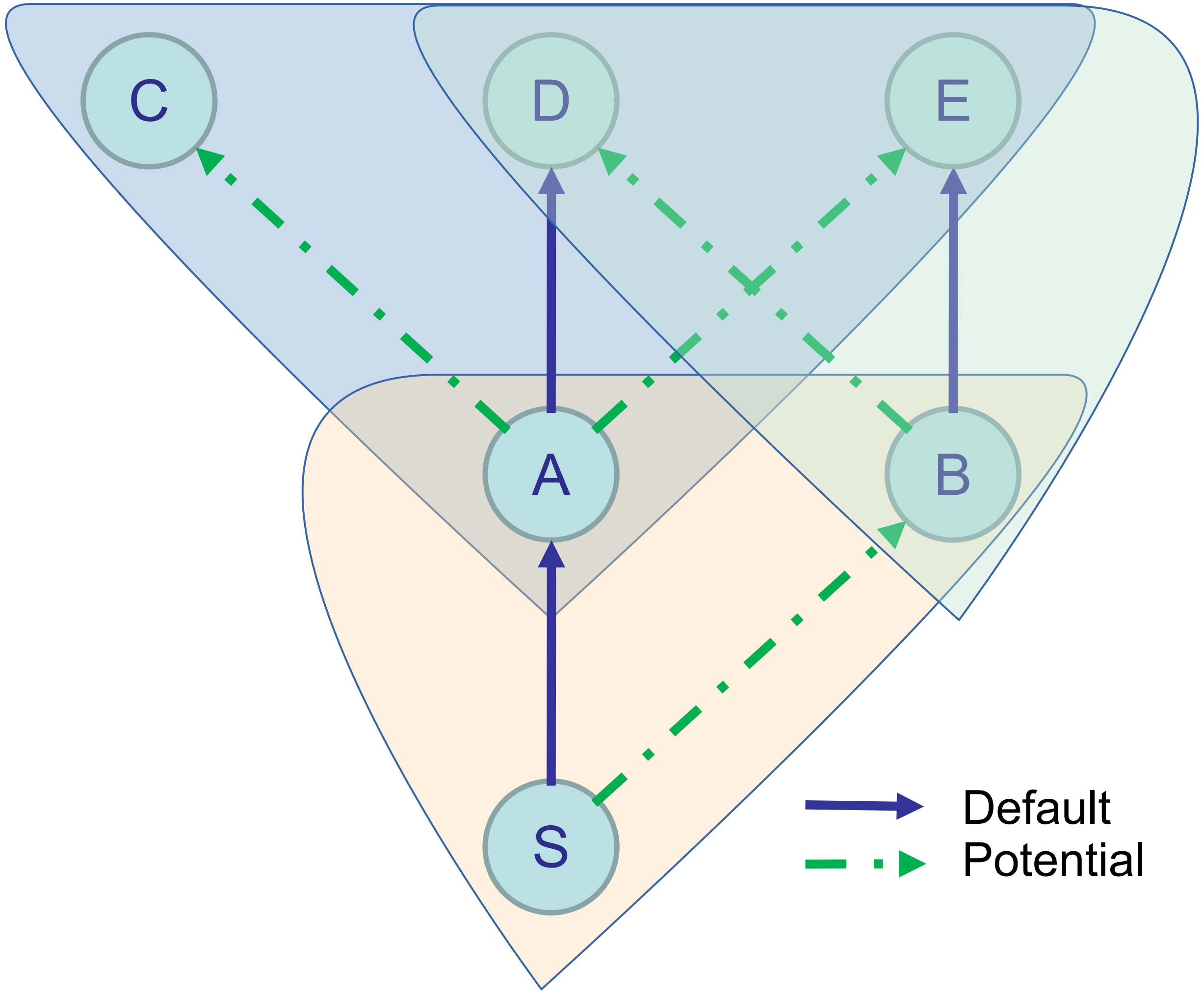
- Parent set S:
  - {<u>A</u>, B}
- Parent set A:
  - {<u>D</u>, C, E}



Alternative Parent Selection

Example

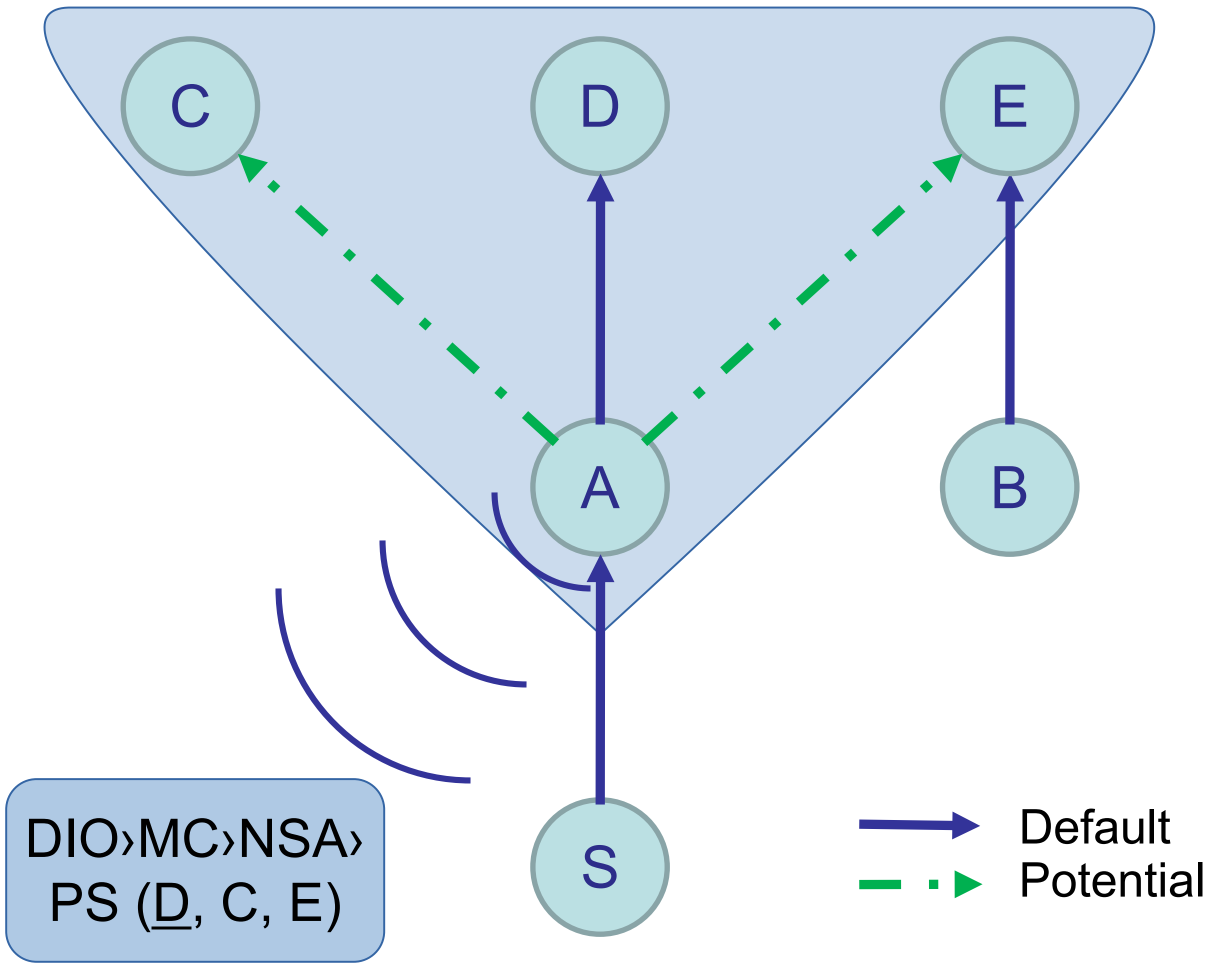
- Parent set S:
  - {<u>A</u>, B}
- Parent set A:
  - {<u>D</u>, C, E}
- Parent set B:
  - {<u>E</u>, D}



Alternative Parent Selection

Example

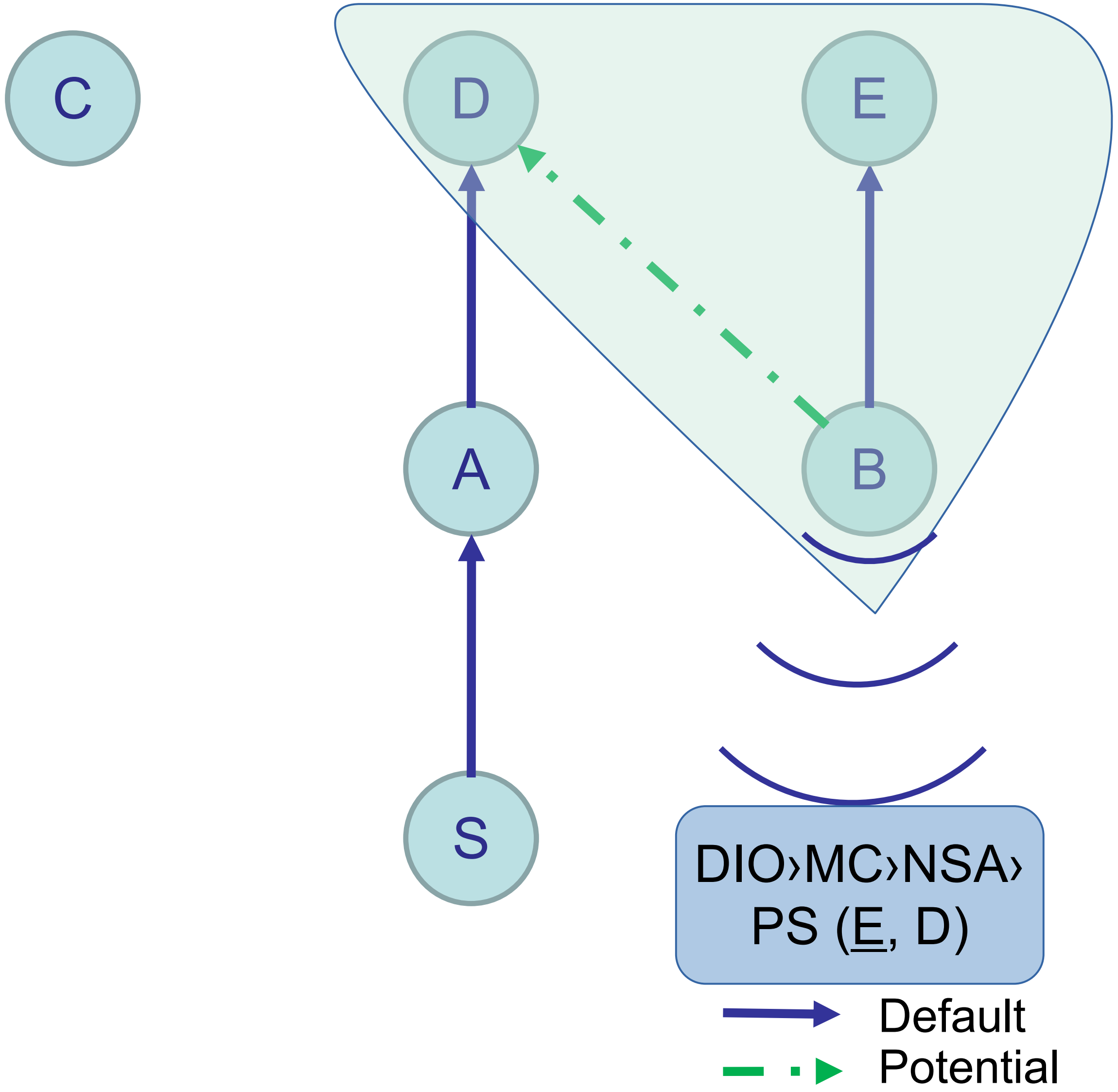
- A's DIO
  - Parent set A: {D, C, E}



Alternative Parent Selection

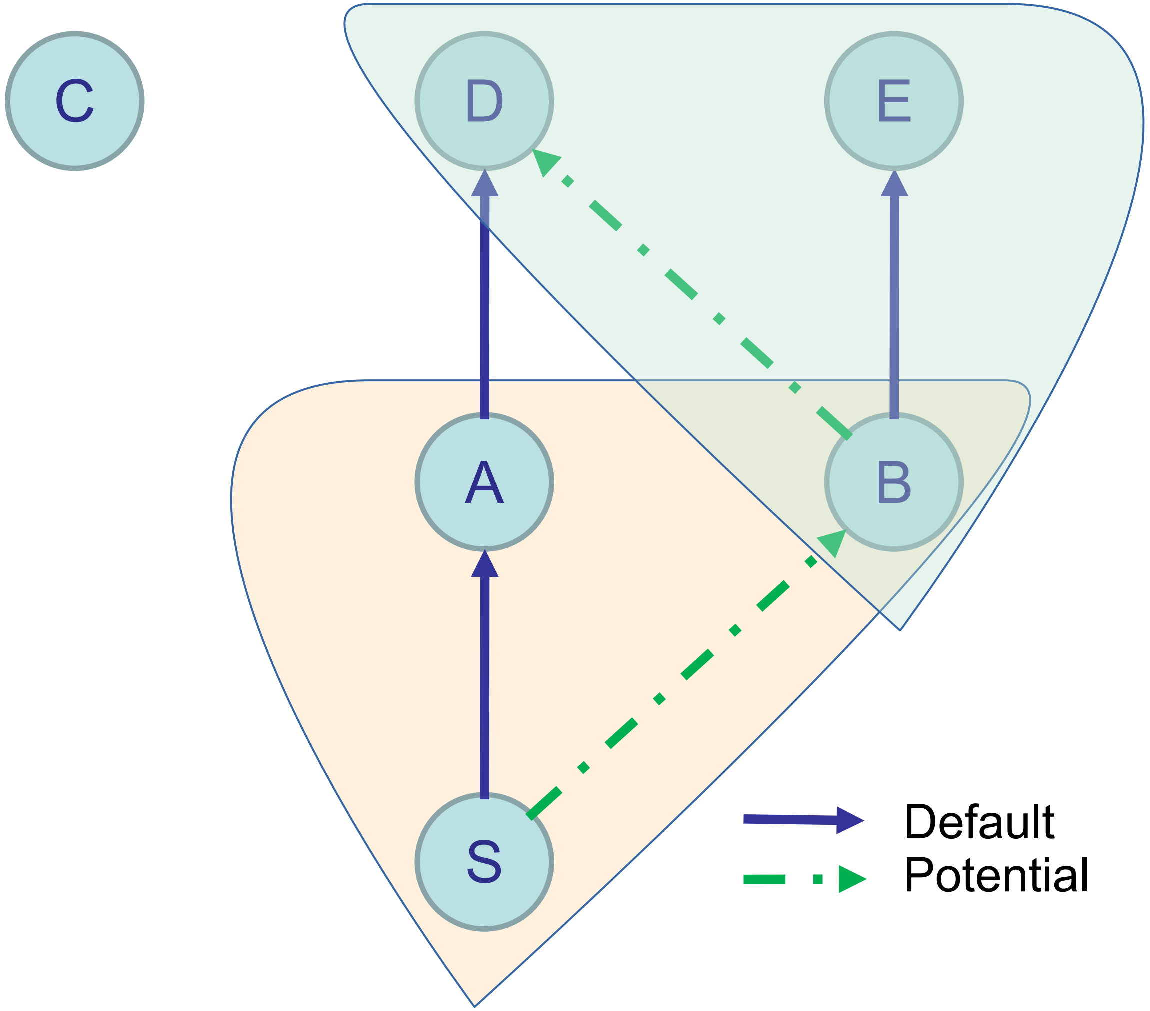
Example

- B's DIO
  - Parent set B: {E, D}



Alternative Parent Selection
Example

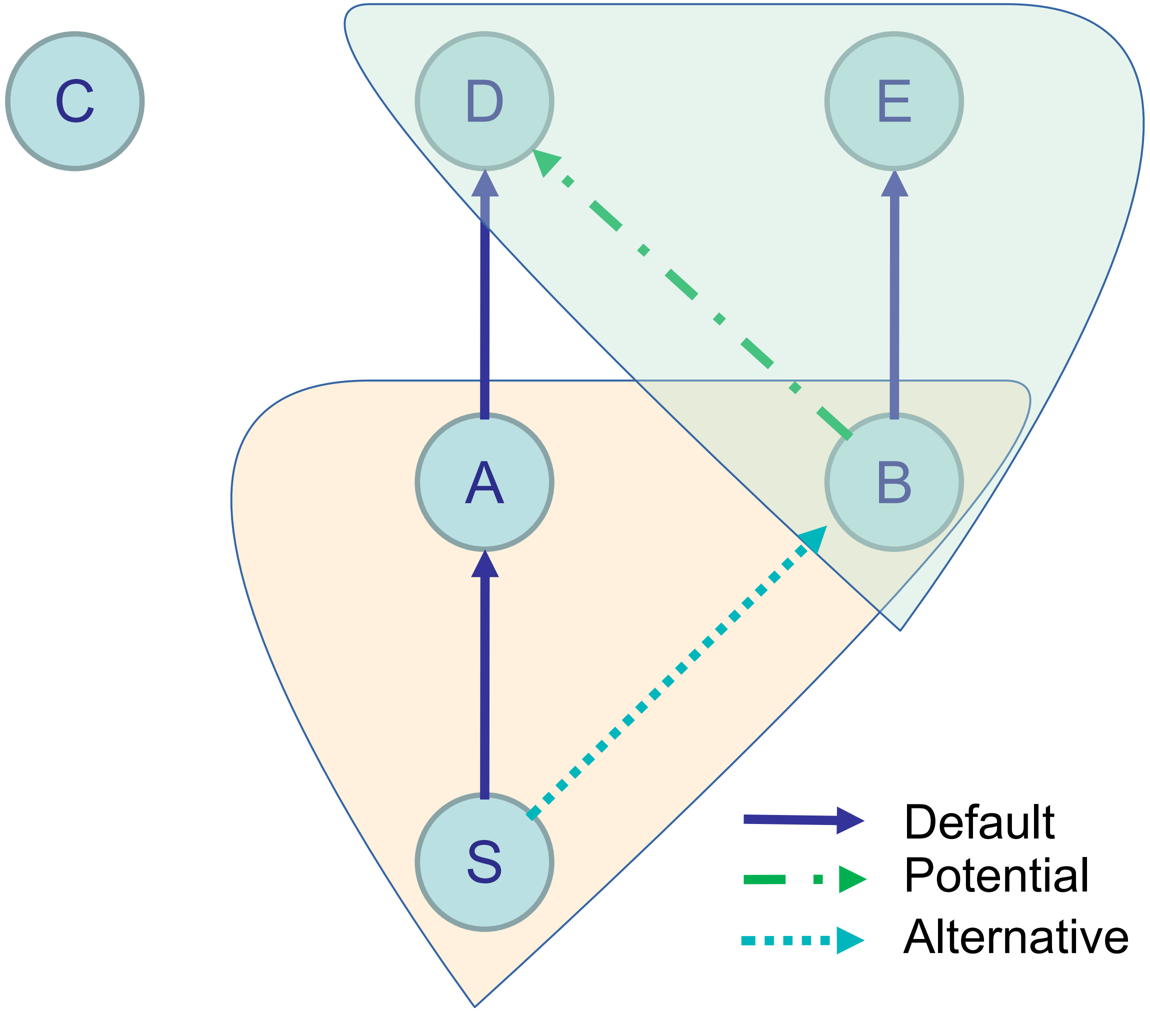
- S via A:
  - Default Grand Parent: D
- S via B:
  - Grand Parent Set: {E, D}
- **D is in {E, D}**



Alternative Parent Selection

Example

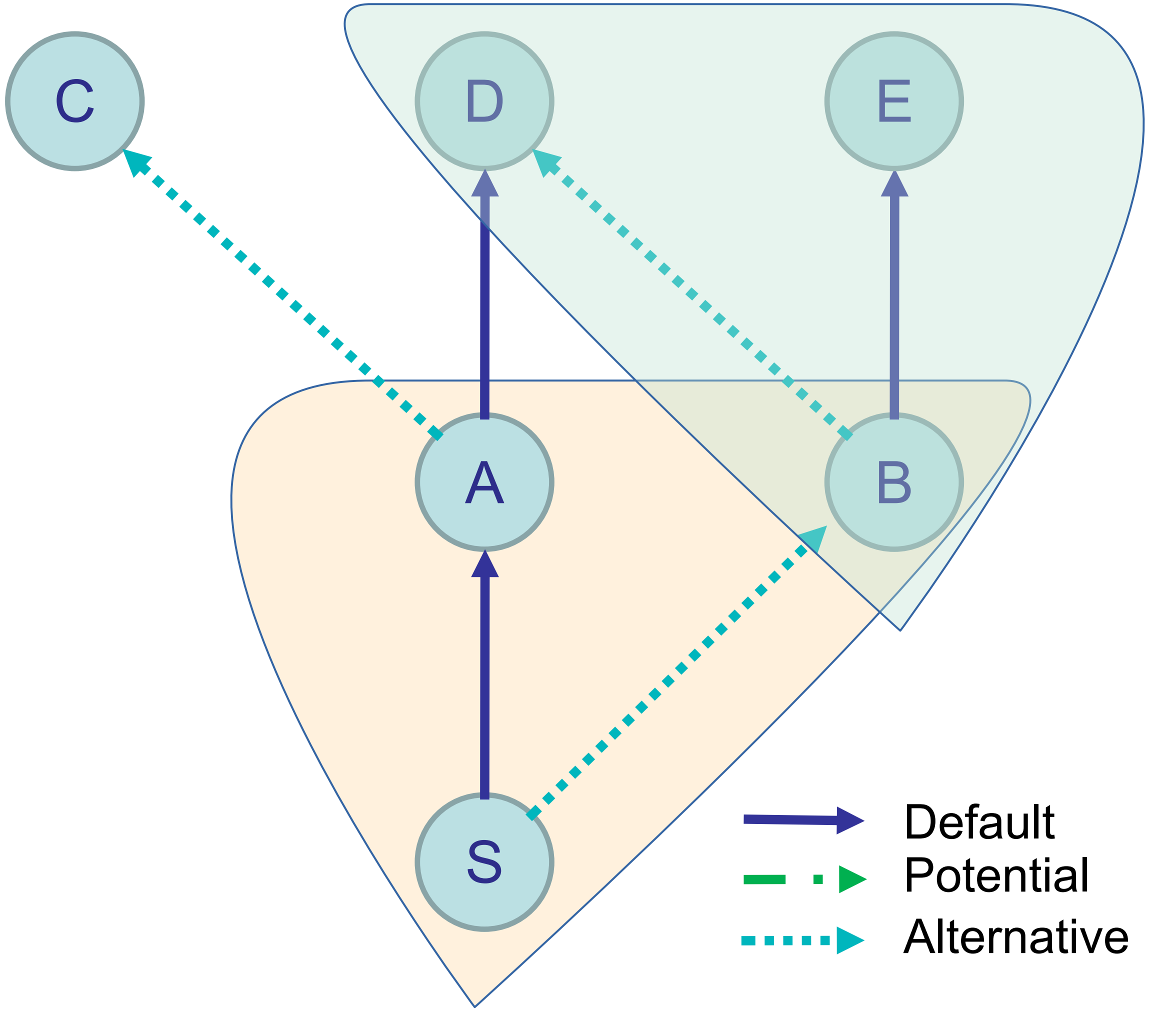
- S → B
  - Alternative Parent



Alternative Parent Selection

Example

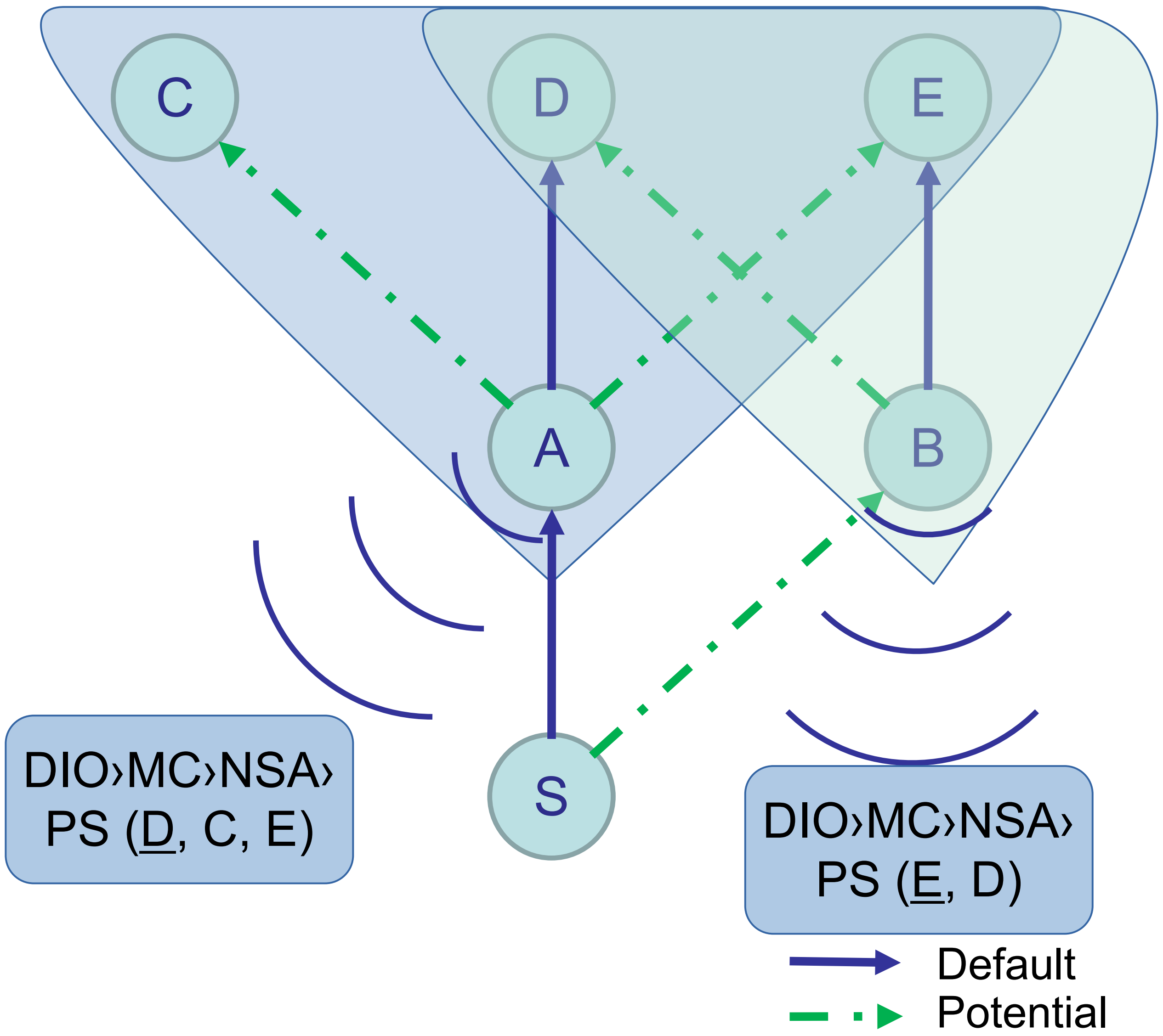
- Similarly, Alternative Parents:
  - A → C
  - B → D



Alternative Parent Selection

Example

- Parent Set A:
  - {D, C, E}
- Parent set B:
  - {E, D}



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PAREO Operation Example

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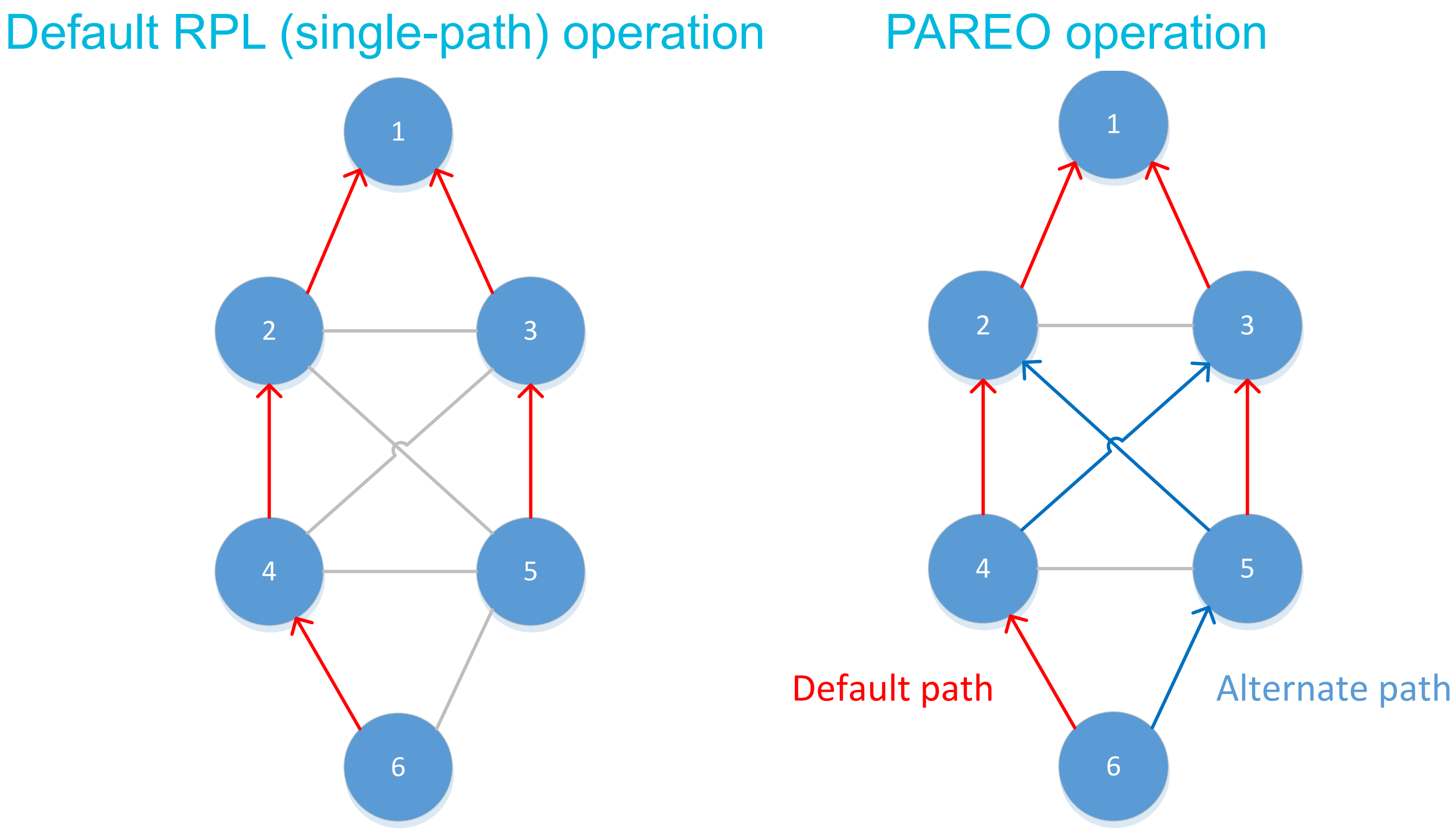
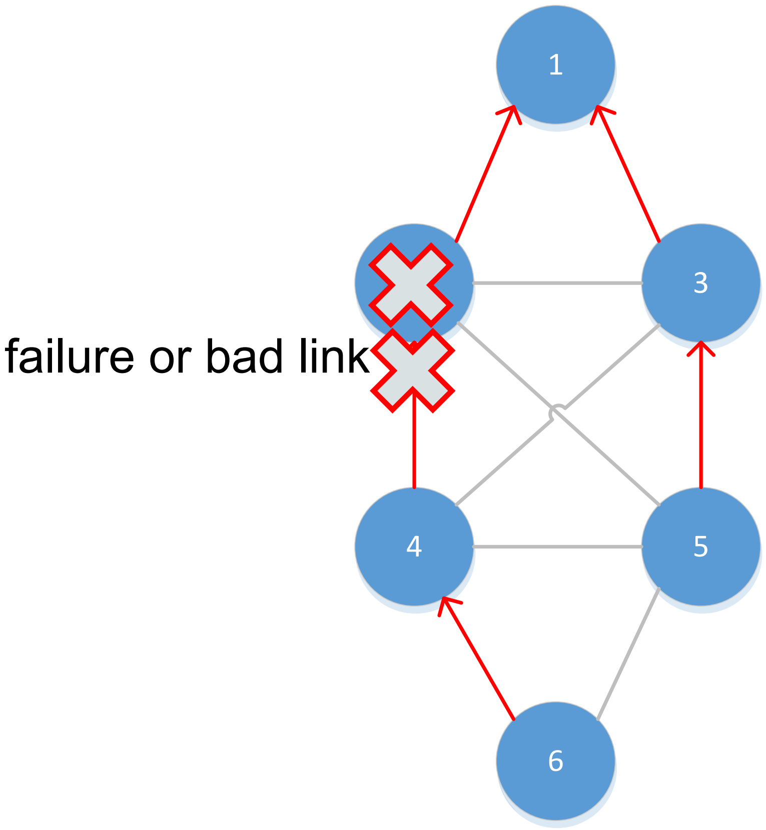
PAREO Operation

Example

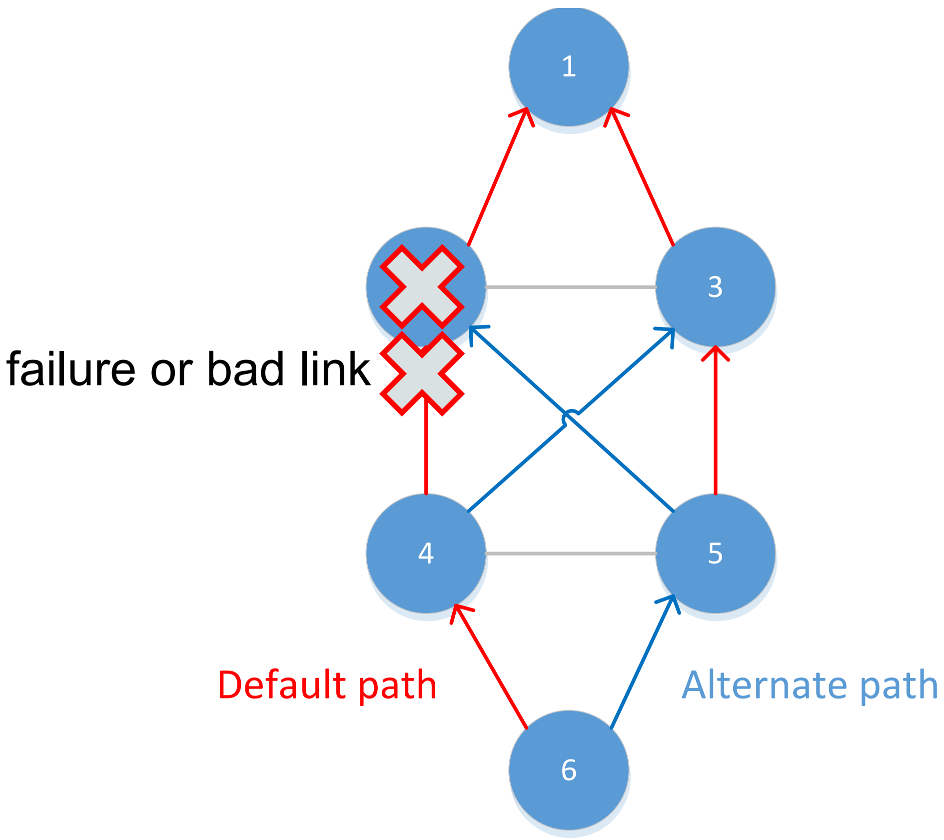


PAREO Operation
Example

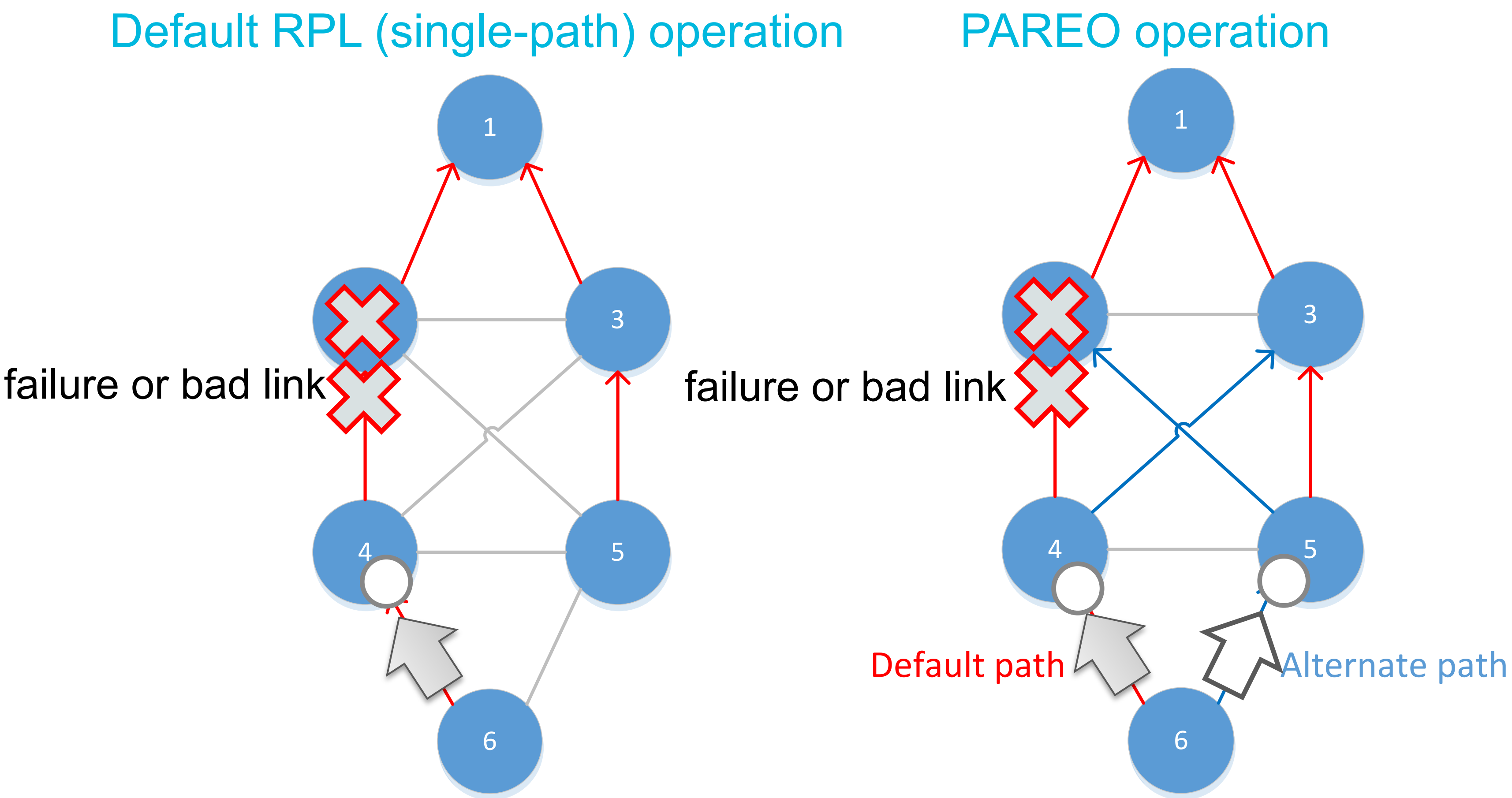
Default RPL (single-path) operation



PAREO operation

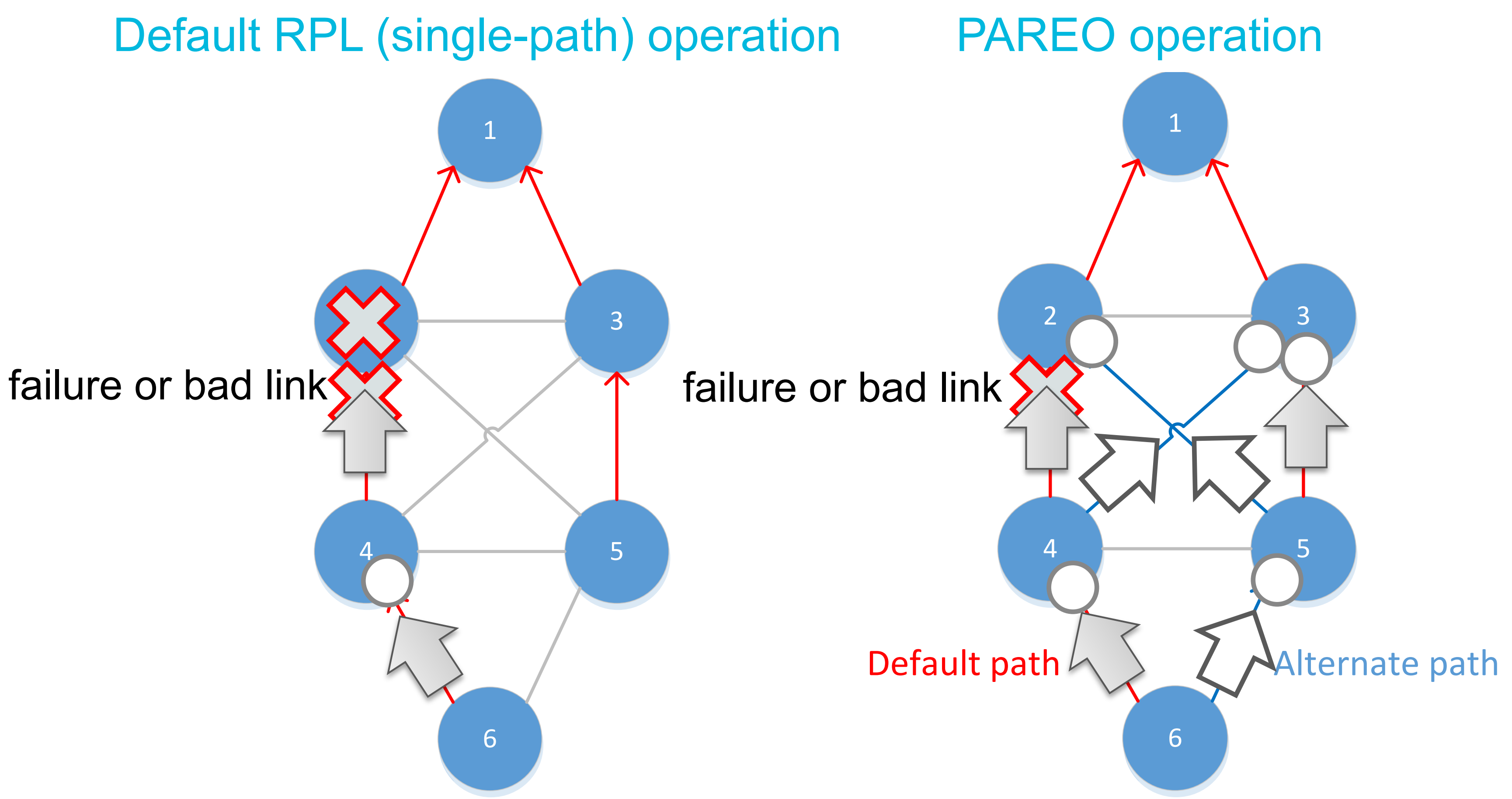


PAREO Operation
Example



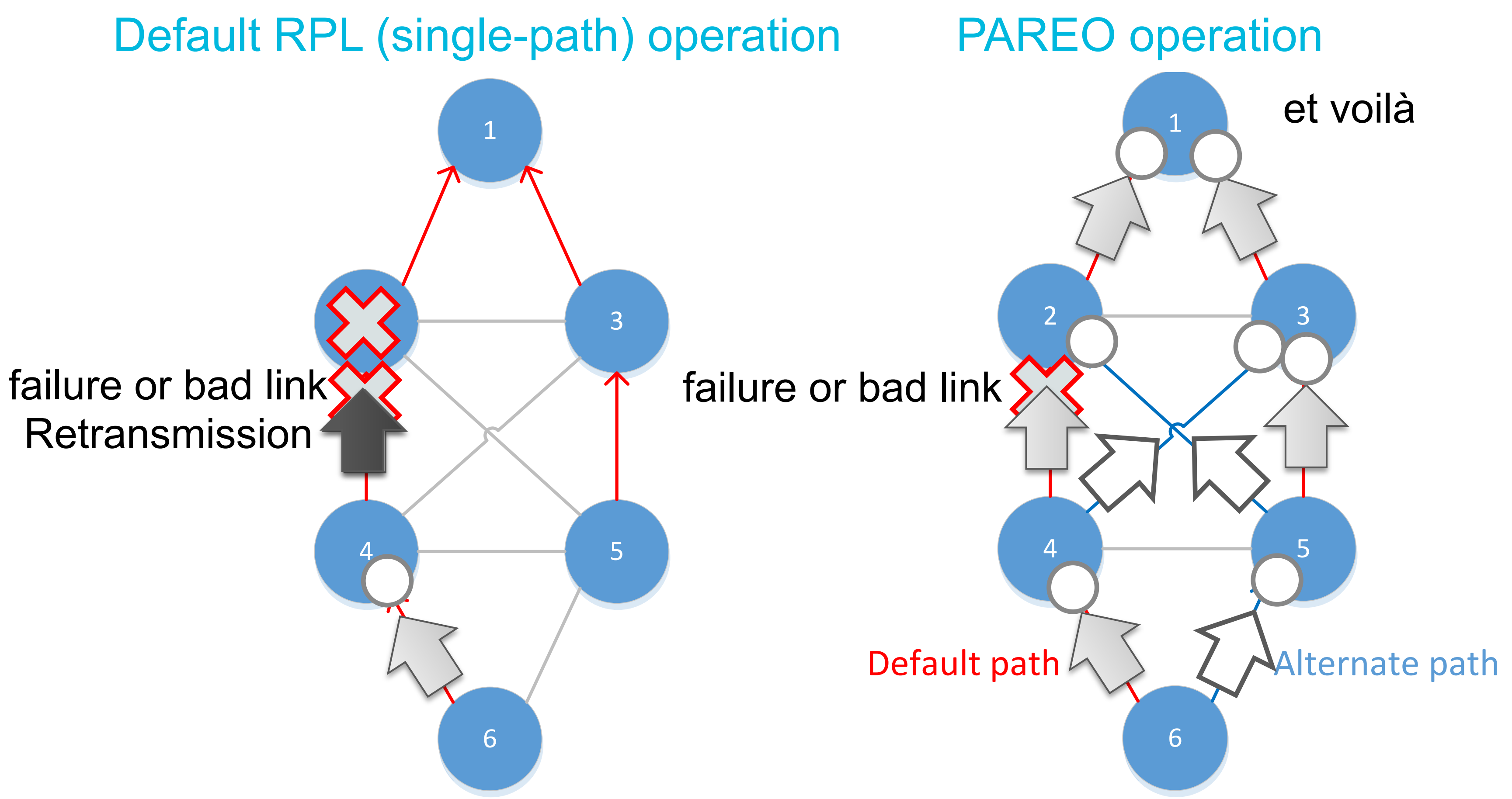
PARAEO Operation

Example



PAREO Operation

Example



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Multi-path Strategies in RPL-based Networks

n-Disjoint Strategies

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"Thorough Investigation of Multi-path Techniques in RPL based Wireless Networks”,
A. Czarnitzki Estrin, T. Lagos Jenschke, G. Z. Papadopoulos, J. I. Alvarez-Hamelin and N. Montavont,
In Proc. **IEEE ISCC 2020** - Rennes, France, July 2020.

n-Disjoint Strategies

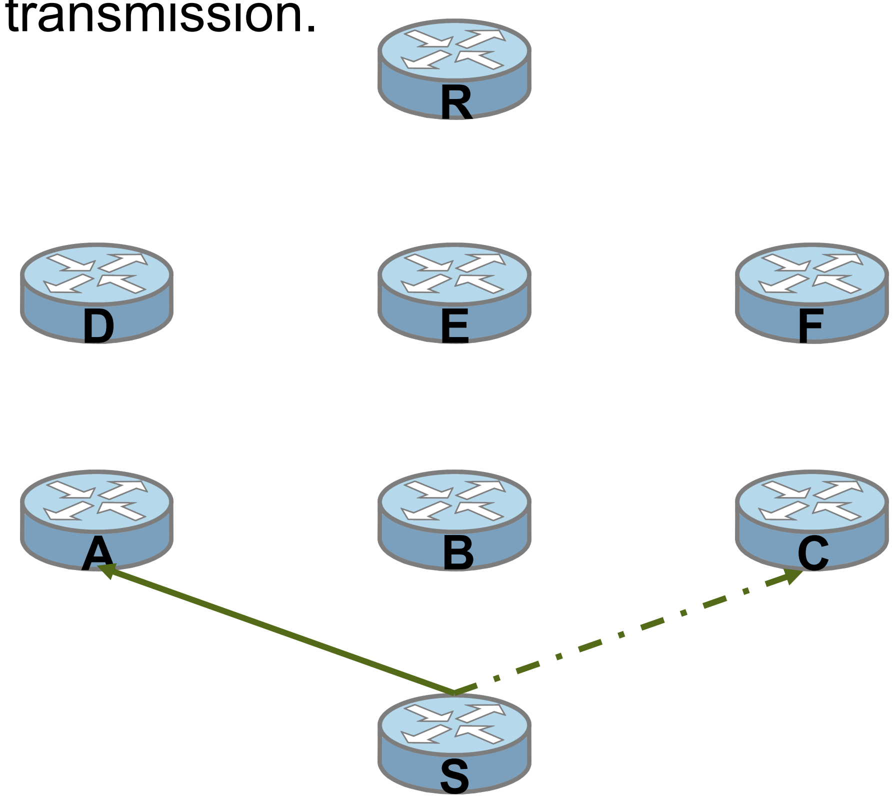
Overview

*The **n-Disjoint** strategy improves the end-to-end network reliability by employing disjoint pattern.*

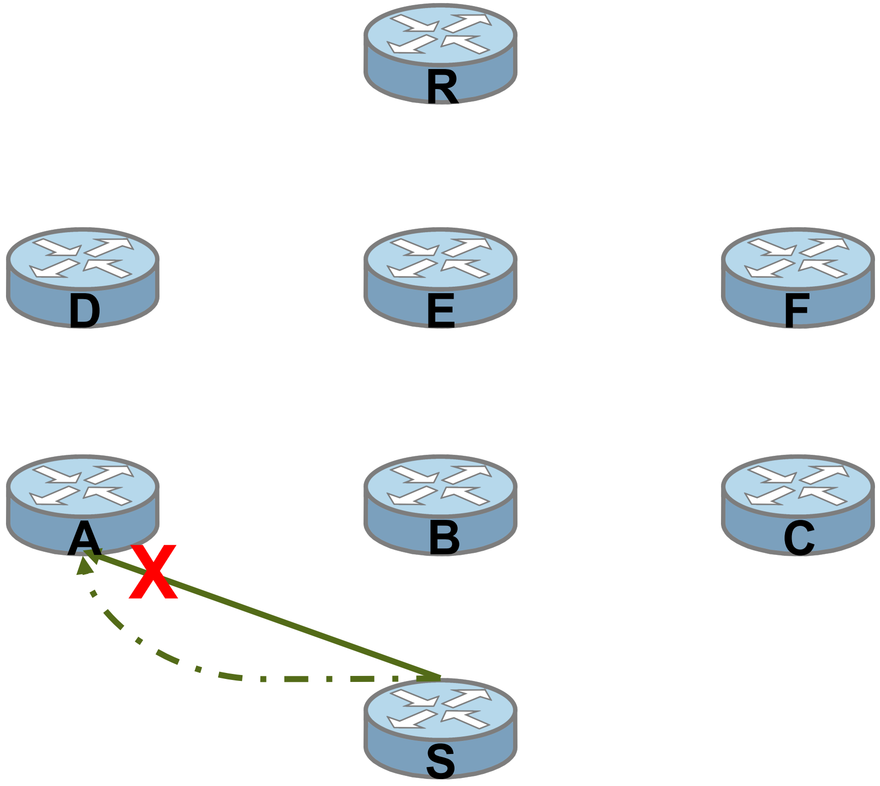
n-Disjoint Strategies

Replicas and Retransmissions

- Replicas:
  - Are copies of a data packet.
  - Each *replica* may follow a different path.
  - Are sent independently of the success of the original transmission.



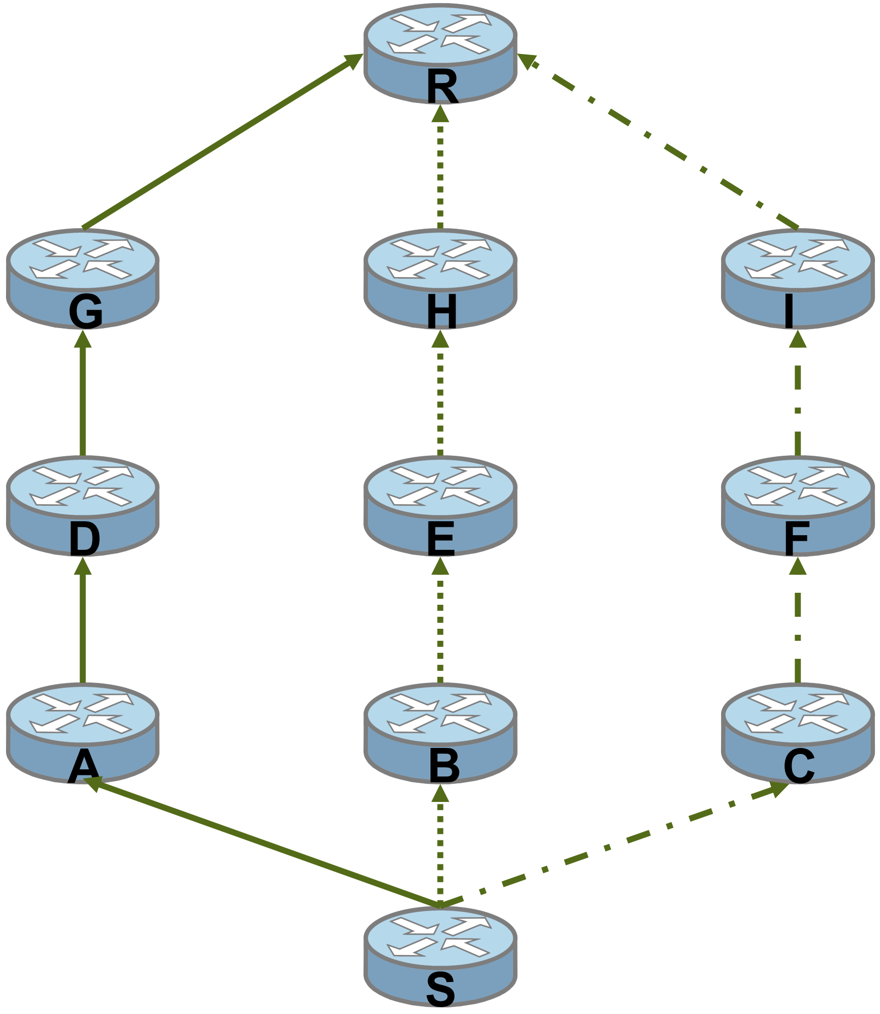
- Retransmissions:
  - Are additional opportunities to successfully deliver a data packet.
  - A *retransmission* of a data packet is enabled when a previous transmission failed.
  - Link-layer retransmission function.



n-Disjoint Strategies

Default Strategy

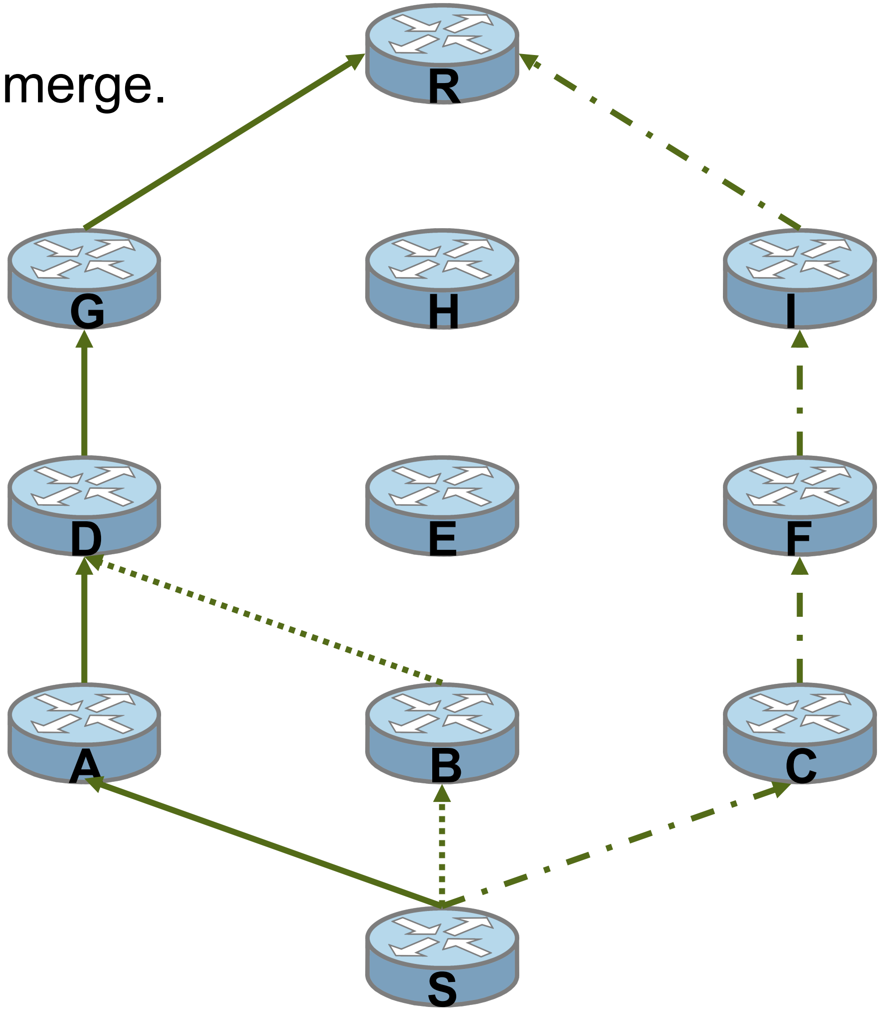
- The source selects n+1 best parents (e.g., ETX metric).
- It sends one copy (Replica) to each of them.
- The relay nodes forward the data packet to their PP.
- This is valid for n < |PS|, where *n* is the # of replicas.



n-Disjoint Strategies

Default Strategy

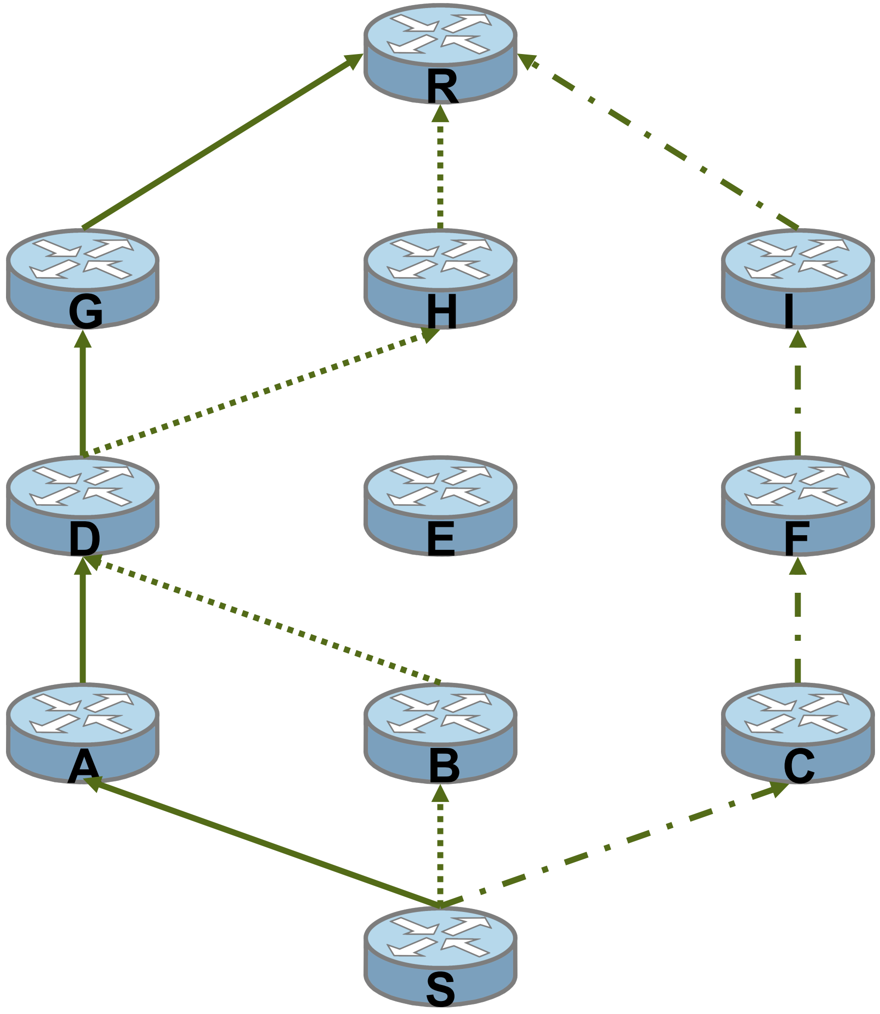
- If two or more nodes have the same PP, their paths will merge.
- If two or more copies arrive at the same node → only one is forwarded.



n-Disjoint Strategies

Advanced Strategy

- If one node detects that a merge takes place, it forwards them to different parents.
- All the relay nodes selects n+1 parents from its PS using the ETX metric.
- If a replica is received, the next best parent is selected.



Common Ancestor (CA) Algorithms

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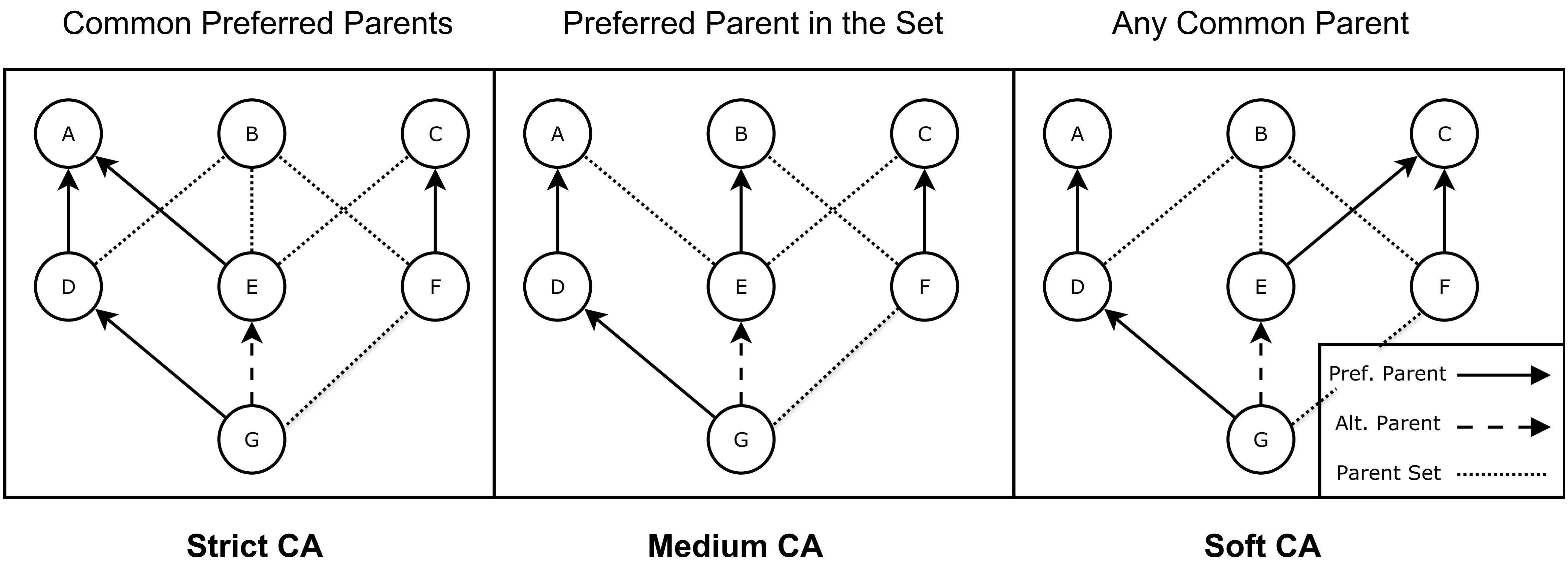
T. Lagos Jenschke, G. Z. Papadopoulos, R. A. Koutsiamanis, N. Montavont,
"Alternative Parent Selection for Multi-Path RPL Networks”,
IEEE WF-IoT, 2019.

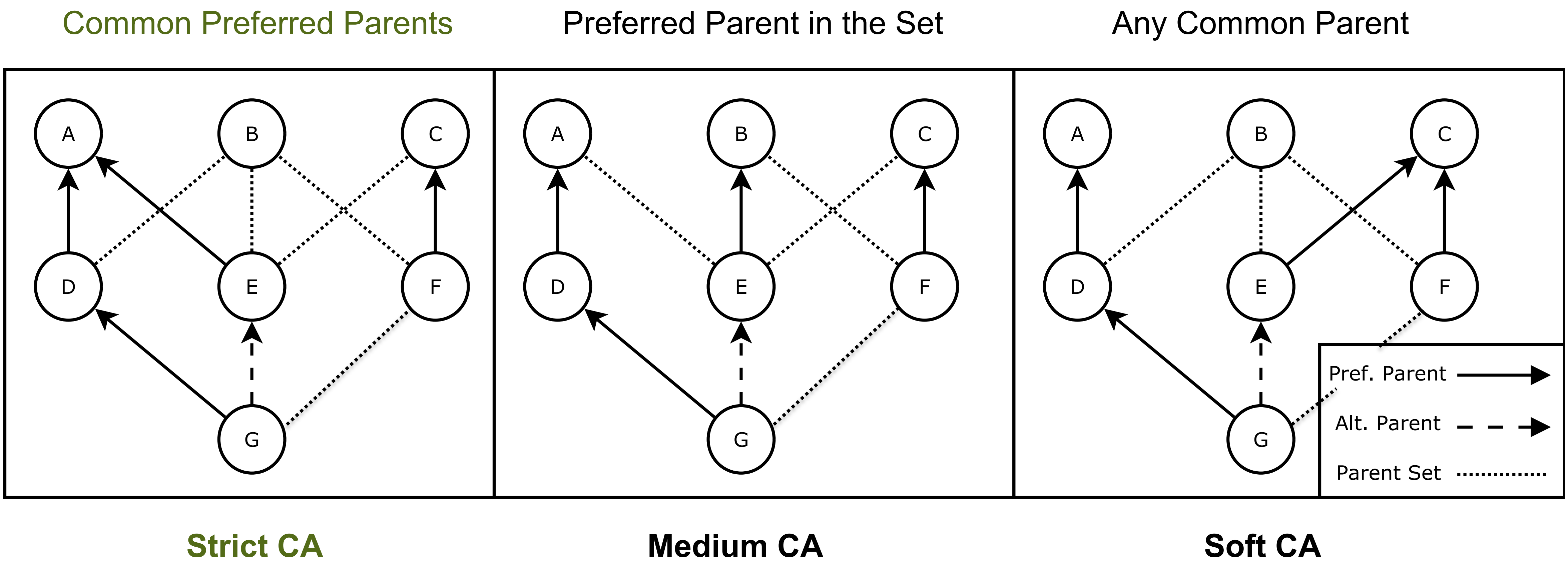
Common Ancestor Algorithms

Strict CA – Medium CA – Soft CA



Common Ancestor Algorithms

Strict CA – Medium CA – Soft CA



Common Ancestor Algorithms

Strict CA mode

$$PP(PP) = PP(AP)$$

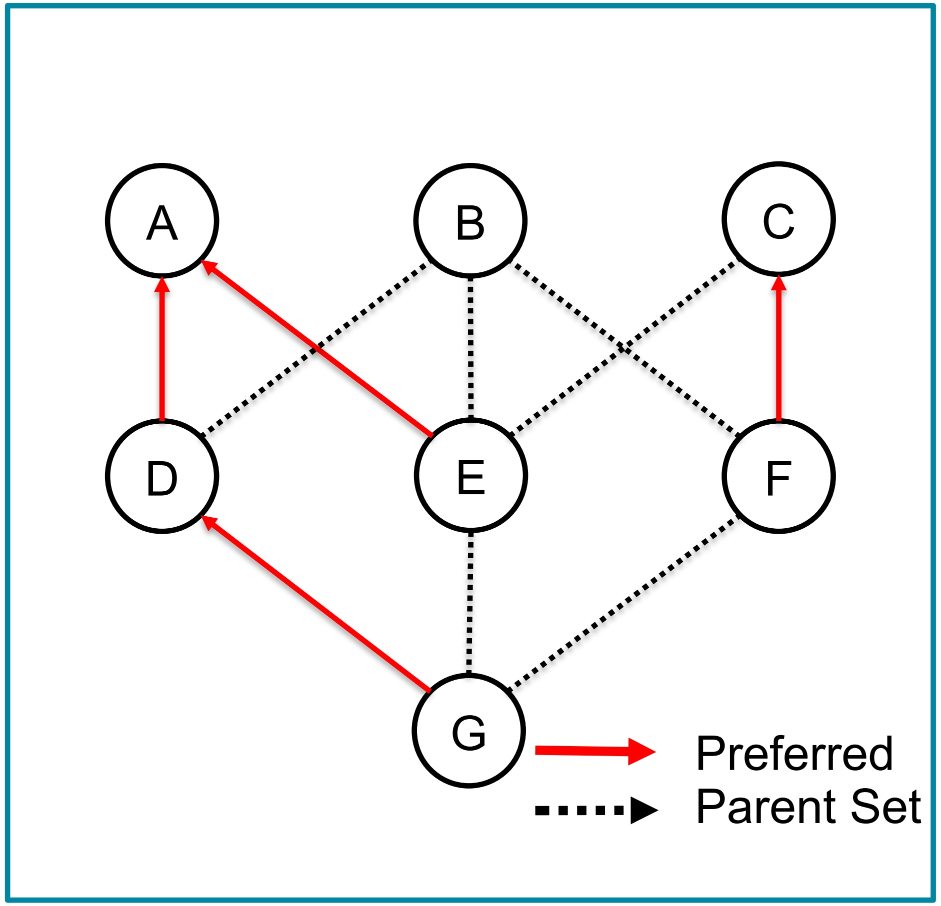
Common Ancestor Algorithms

Strict CA mode

$$PP(PP) = PP(AP)$$

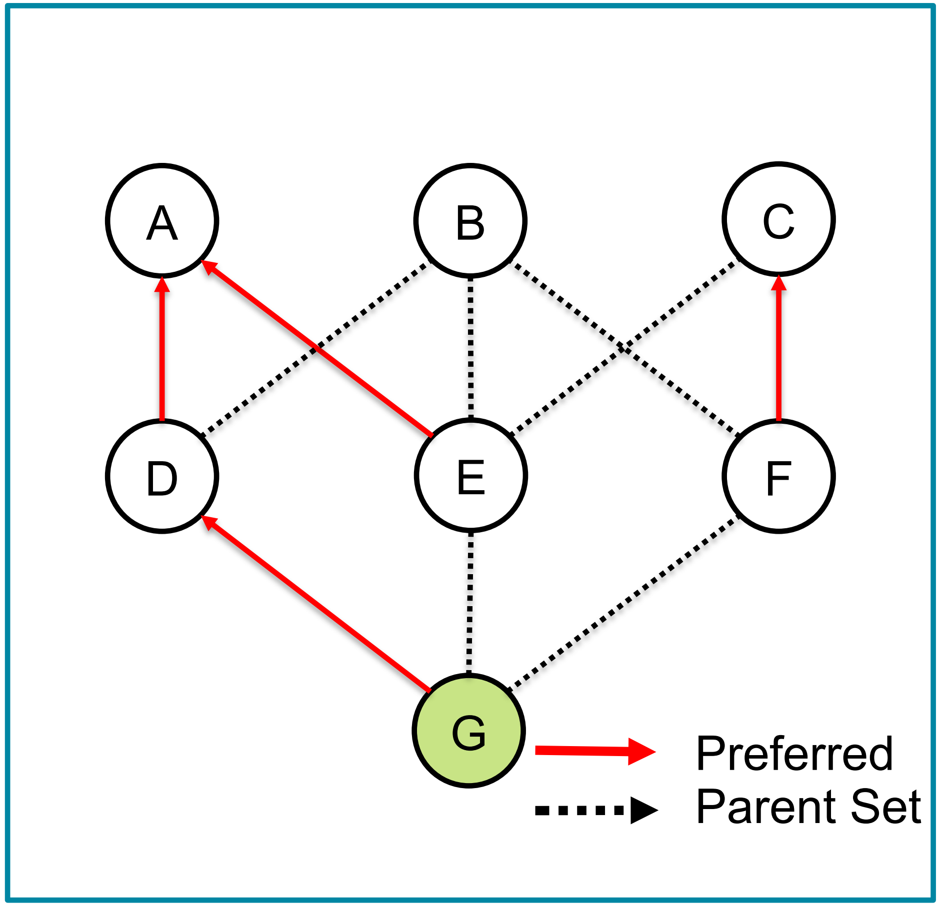
- *The Red lines indicate the Preferred Parents*
- *The Dotted lines indicate the Parent Set*

- In this example :
  - **D** has Preferred Parent **A**, and **B** in its Parent Set
  - **E** has Preferred Parent **A**, and **B** & **C** in its Parent Set
  - **F** has Preferred Parent **C**, and **B** in its Parent Set



$$PP(PP) = PP(AP)$$

- We will take **G** as the **example node** :

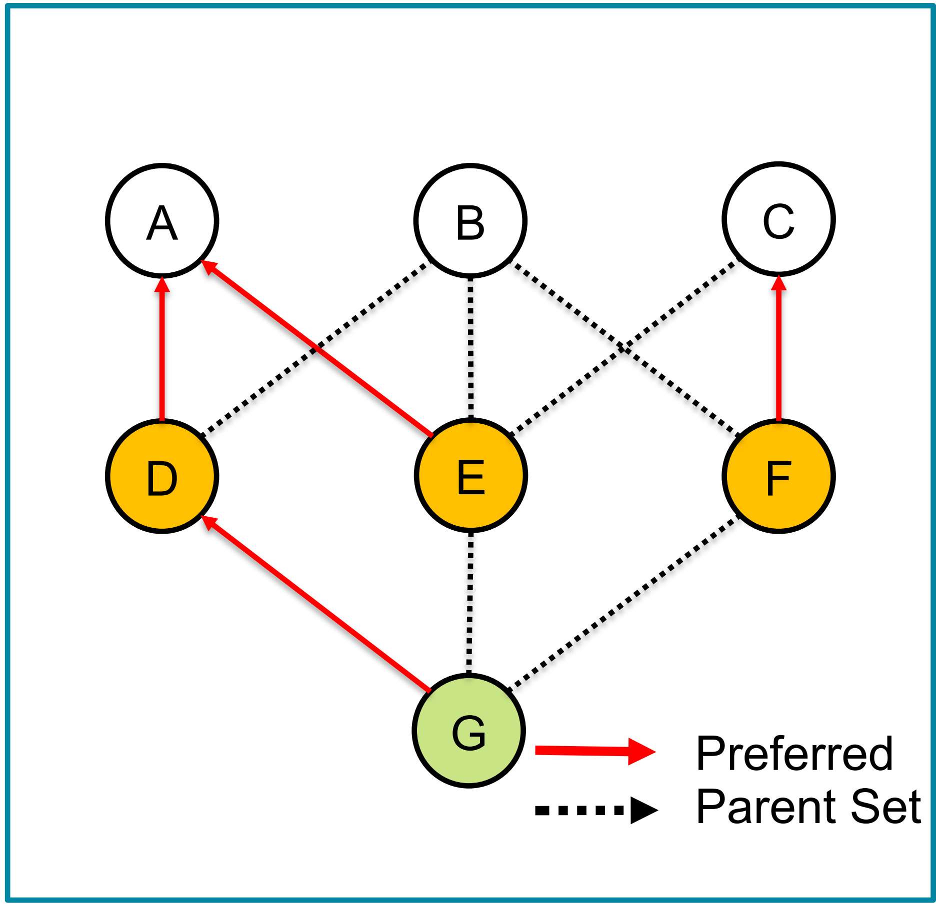


Common Ancestor Algorithms

Strict CA mode

$$PP(PP) = PP(AP)$$

- We will take **G** as the **example node** :
  - **G** has **D** as PP, and **E** & **F** in its Parent Set

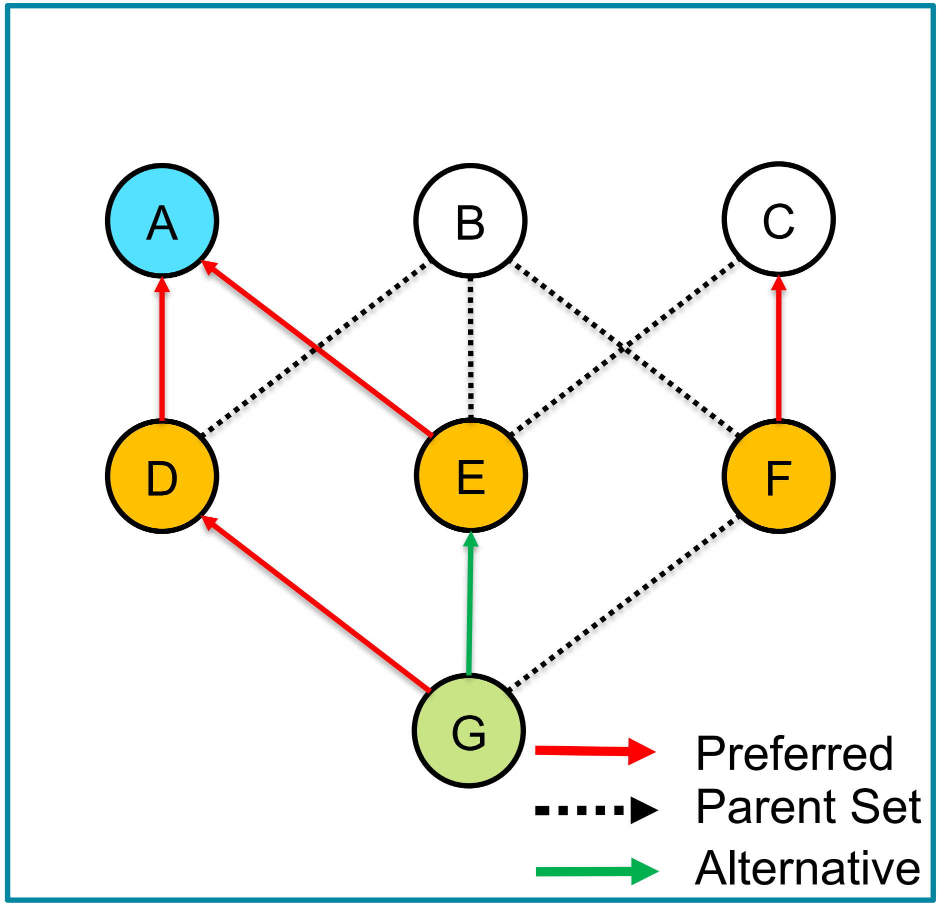


Common Ancestor Algorithms

Strict CA mode

$$PP(PP) = PP(AP)$$

- We will take **G** as the **example node**
  - **G** has **D** as PP, and **E** & **F** in its Parent Set
  - ***Only node E fulfils the condition →***
    As A is the PP of D, and of E



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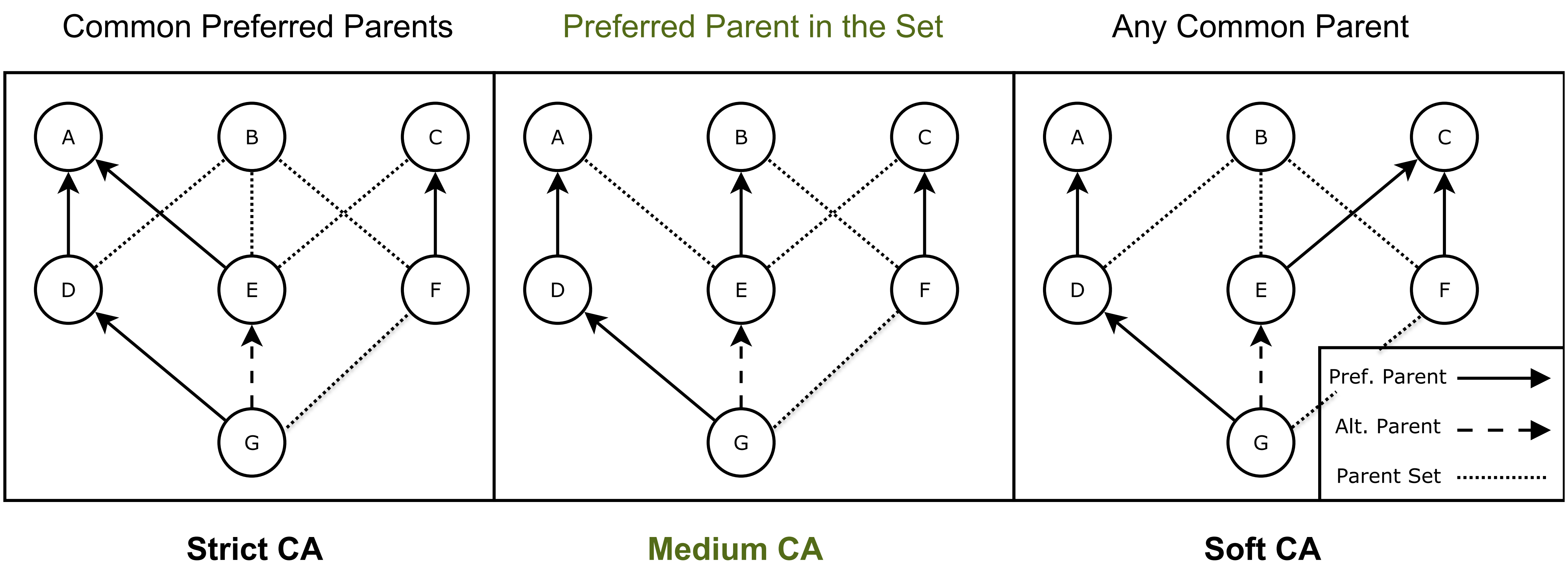
Common Ancestor Algorithms

Strict CA – Medium CA – Soft CA



Common Ancestor Algorithms

Medium CA mode

$$PP(PP) \in PS(AP)$$

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Common Ancestor Algorithms

Medium CA mode

$$PP(PP) \in PS(AP)$$

- *The Red lines indicate the Preferred Parents*
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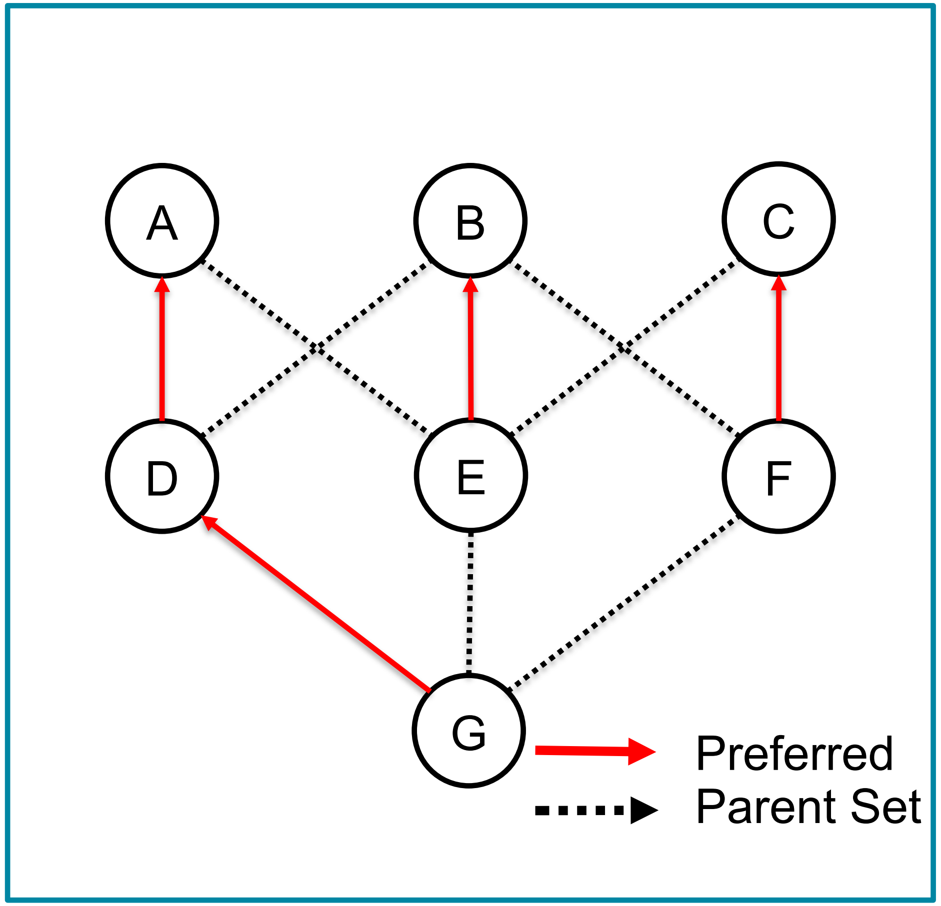
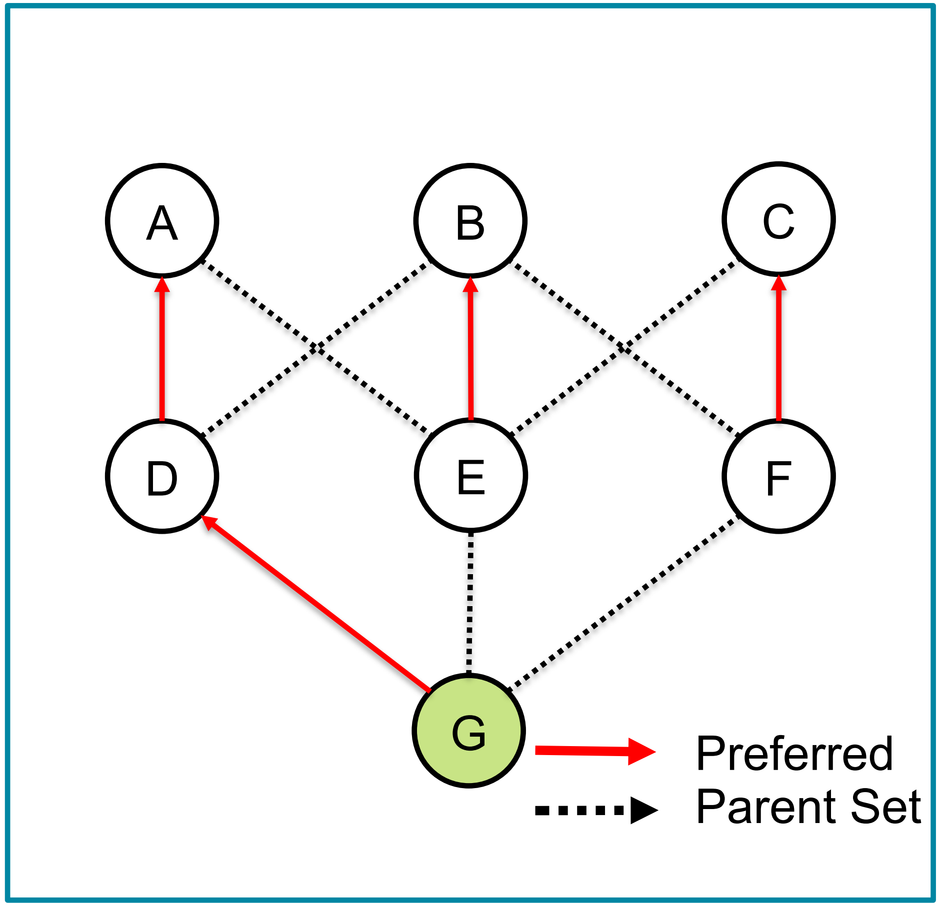
- In this example :
  - **D** has Preferred Parent **A**, and **B** in its Parent Set
  - **E** has Preferred Parent **B**, and **A** & **C** in its Parent Set
  - **F** has Preferred Parent **C**, and **B** in its Parent Set



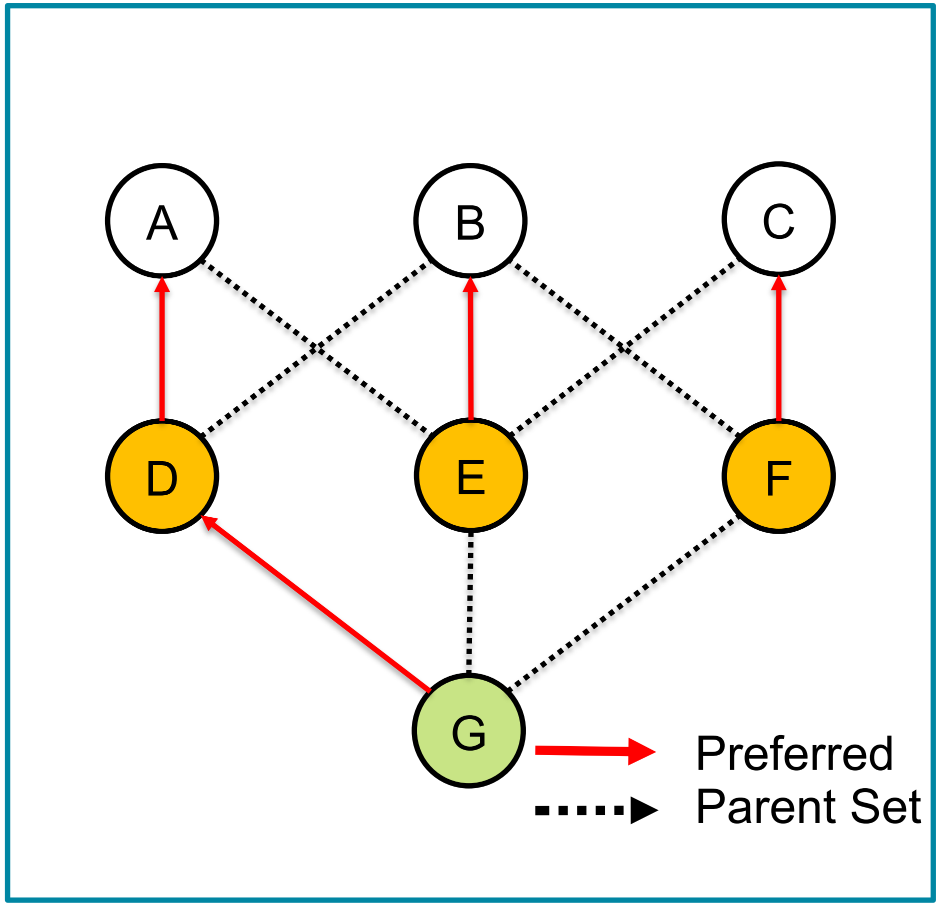
$$PP(PP) \in PS(AP)$$

- We will take **G** as the **example node** :



$$PP(PP) \in PS(AP)$$

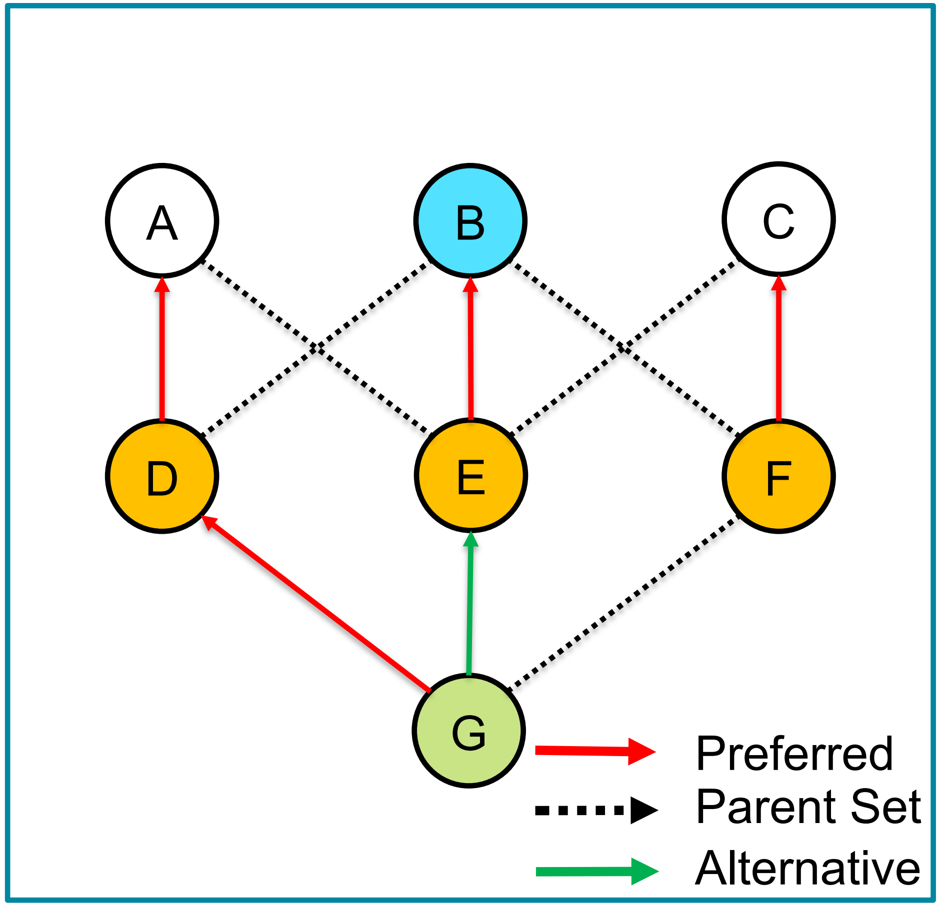
- We will take **G** as the **example node** :
  - **G** has **D** as PP, and **E** & **F** in its Parent Set



Common Ancestor Algorithms
Medium CA mode

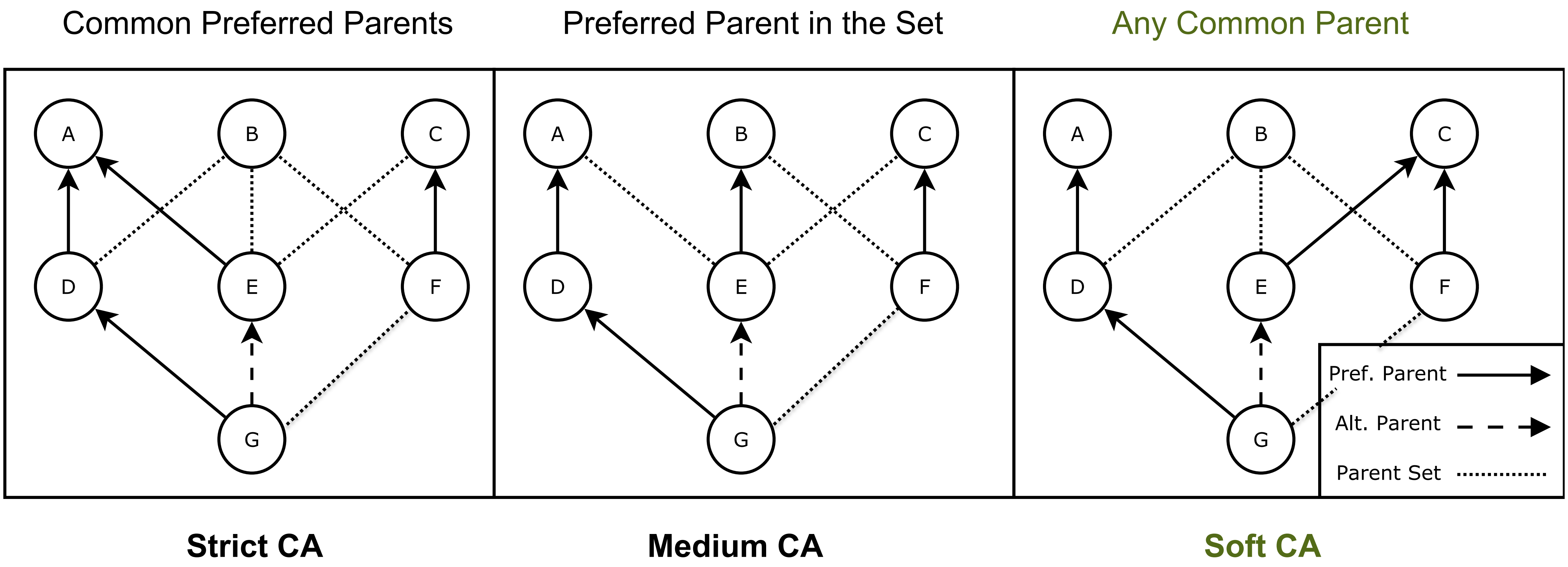
$$PP(PP) \in PS(AP)$$

- We will take **G** as the **example node** :
  - **G** has **D** as PP, and **E** & **F** in its Parent Set
  - ***Only node E fulfils the condition →***
    As A (the PP of D) is in the PS of E, [A, B, C]



Common Ancestor Algorithms

Strict CA – Medium CA – Soft CA



$$PS(PP) \cap PS(AP) \neq \emptyset$$

$$PS(PP) \cap PS(AP) \neq \emptyset$$

- *The Red lines indicate the Preferred Parents*
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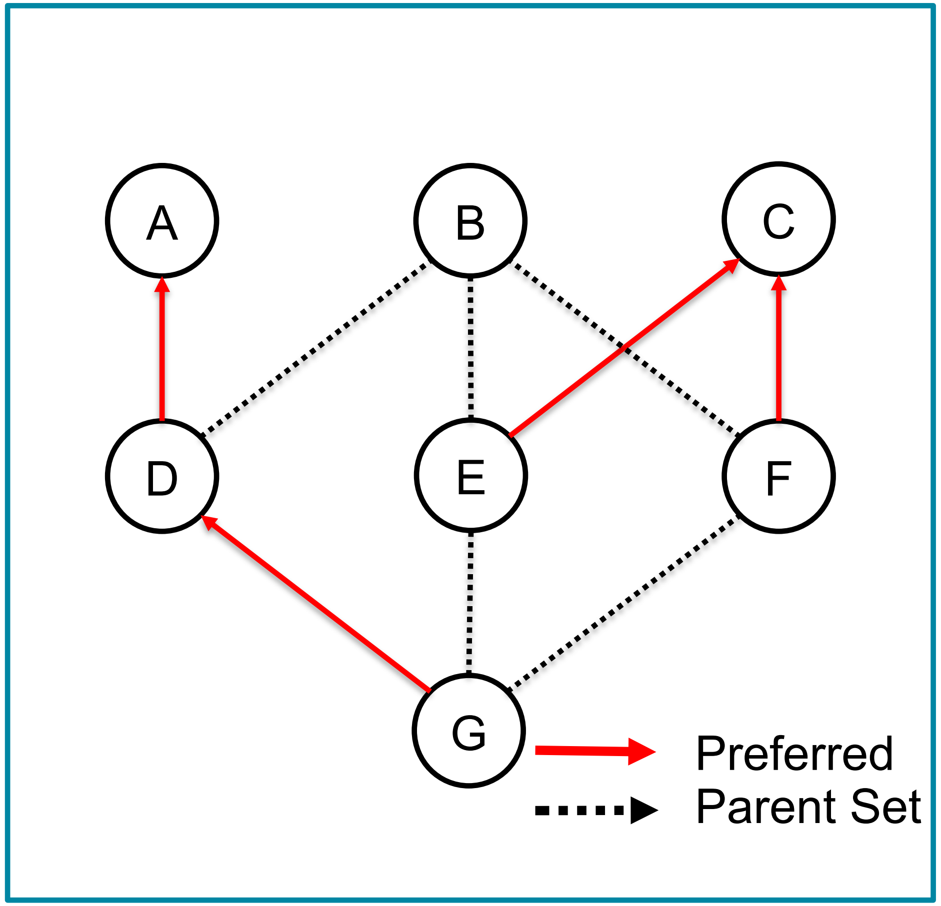
  - **E** has Preferred Parent **C**, and **B** in its Parent Set
  - **F** has Preferred Parent **C**, and **B** in its Parent Set



$$PS(PP) \cap PS(AP) \neq \emptyset$$

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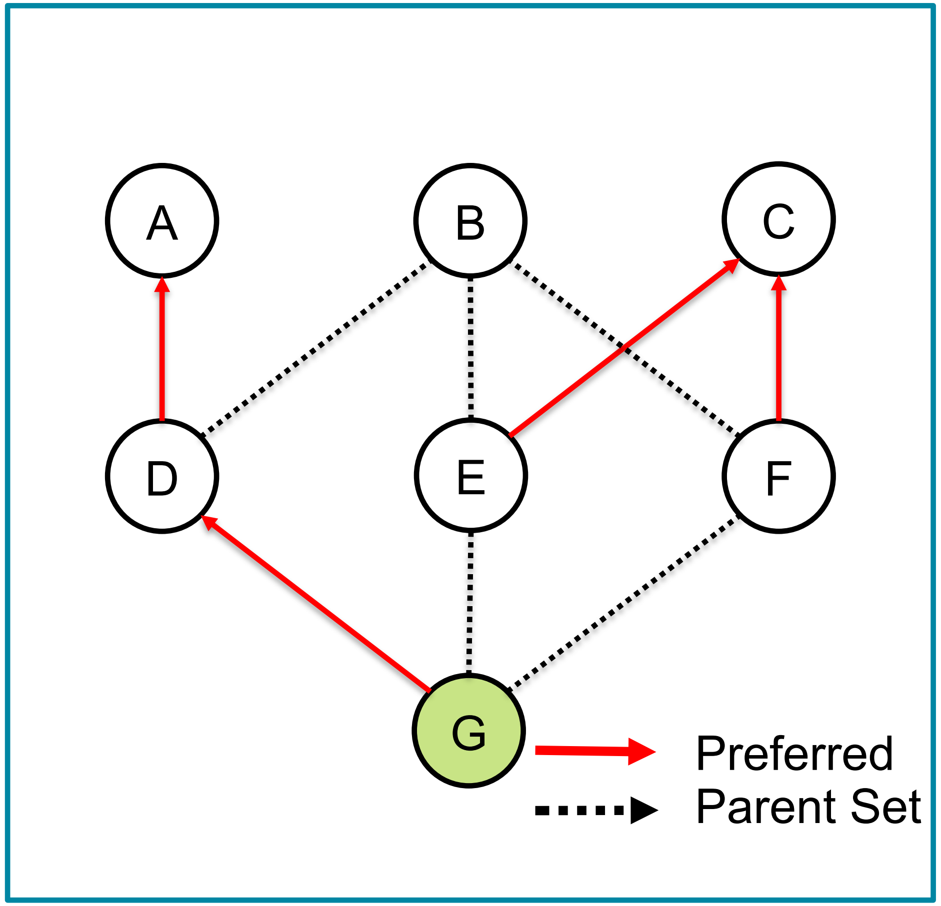
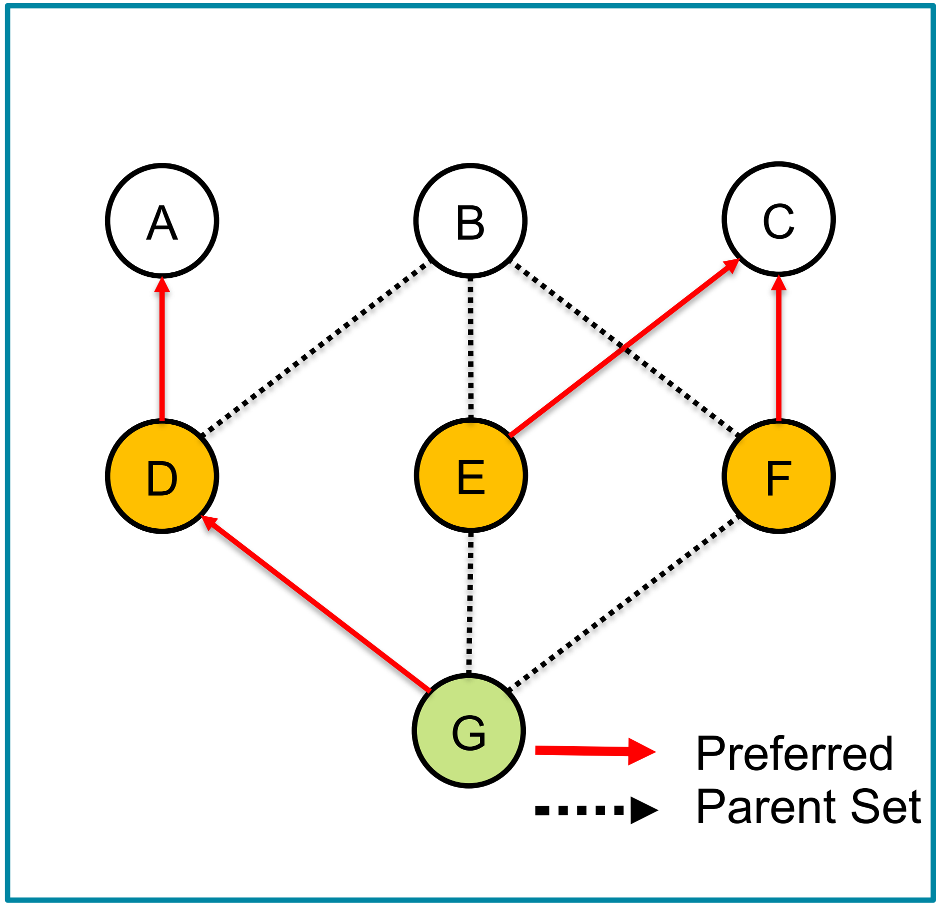


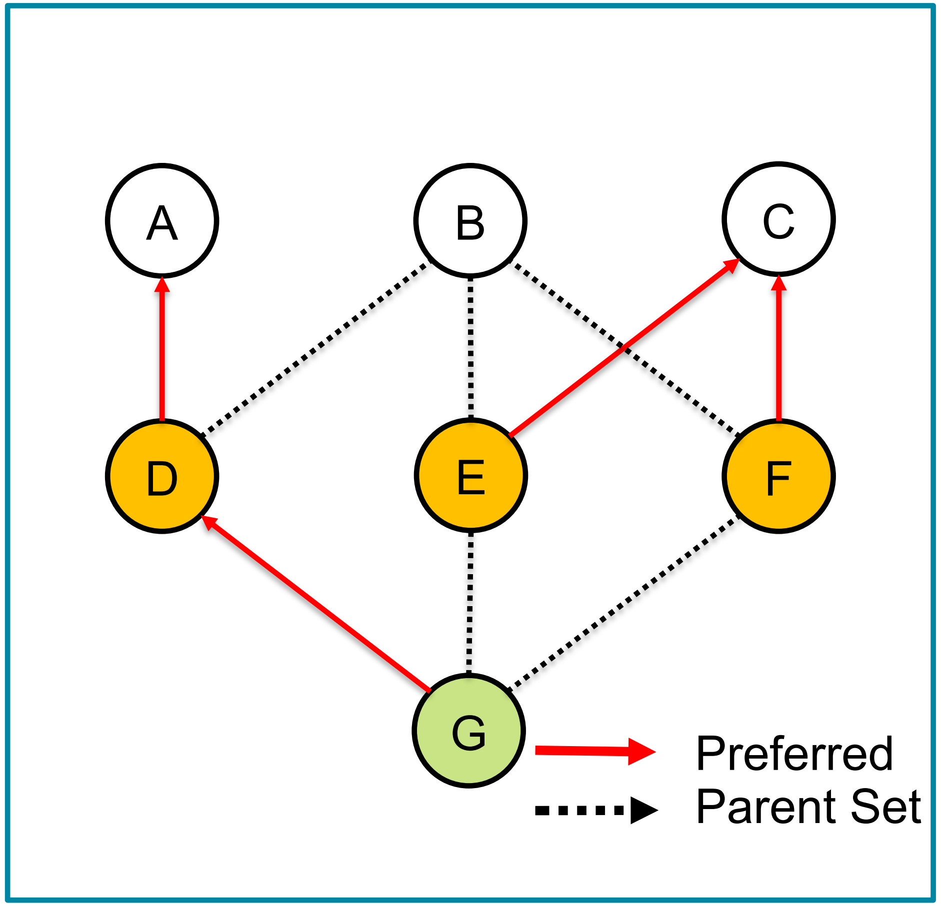
$$PS(PP) \cap PS(AP) \neq \emptyset$$

- We will take **G** as the **example node** :
  - **G** has **D** as PP, and **E** & **F** in its Parent Set



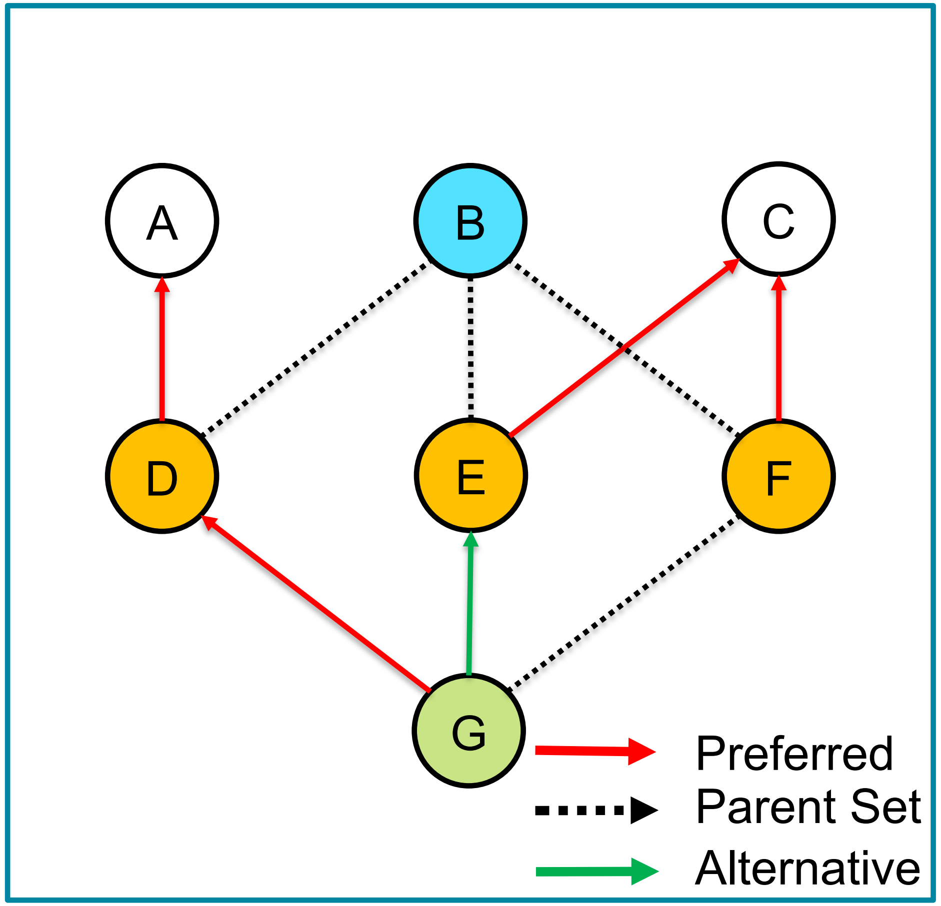
$$PS(PP) \cap PS(AP) \neq \emptyset$$

- We will take **G** as the **example node** :
  - **G** has **D** as PP, and **E** & **F** in its Parent Set
  - ***Both nodes E and F fulfil the condition →***
    As B is in the PS of D, and it is in the PS of E and F



$$PS(PP) \cap PS(AP) \neq \emptyset$$

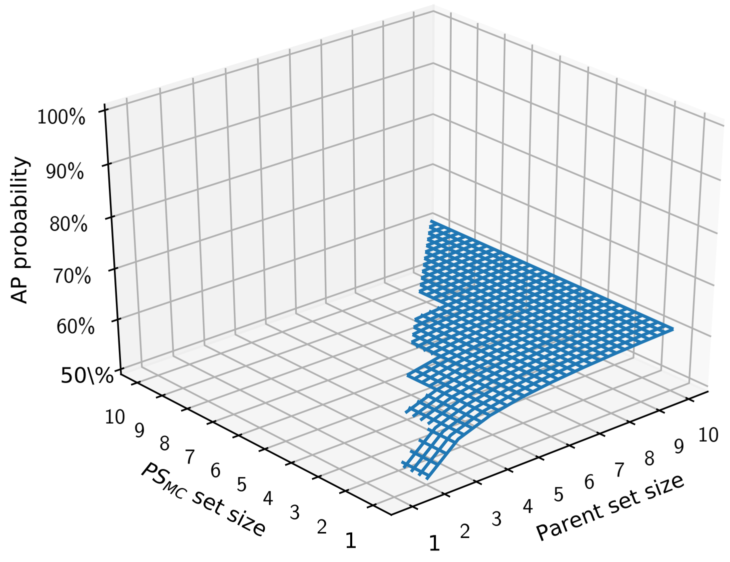
- We will take **G** as the **example node** :
  - **G** has **D** as PP, and **E** & **F** in its Parent Set
  - ***Both nodes E and F fulfil the condition***
  - ***G selects the AP with the best ETX value***



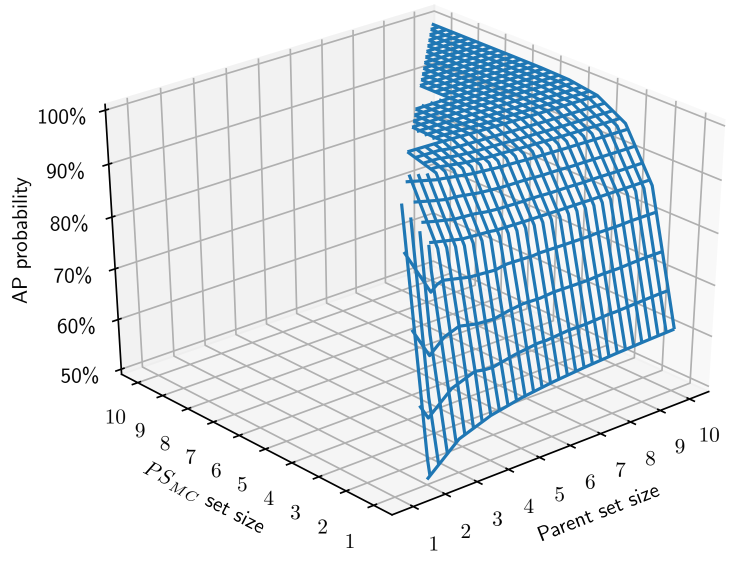
Common Ancestor Algorithms

Probability of obtaining an Alternative Parent

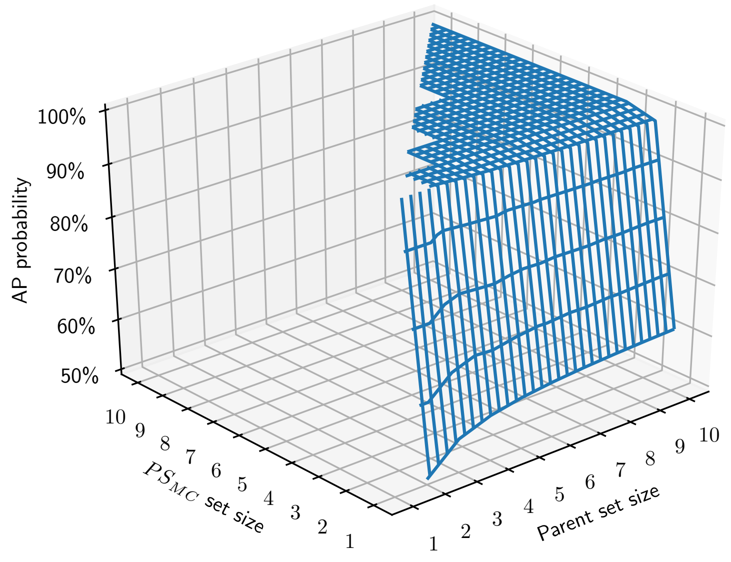
Strict CA



Medium CA



Soft CA



- As the **probability** of obtaining an **AP improves**, so does the network **reliability**.
- As more **nodes** are **used**, the **higher** the **power consumption** will be.

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On-Demand Selection (ODeSe)

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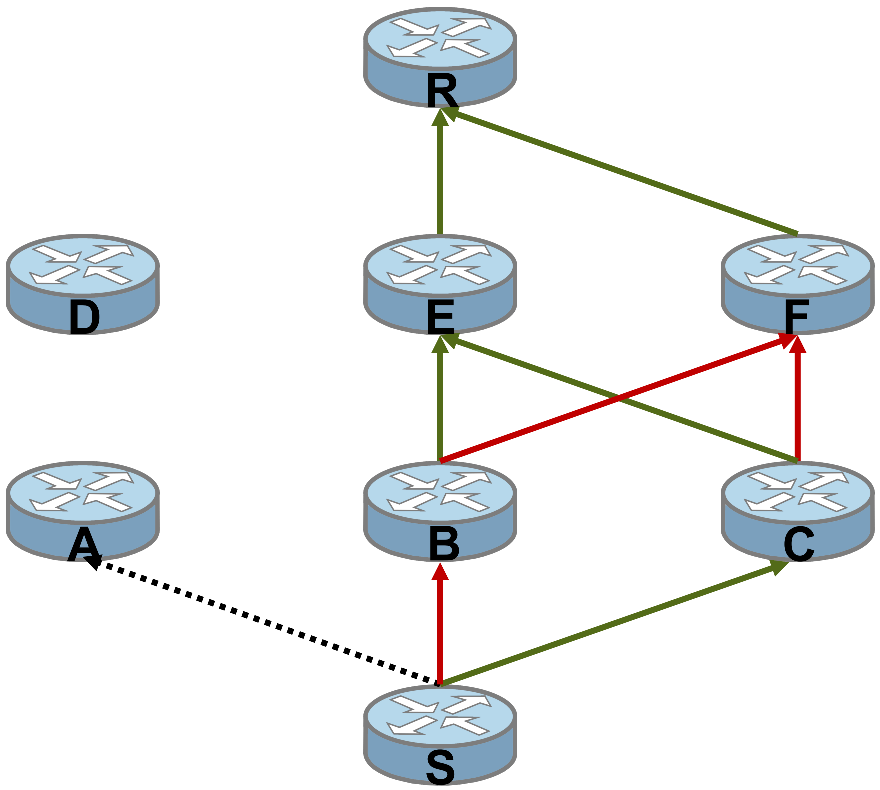
On-Demand Selection (ODeSe)

Ideal (Optimal) Scenario

- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.



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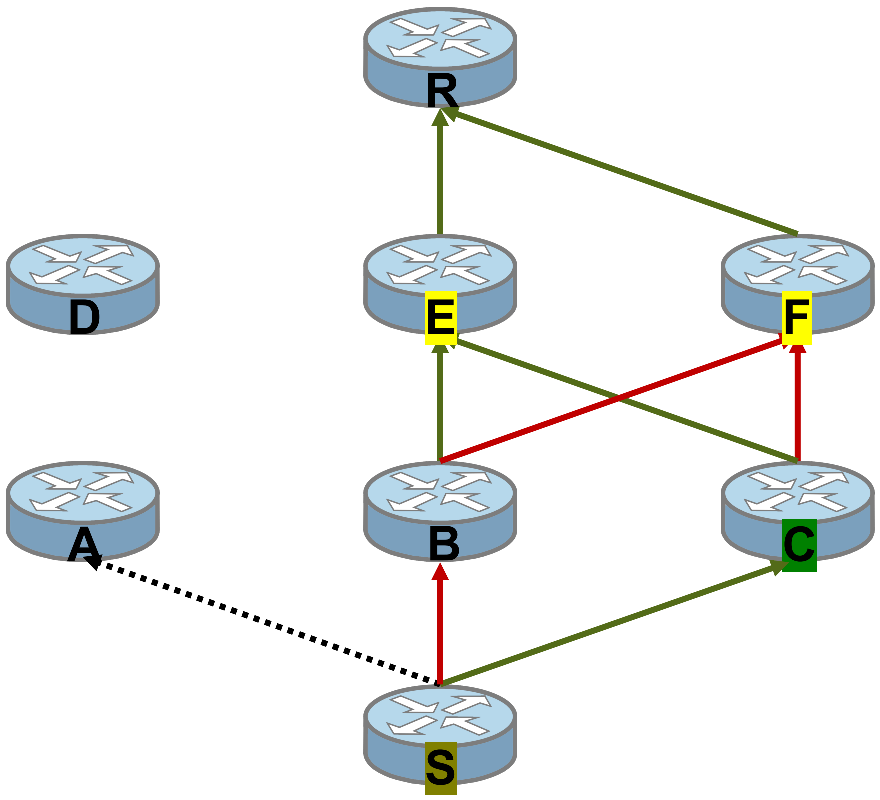
On-Demand Selection (ODeSe)

Ideal (Optimal) Scenario

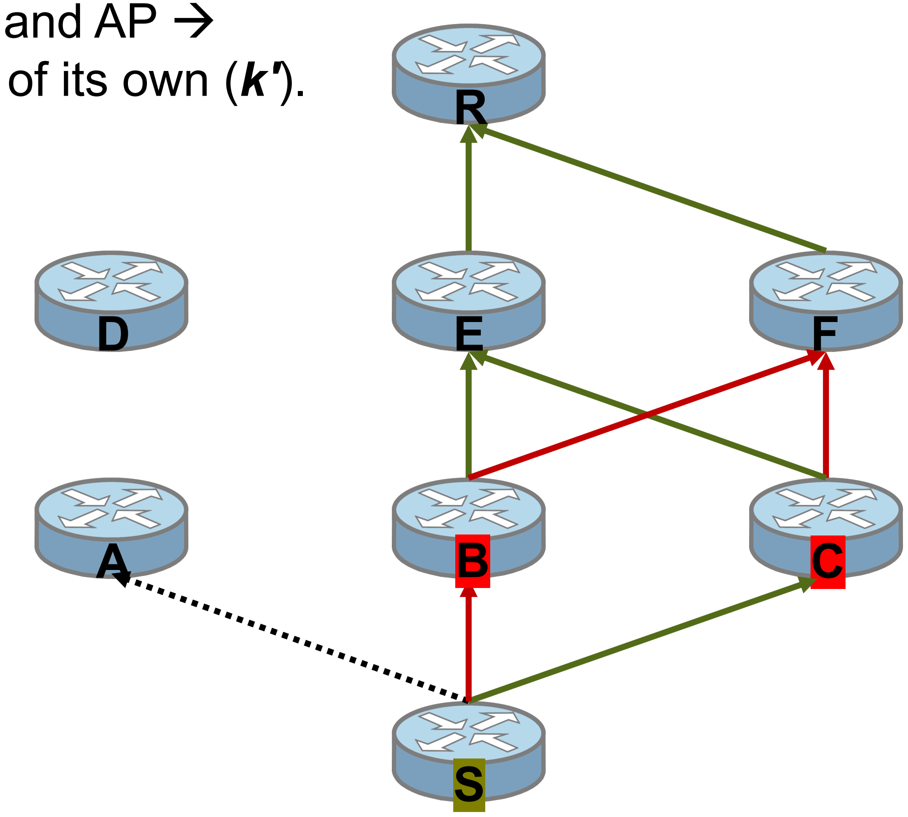
- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.
- The PP and AP addresses of the current (node ***k***) PP are transported within the data packet.



On-Demand Selection (ODeSe)

Ideal (Optimal) Scenario

- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.
- The PP and AP addresses of the current (node ***k***) PP are transported within the data packet.
- Each of the Relay nodes (***k'***) check:
  1. if the carried addresses (HbH_{PP} and HbH_{AP}) are ***valid*** for PP and AP →
  i.e., if the ranks of the HbH_{PP} and HbH_{AP} are lower than the rank of its own (***k'***).
  2. if the HbH_{PP} and HbH_{AP} ***guarantee*** Strict Braided Pattern.



On-Demand Selection (ODeSe)

Ideal (Optimal) Scenario

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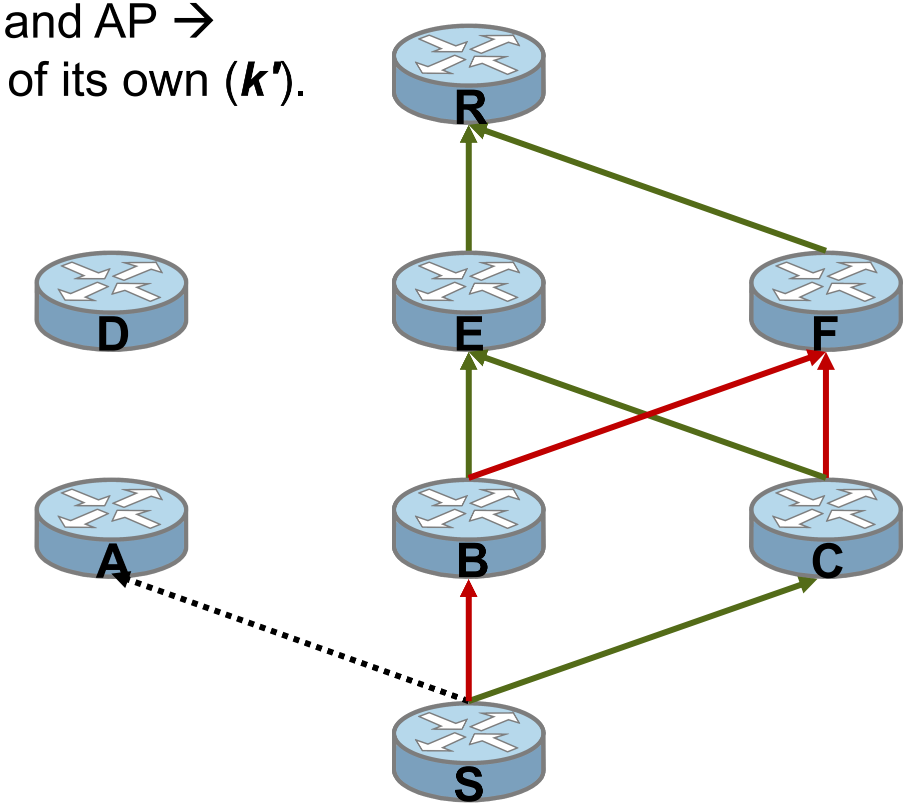
  2. if the HbH_{PP} and HbH_{AP} ***guarantee*** Strict Braided Pattern.
- If **yes**, then, the ODeSe cycle starts again.

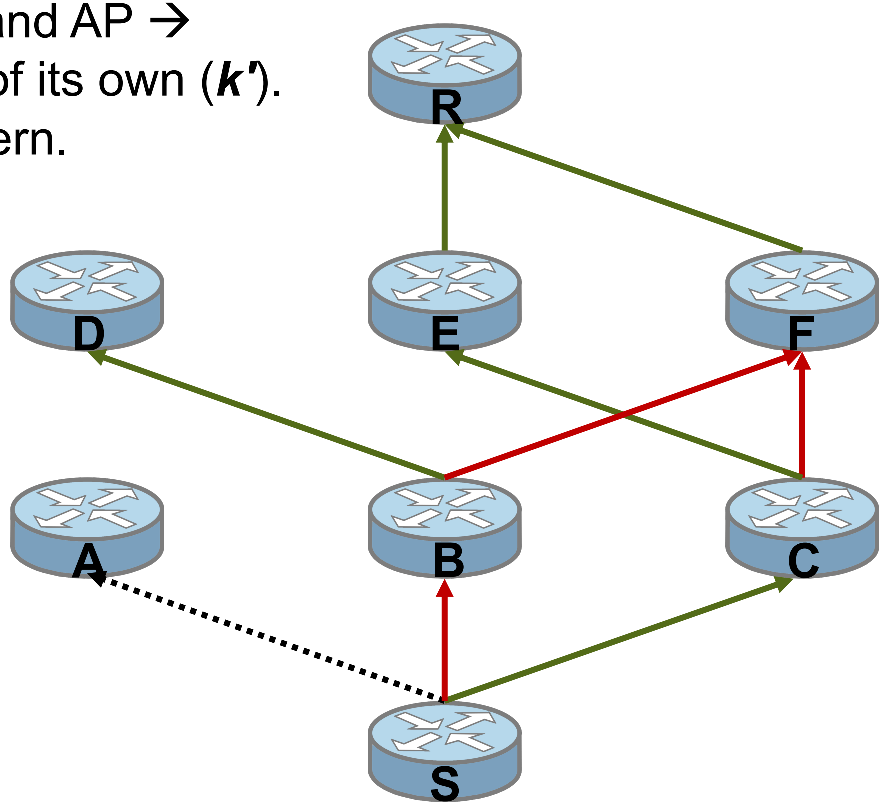


On-Demand Selection (ODeSe)

Parent Changing Scenario

- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.
- The PP and AP addresses of the current (node ***k***) PP are transported within the data packet.
- Each of the Relay nodes (***k'***) check:

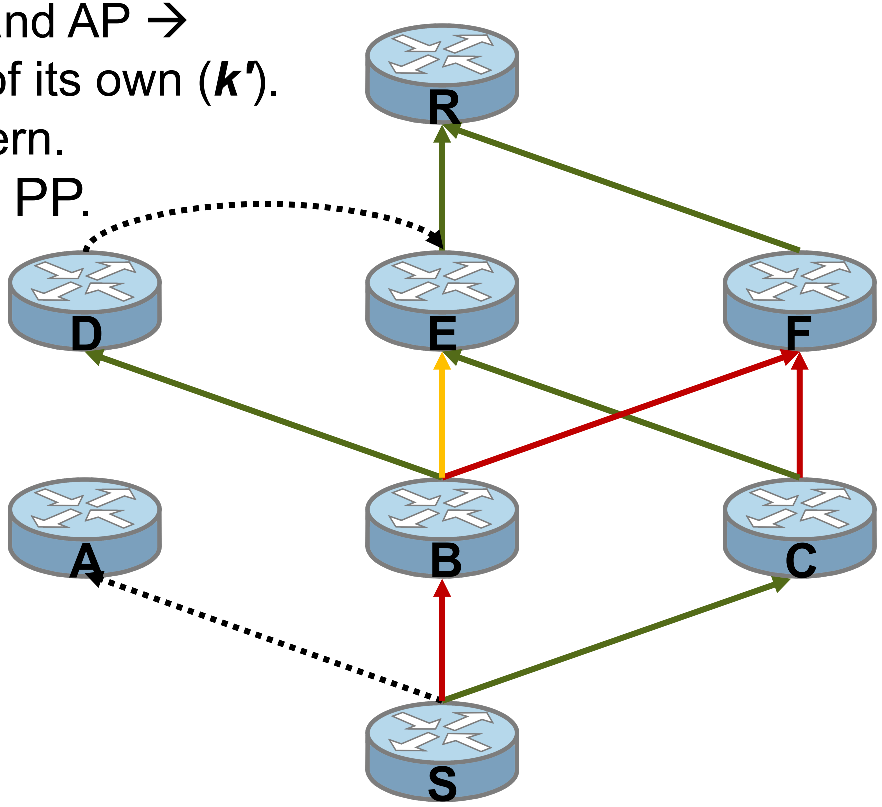
1. if the carried addresses (HbH_{PP} and HbH_{AP}) are ***valid*** for PP and AP → i.e., if the ranks of the HbH_{PP} and HbH_{AP} are lower than the rank of its own (***k'***).
2. if the HbH_{PP} and HbH_{AP} ***do not guarantee*** Strict Braided Pattern.



On-Demand Selection (ODeSe)

Parent Changing Scenario

- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.
- The PP and AP addresses of the current (node ***k***) PP are transported within the data packet.
- Each of the Relay nodes (***k'***) check:
  1. if the carried addresses (HbH_{PP} and HbH_{AP}) are ***valid*** for PP and AP → i.e., if the ranks of the HbH_{PP} and HbH_{AP} are lower than the rank of its own (***k'***).
  2. if the HbH_{PP} and HbH_{AP} ***do not guarantee*** Strict Braided Pattern.
- Then, the carried parent address (HbH_{PP}) is established as PP.



On-Demand Selection (ODeSe)

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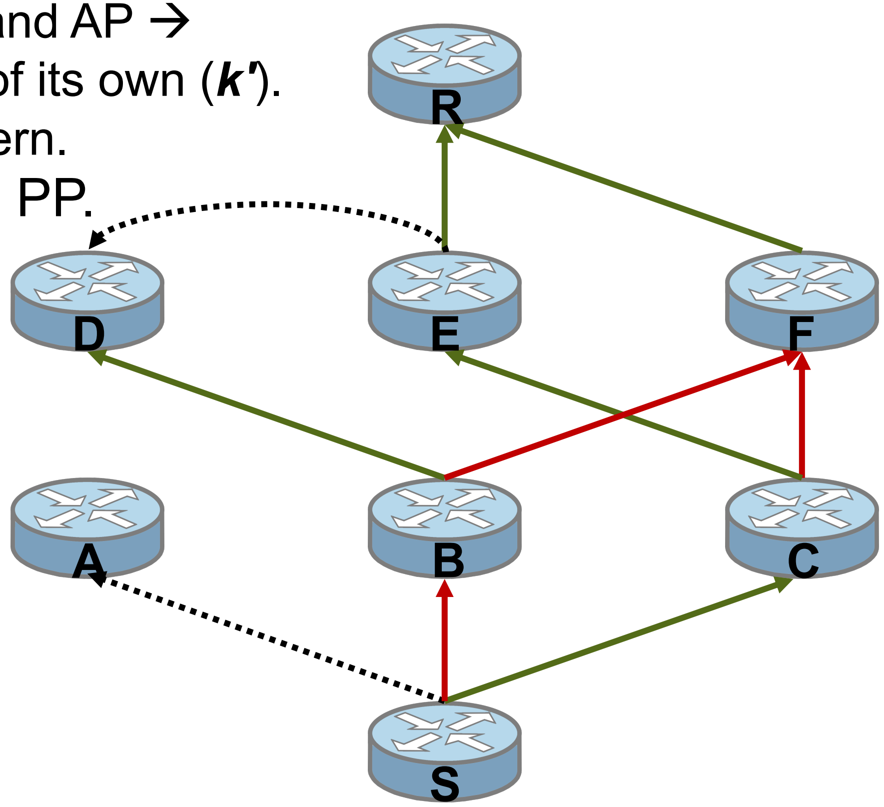
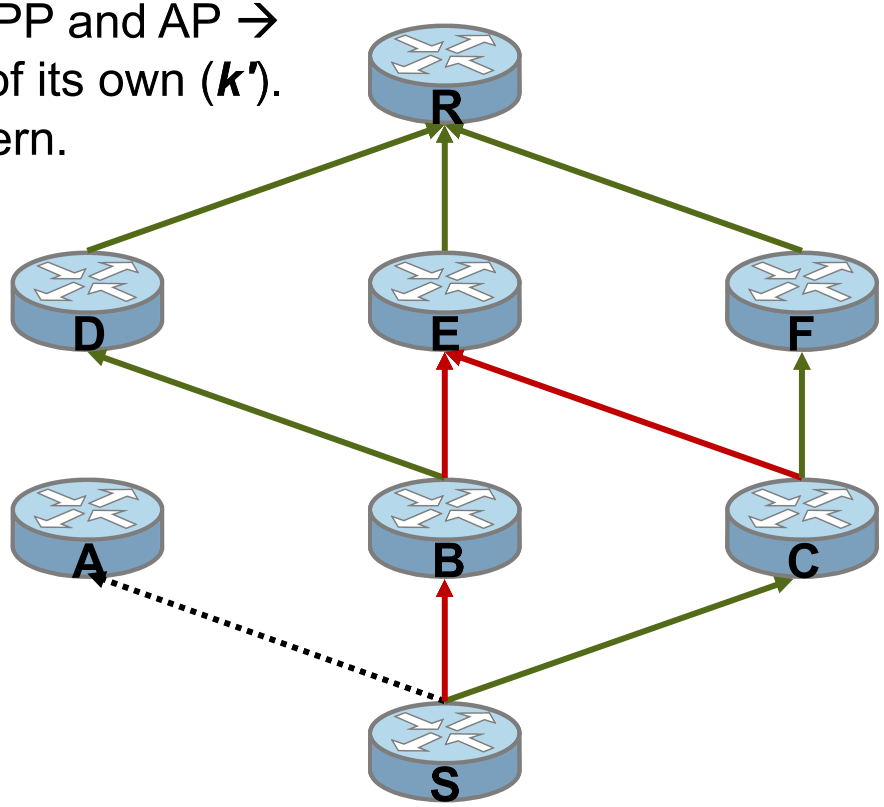
- The PP and AP addresses of the current (node ***k***) PP are transported within the data packet.
- Each of the Relay nodes (***k'***) check:
  1. if the carried addresses (HbH_{PP} and HbH_{AP}) are ***valid*** for PP and AP →
  i.e., if the ranks of the HbH_{PP} and HbH_{AP} are lower than the rank of its own (***k'***).
  2. if the HbH_{PP} and HbH_{AP} ***do not guarantee*** Strict Braided Pattern.
- Then, the carried parent address (HbH_{PP}) is established as PP.
- Next, the ODeSe cycle starts again.
- And the original configurations are restored.



On-Demand Selection (ODeSe)

Route Adaptation (Worst Case Scenario)

- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.
- The PP and AP addresses of the current (node ***k***) PP are transported within the data packet.
- Each of the Relay nodes (***k'***) check:
  1. if the carried addresses (HbH_{PP} and HbH_{AP}) are ***not valid*** for PP and AP → i.e., if the ranks of the HbH_{PP} and HbH_{AP} are lower than the rank of its own (***k'***).
  2. if the HbH_{PP} and HbH_{AP} ***do not guarantee*** Strict Braided Pattern.



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On-Demand Selection (ODeSe)

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- Each node ***k*** starts with a Strict, Medium or Soft CA strategy to select its PP and AP.
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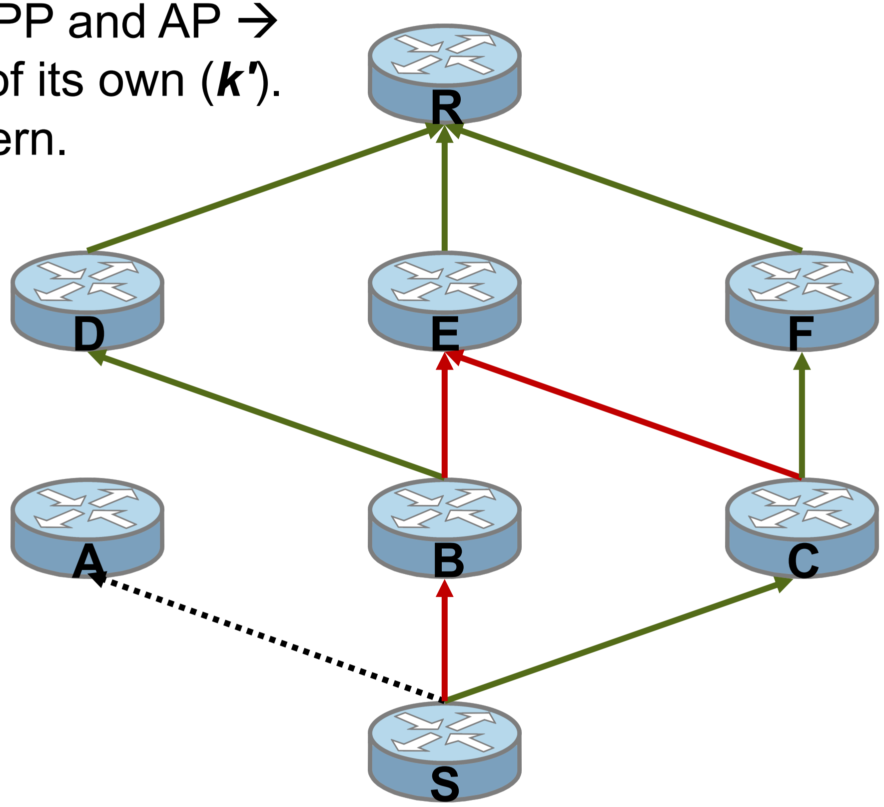
  1. if the carried addresses (HbH_{PP} and HbH_{AP}) are ***not valid*** for PP and AP → i.e., if the ranks of the HbH_{PP} and HbH_{AP} are lower than the rank of its own (***k'***).
  2. if the HbH_{PP} and HbH_{AP} ***do not guarantee*** Strict Braided Pattern.
- Then, the default PP of the Relay node is used.
- If there is none AP, a Soft CA strategy is used.
- Finally, the ODeSe cycle starts again.



Performance Evaluation

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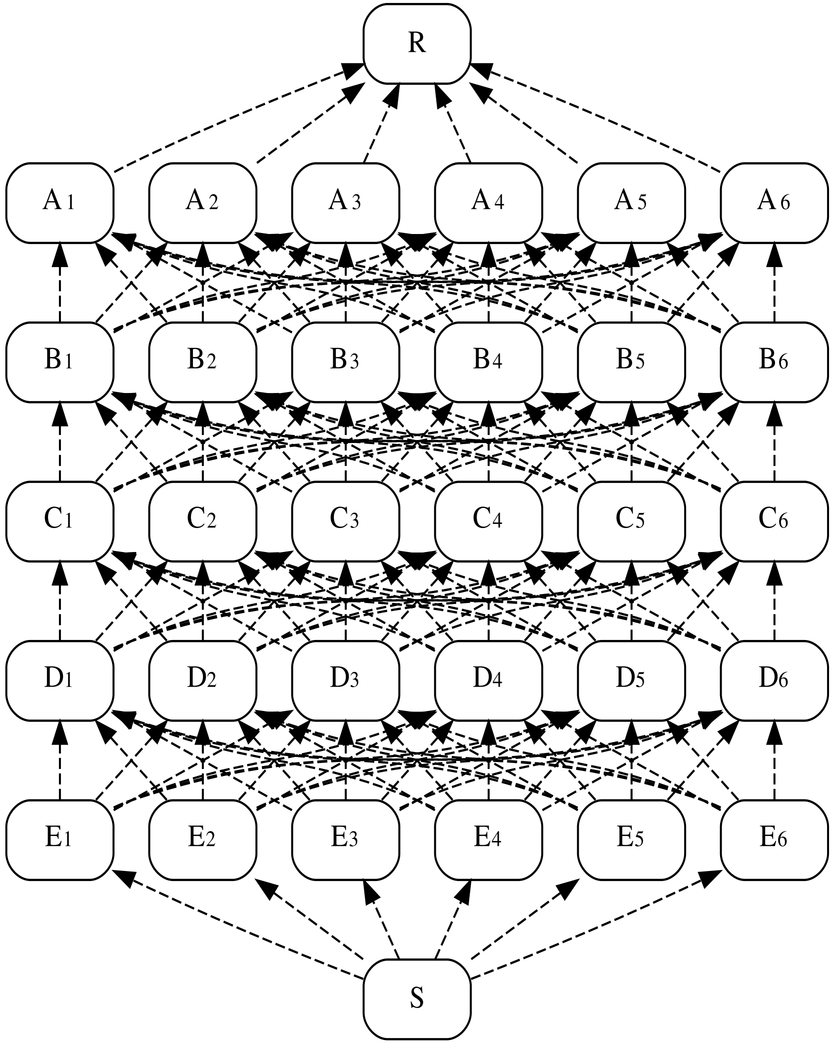
Simulation Setup

Contiki OS & Cooja, Single-path, n-Disjoint, CA, ODeSe

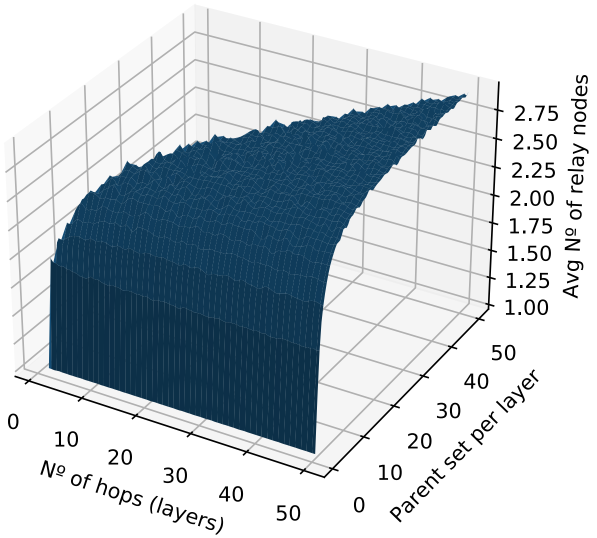
Simulation		Topology	
Duration	Until 5000 pkts	Topology	Mesh topology
Data traffic	1 pkt/ 15 sec	Nº of nodes	32
Routing protocol	RPL	Nº of layers (L)	5
Parent set size (N)	6	Nº of sources	1
PS_{MC} size (M)	6	Link Quality	50%, 75%
TSCH		Single-path & Multi-path	
Scheduling		Centralized	
Timeslot length		10 ms	
Nº of channels		1	
Slotframe length		357 Timeslots	
Slotframe length (N-Disjoint)		345 Timeslots	



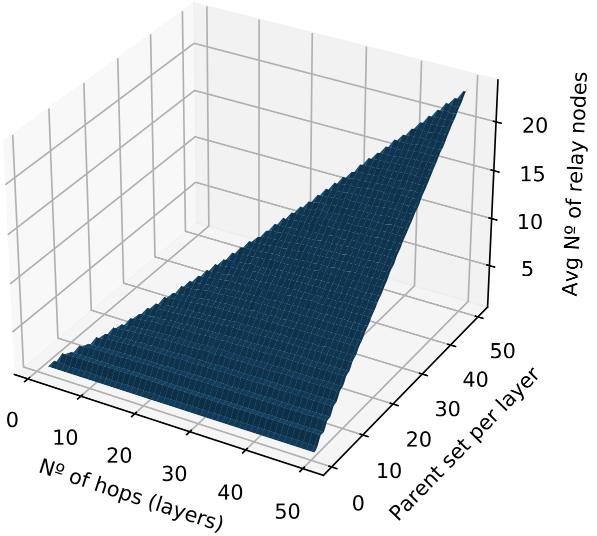
Common Ancestor Algorithms

Average # of relay nodes used per layer: based on Monte Carlo method

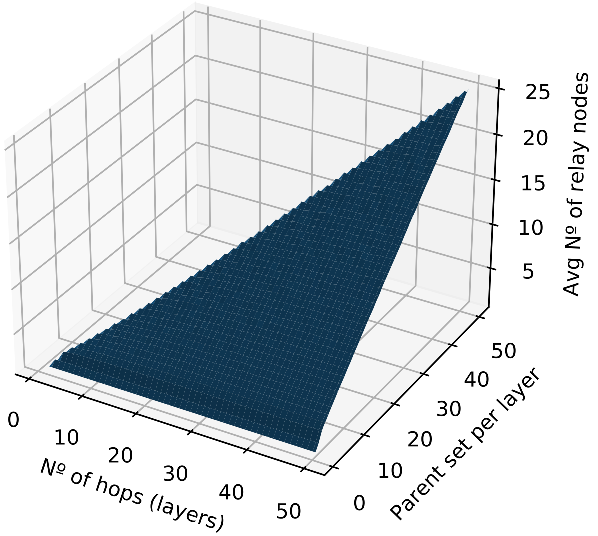
Strict CA



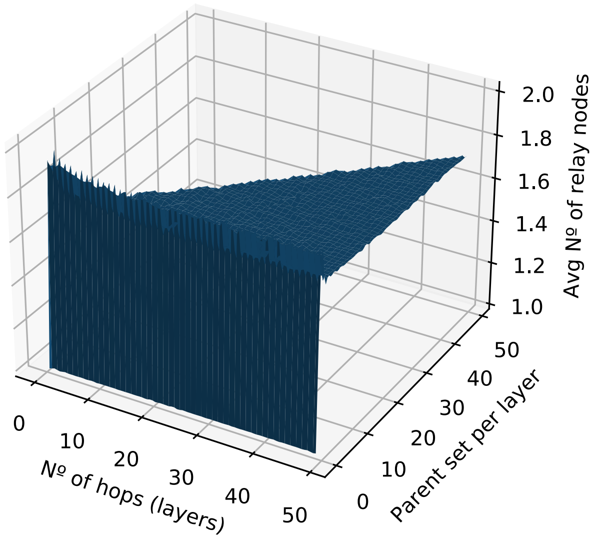
Medium CA



Soft CA



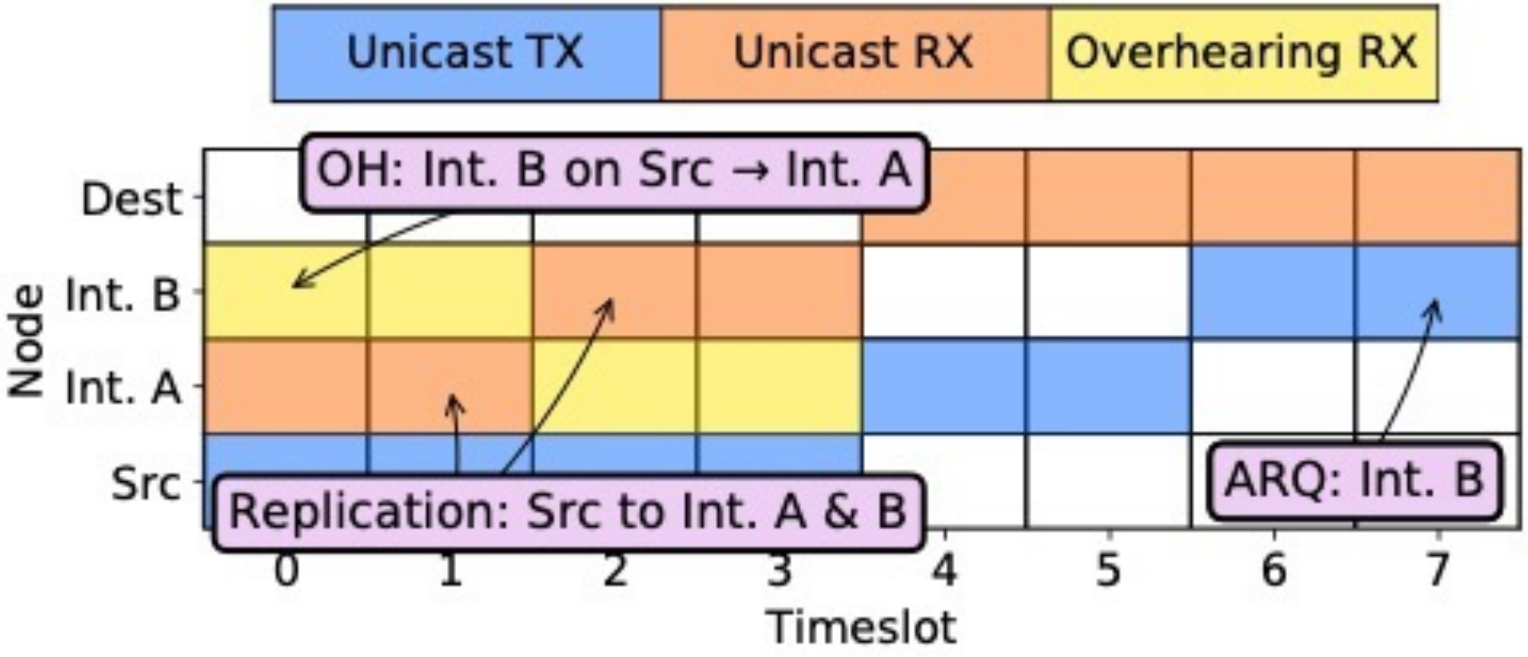
ODeSe

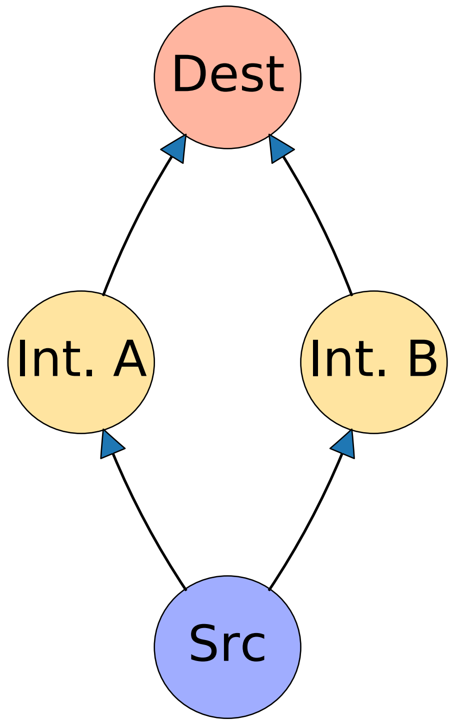


- The average number of nodes used is close to 2 nodes.
- Multi-path resources are optimized.

Simulation Setup

An example of the employed TSCH-based Schedule

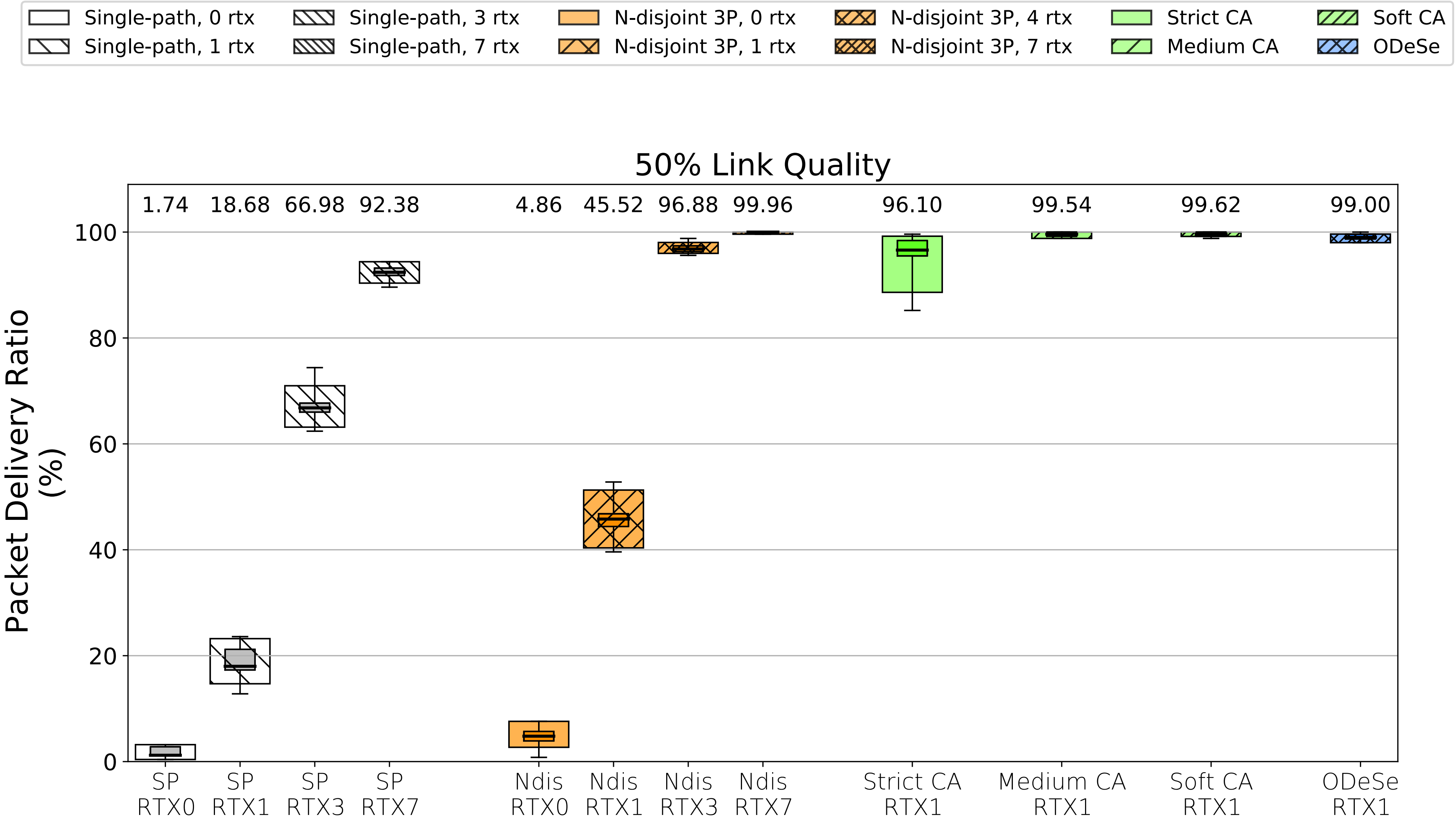




R.-A. Koutsiamanis, G. Z. Papadopoulos, B. Quoitin and N. Montavont,
"A Centralized Controller for Reliable and Available Wireless Schedules in Industrial Networks",
In Proc. **MSN 2020**.

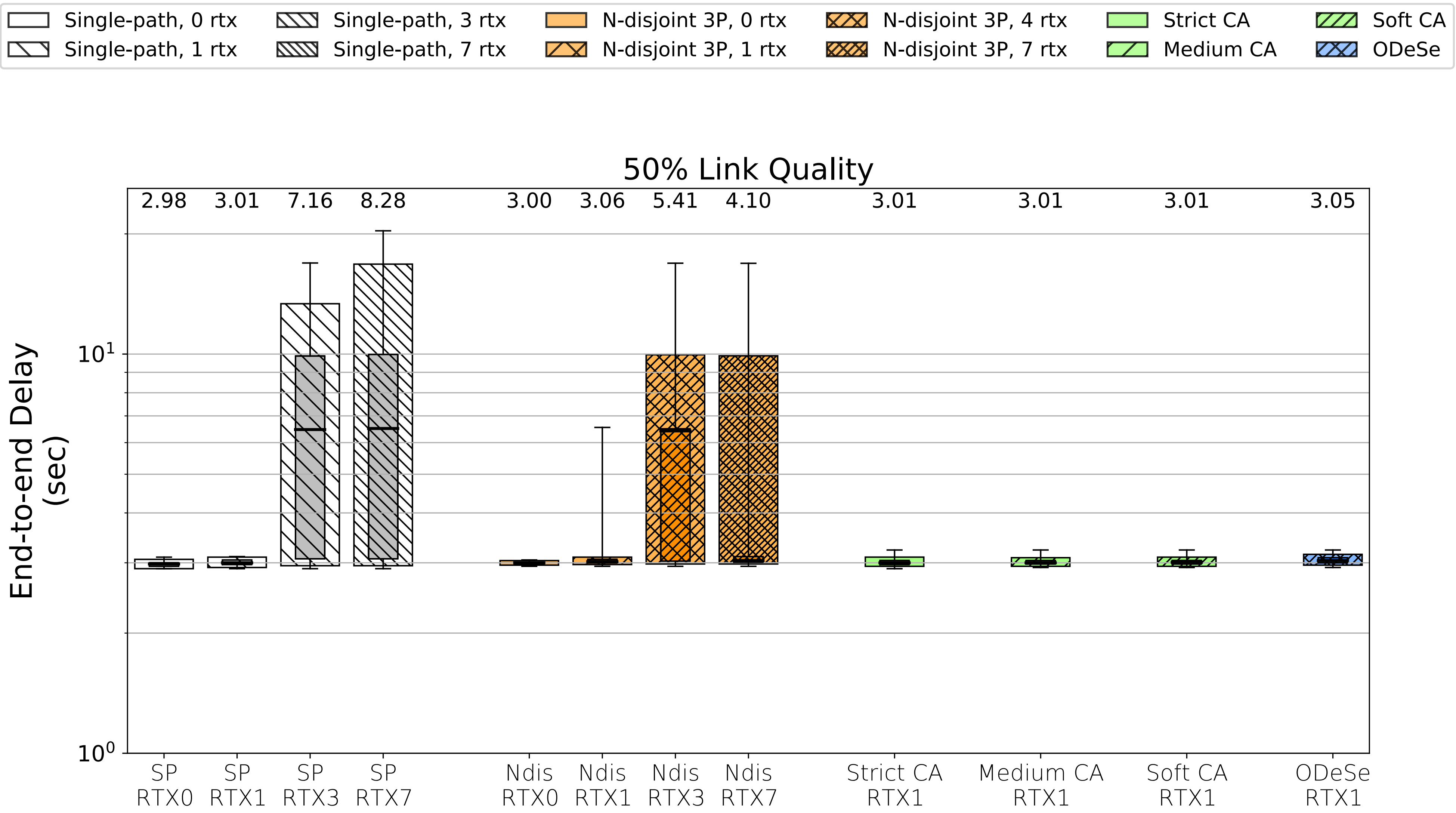
Simulation Results

50% Link Quality : PDR



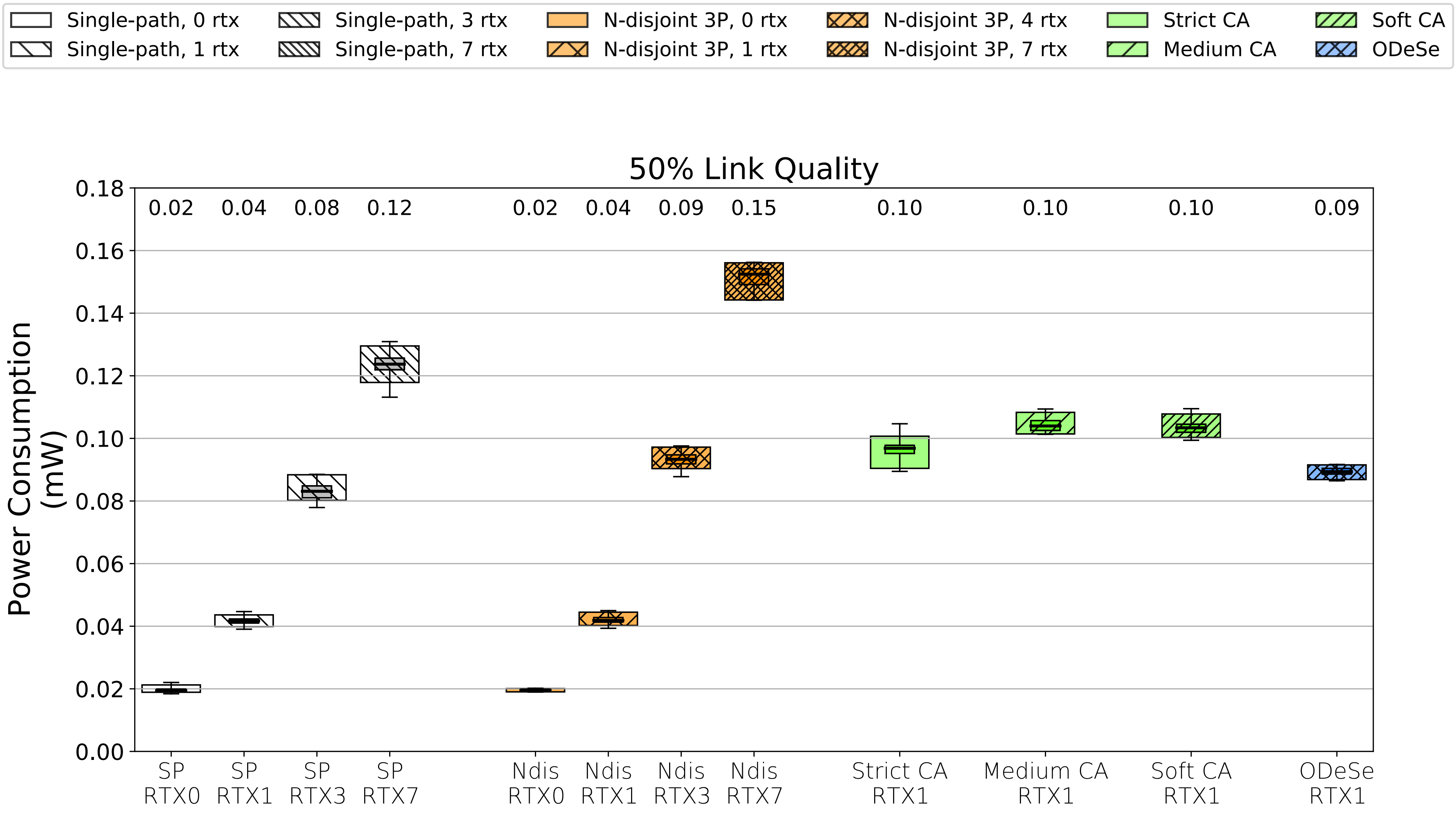
Simulation Results

50% Link Quality : End-to-end latency



Simulation Results

50% Link Quality : Power consumption per algorithm



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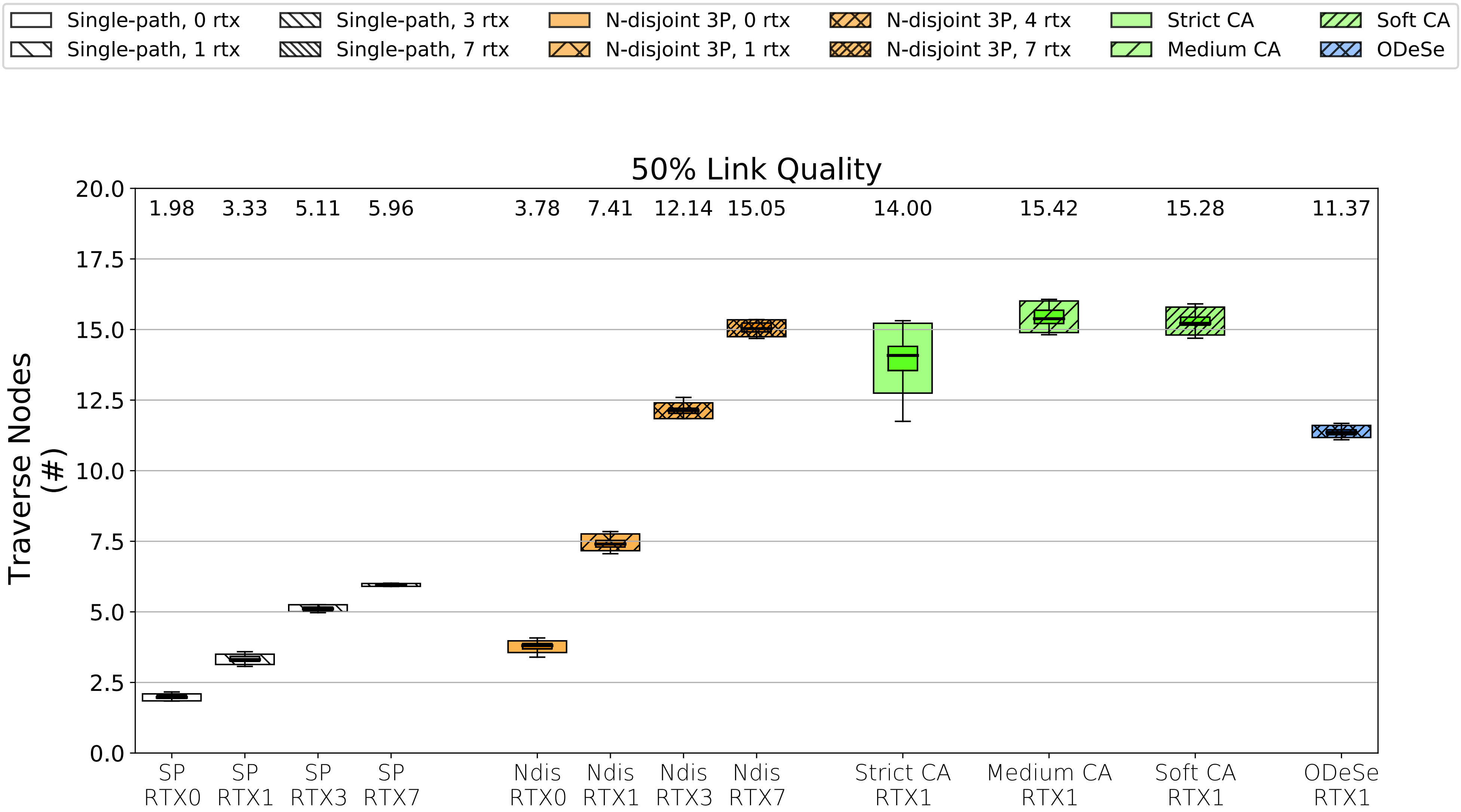
Simulation Results

50% Link Quality : Average number of **relay nodes** per data packet



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Key Takeaways

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Key takeaways

- Tackled with deterministic flows for Industrial IoT wireless networks;
- Introduced the PAREO Functions (ARQ, Overhearing, Replication, Elimination).
- Presented the n-Disjoint Strategies, CA Algorithms, and ODeSe.
- Achieved:
  - Bounded latency performance (at the cost of energy and bandwidth).
  - End-to-end network reliability of 99.96%!

Ongoing work

- Extending to FEC algorithms
  - FEC + Multipath
  - IETF

- SDN approach to support ubiquitous IoT technologies
  - 100% centralized approach
  - PCE/PSE

- Applying these technologies to real-world use-cases, Wireless BMS (Renault)

Miscellaneous

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Scientific Contributions

- T. Lagos Jenschke, R.-A. Koutsiamanis, G. Z. Papadopoulos and N. Montavont, "ODeSe: On-Demand Selection for Multi-path RPL Networks," In **Elsevier Ad Hoc Networks**, vol. 114, pp. 102431, April **2021**.
- R.-A. Koutsiamanis, G. Z. Papadopoulos, B. Quoitin and N. Montavont, "A Centralized Controller for Reliable and Available Wireless Schedules in Industrial Networks," In Proc. **MSN 2020**.
- R.-A. Koutsiamanis, G. Z. Papadopoulos, T. Lagos Jenschke, P. Thubert and N. Montavont, "Meet the PAREO Functions: Towards Reliable and Available Wireless Networks," In Proc. **IEEE ICC 2020**.
- A. Czarnitzki Estrin, T. Lagos Jenschke, G. Z. Papadopoulos, J. I. Alvarez-Hamelin and N. Montavont, "Thorough Investigation of Multi-path Techniques in RPL based Wireless Networks," In Proc. **IEEE ISCC 2020**.
- T. Lagos Jenschke, G. Z. Papadopoulos, R. A. Koutsiamanis, N. Montavont, "Alternative Parent Selection for Multi-Path RPL Networks", In Proc. **IEEE WF-IoT, 2019**.
- R. A. Koutsiamanis, G. Z. Papadopoulos, X. Fafoutis, J. M. Del Fiore, P. Thubert and N. Montavont, "From Best-Effort to Deterministic Packet Delivery for Wireless Industrial IoT Networks", In **IEEE Transactions on Industrial Informatics**, **2018**.
- T. Lagos, R. A. Koutsiamanis, G. Z. Papadopoulos and N. Montavont, "Multi-path Selection in RPL based on Replication and Elimination," **AdHoc-Now 2018**.
- G. Z. Papadopoulos, T. Matsui, P. Thubert, G. Texier, T. Watteyne and N. Montavont, "Leapfrog Collaboration: Toward Determinism and Predictability in Industrial-IoT applications," in Proc. **IEEE ICC 2017**.
- T. Matsui, G. Z. Papadopoulos, P. Thubert, T. Watteyne, N. Montavont, "Poster: 4th Industrial Revolution: Toward Deterministic Wireless Industrial Networks," In Proc. **EWSN 2017**.
- H. Jiang, Z. Brodard, T. Chang, A. Bouabdallah, N. Montavont, G. Texier, P. Thubert, T. Watteyne, G. Z. Papadopoulos, "Dependability Competition: Controlled Replication for Higher Reliability and Predictability in Industrial IoT Networks," In Proc. **EWSN 2017**.
- M. Kersalé, G. Z. Papadopoulos, J. M. Del Fiore, P. Thubert and N. Montavont, "Vers les Réseaux Industriels Déterministes," In Proc. **CoRes 2017**.

IETF Standardization Efforts

- "*RPL DAG Metric Container (MC) Node State and Attribute (NSA) object type extension*",
  R. A. Koutsiamanis, G. Z. Papadopoulos, N. Montavont and P. Thubert,
  draft-ietf-roll-nsa-extension-10, 29 October 2020,
  [Submitted to IESG for Publication], 10 March 2021.
- "*Reliable and Available Wireless Architecture/Framework*",
  P. Thubert, G. Z. Papadopoulos and L. Berger,
  draft-ietf-raw-architecture-01, 28 July 2021.
- "*RAW use cases*",
  G. Z. Papadopoulos, P. Thubert, F. Theoleyre and CJ. Bernardos,
  draft-ietf-raw-use-cases-02, 12 July 2021.
- "*Operations, Administration and Maintenance (OAM) features for RAW*",
  F. Theoleyre, G. Z. Papadopoulos, G. Mirsky and CJ. Bernardos,
  draft-ietf-raw-oam-support-02, 3 June 2021.
- "*Framework of Operations, Administration and Maintenance (OAM) for Deterministic Networking (DetNet)*",
  G. Mirsky, F. Theoleyre, *G. Z. Papadopoulos*, C. Bernardos, B. Varga and J. Farkas,
  draft-ietf-detnet-oam-framework-04, 14 September 2021.

Tutorials & Invited talks

- **Tutorial** : Georgios Z. Papadopoulos, "*Reliable & Available Wireless Mesh Networking*", IEEE **ISCC 2021**, September **2021**, Athens, Greece, [**3 hours**].

- **Tutorial** : Georgios Z. Papadopoulos, Nicolas Montavont, "*Industrial Internet of Things: from Best Effort to Quality of Service*", IEEE **WF-IoT**, April **2019**, Limerick, Ireland, [**4 hours**].

- **Keynote talk** : Georgios Z. Papadopoulos, Nicolas Montavont, "*Enabling Quality of Service in Low-power and Lossy Networks*" 2nd Mini-workshop on Wireless Sensor Networks and IoT @ **Université de Mons**, January **2019**, Mons, Belgium, [**90 minutes**].

- **Tutorial** : Georgios Z. Papadopoulos, Nicolas Montavont, "*Toward Deterministic Traffic in 6TiSCH Networks*" **GIIS**, October **2018**, Thessaloniki, Greece, [**2 hours**].

- **Invited talk** : Georgios Z. Papadopoulos, "*Enabling Deterministic Traffic in 6TiSCH Networks*" **Journée thématique** L'Internet des Objets Industriels (IIoT), organized by GDR RSD ResCom / MACS, July **2018**, Strasbourg, France, [**30 minutes**].

Education

- Lectures : IMT Atlantique, University of Rennes 1, IHU (Greece)
  - MAC, Compression/Fragmentation, and Routing layers in Internet of Things
- Laboratory Sessions :
  - 3 x Labs over Cooja simulator and Contiki OS : 9 hours
  - 1 x Lab over OpenMotes and Contiki OS : 5 hours
  - … and we are extending it!

Credits

- Tomas Lagos, Aris Koutsiamanis, Ana Czarnitzki Estrin, Julian Del Fiore, Maurine Kersale, Tadanori Matsui
- Georgios Z. Papadopoulos, Nicolas Montavont and Pascal Thubert

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Toward Reliable & Available Wireless Low-power Mesh Networking

École d’Été Temps Réel #ETR2021

Georgios Z. **PAPADOPOULOS**
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PAREO Performance Evaluation

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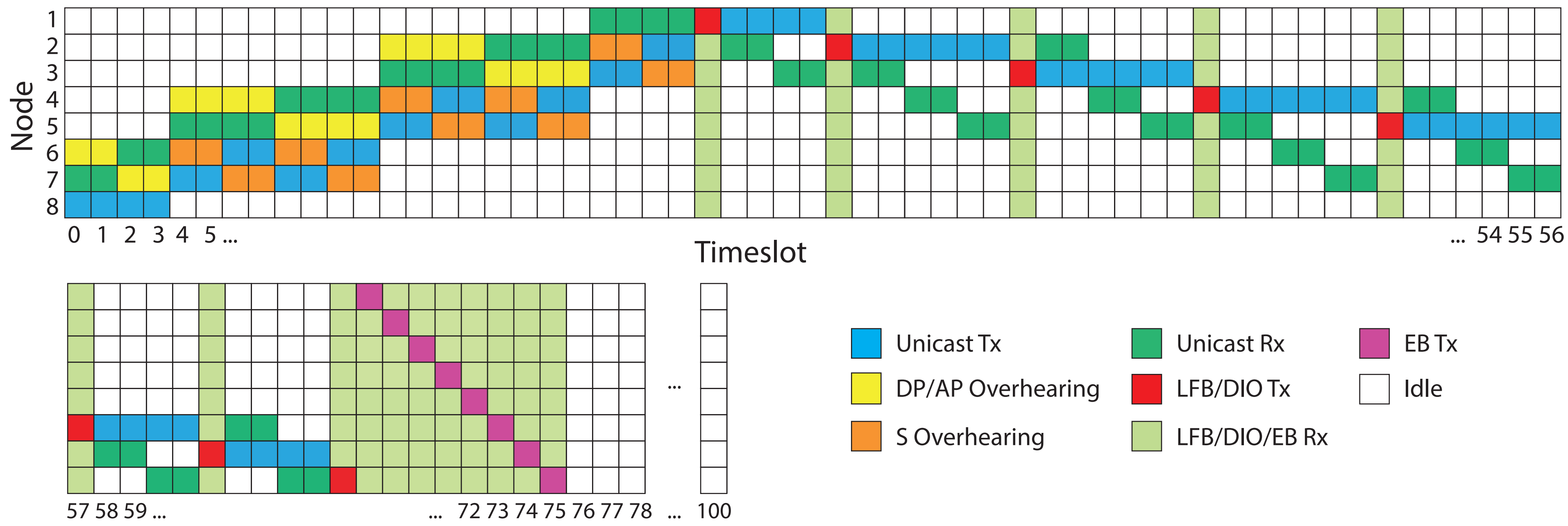
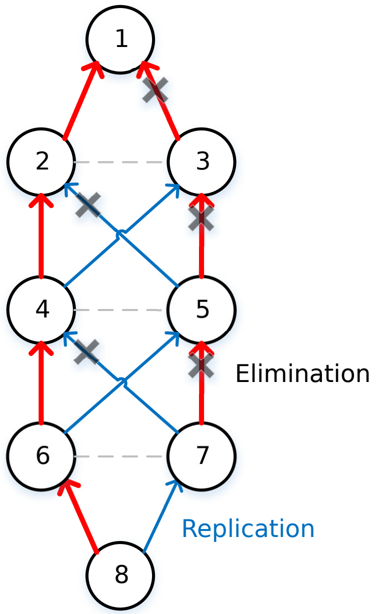
R. A. Koutsiamanis, G. Z. Papadopoulos, X. Fafoutis, J. M. Del Fiore, P. Thubert, N. Montavont,
"From Best-Effort to Deterministic Packet Delivery for Wireless Industrial IoT Networks",
IEEE Transactions on Industrial Informatics, vol. 14, pp. 4468-4480, July 2018.

Simulation Setup

TSCH-based Schedule, Network Topology, Contiki OS & Cooja

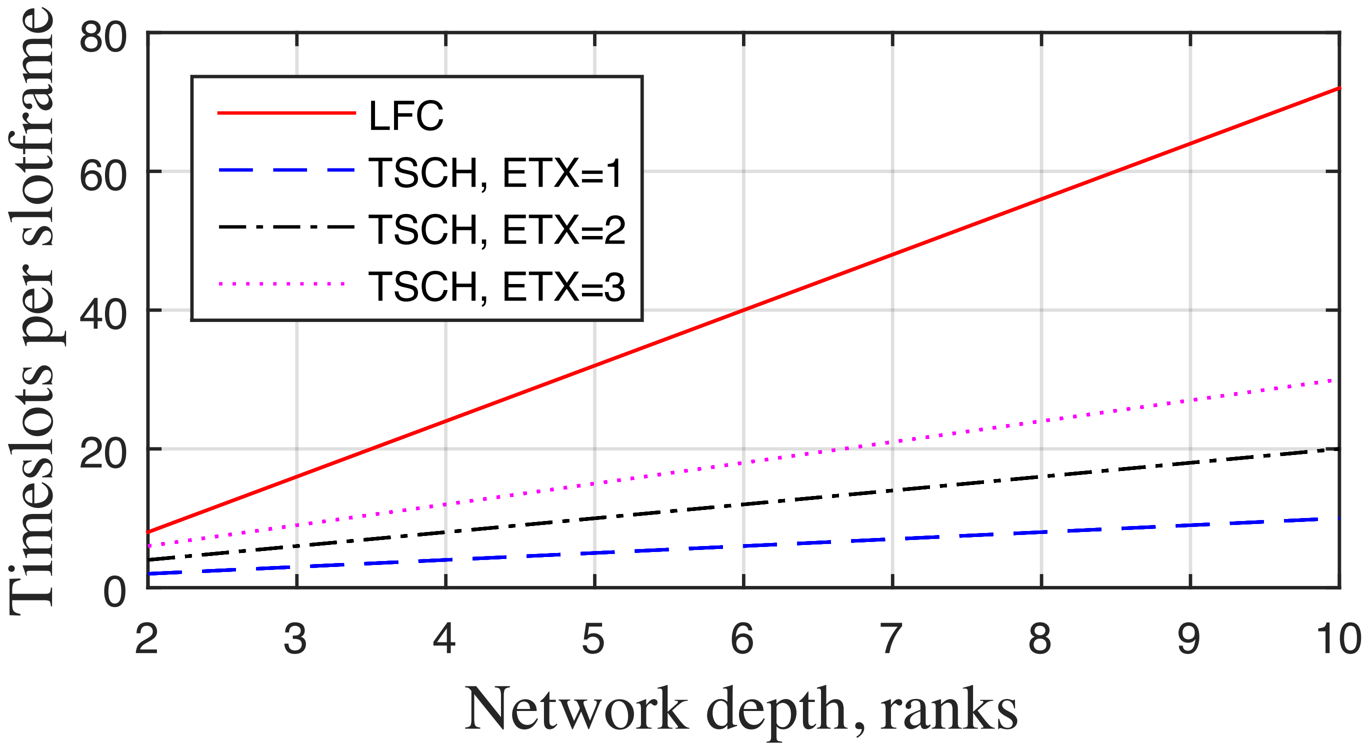




- Contiki OS/Cooja
- Multi-hop network of 8 nodes
- Compared against: Defaults TSCH/RPL, LinkPeek
- Static link qualities of 90%, 80%, 70%, and dynamic link qualities between 70% - 100%

PAREO Performance Evaluation

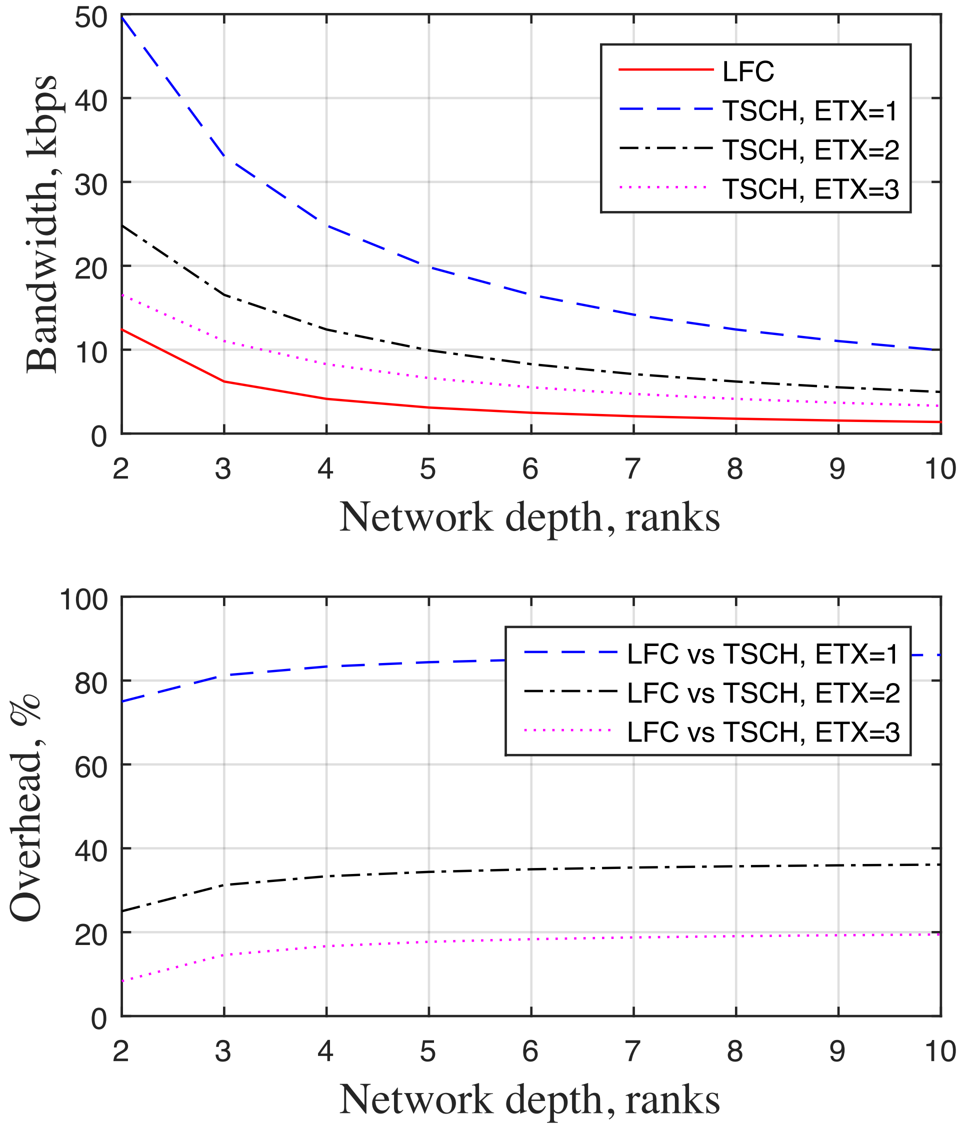
The Capacity Loss Trade-off: The number of timeslots per slotframe



- LFC sacrifices throughput for high reliability, low delay and low jitter.

PAREO Performance Evaluation

The Capacity Loss Trade-off: the available bandwidth, & bandwidth overhead



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PAREO Functions

- Pool of functions :
  - Packet Transmission
  - Automatic Repeat reQuest (ARQ)
  - Replication
  - Overhearing
  - Elimination

- and more such as :
  - Forward Error Correction (FEC)
  - Constructive Interference
  - (Re)Ordering