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UMR IRISA

Reliable and Available Low-Power Wireless Mesh Networks

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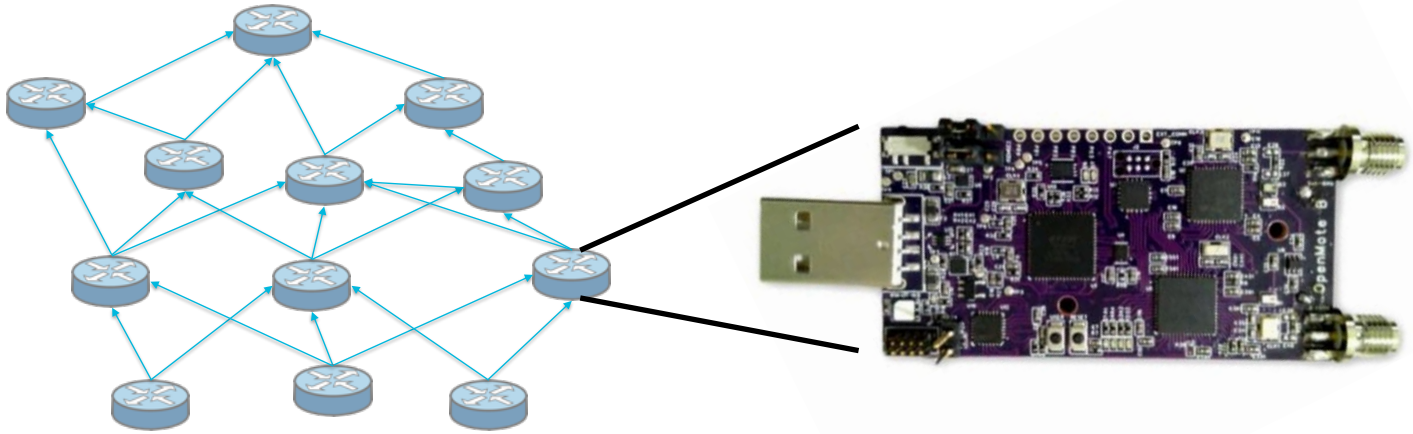
youtube: www.youtube.com/c/gzpapadopoulos

cnrs GDR Groupement de recherche
RSD
Réseaux et Systèmes Distribués

Low-Power Wireless Mesh Networks

Overview

A typical Mesh (multi-hop) Topology



LPWMN consist of "**smart**", **uniquely identifiable** and typically **wirelessly** connected objects such as Sensors & Actuators that cooperatively construct a wireless **network of things**, i.e., IoT.

- **Sensors**: Temperature, Humidity, Pressure, Current.
- **Actuators**: Light, Buzzers, Locks, Valves.

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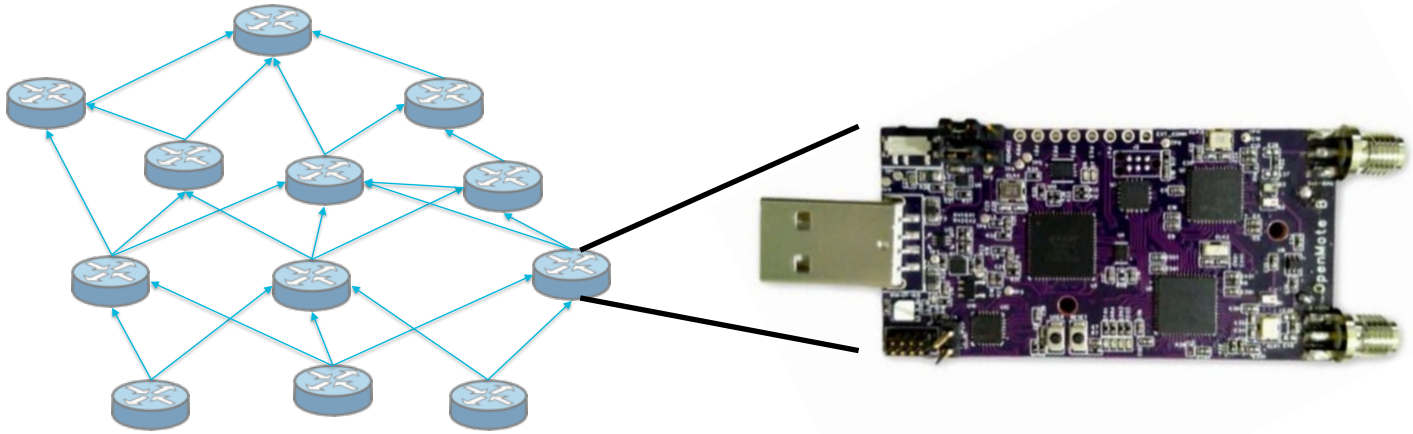

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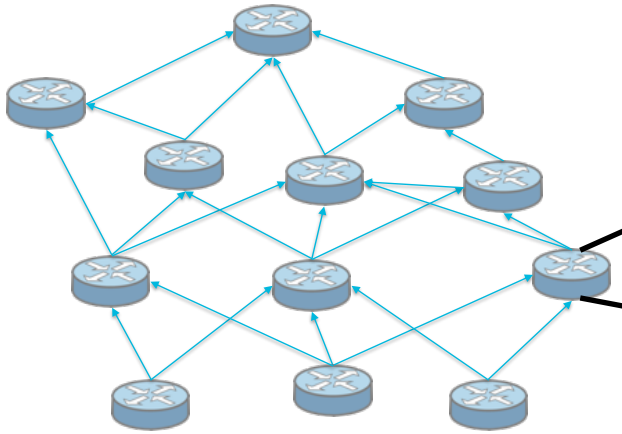

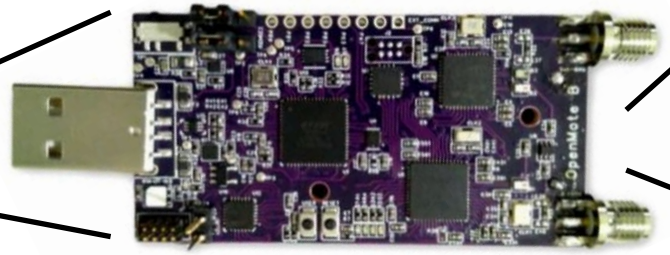

Applications	CoJP	
CoAP / OSCORE	6LoWPAN ND	RPL
UDP	ICMPv6	
IPv6		
6LoWPAN HC / 6LoRH HC	Scheduling Function (MSF)	
6top inc. 6top Protocol (6p)		
IEEE Std 802.15.4 TSCH		
IEEE Std 802.15.4 PHY		

A typical IoT Protocol Stack

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Low-Power Wireless Mesh Networks

OSI Model vs **6TiSCH** Protocol Stack

	Layer	Protocol data unit (PDU)
Host layers	7. Application	Data
	6. Presentation	Data
	5. Session	Data
	4. Transport	Segments, Datagram
Media layers	3. Network	Packets
	2. Data Link	Frames
	1. Physical	Bits

IETF®

Applications	CoJP	
CoAP / OSCORE	6LoWPAN ND	RPL
UDP	ICMPv6	
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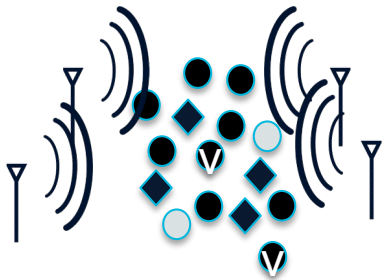
IEEE

Throughput : Gbit/s
MTU : ~1000 Bytes



Throughput : 100 Kbit/s
MTU : ~100 Bytes

Toward Reliable & Available Low-Power (Wireless) Mesh Networks

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Toward Reliable & Available LPWMNs

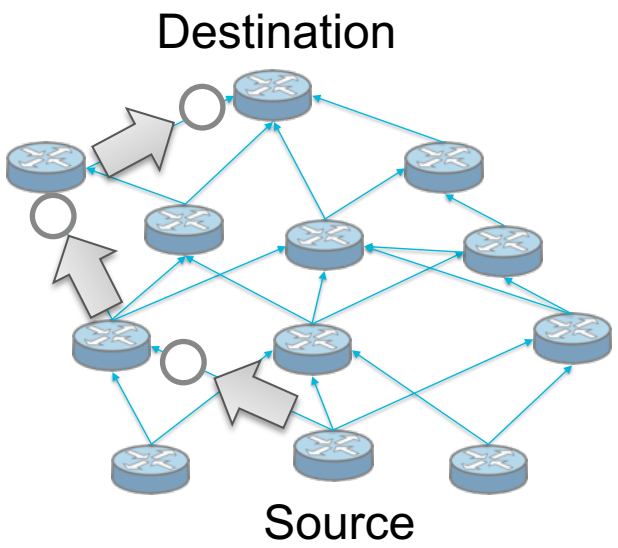
Analogy of Reliable and Available LPWMN from Real-world

The goal of the reserved bus lanes in a city (*for the buses*) is ***to avoid delays*** due to traffic jams!

Toward Reliable & Available LPWMNs

The Challenge in QoS-hungry networks

The information should be carried out **in a pre-defined** and **constant delay**!



Toward Reliable & Available LPWMNs

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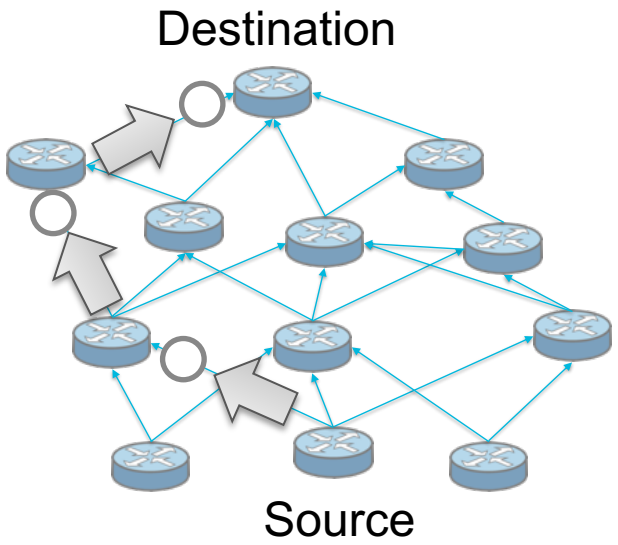
Thus, in addition to high reliability is to provide a **bounded latency**.



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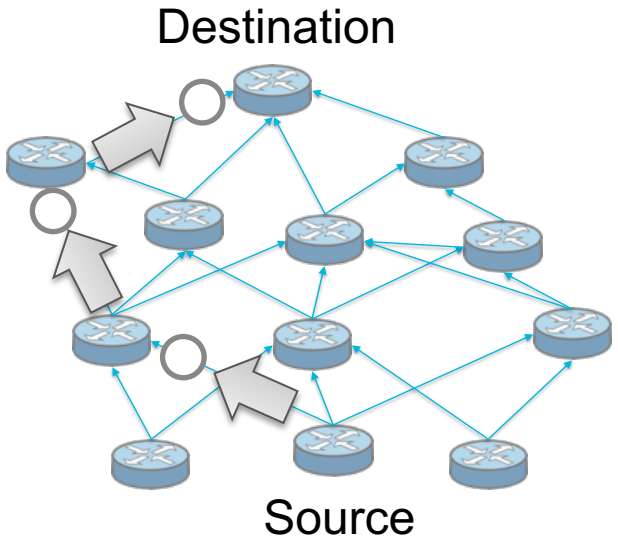

There's no such thing as a Free Lunch!

- Throughput (network capacity)
- Energy consumption

Toward Reliable & Available LPWMNs

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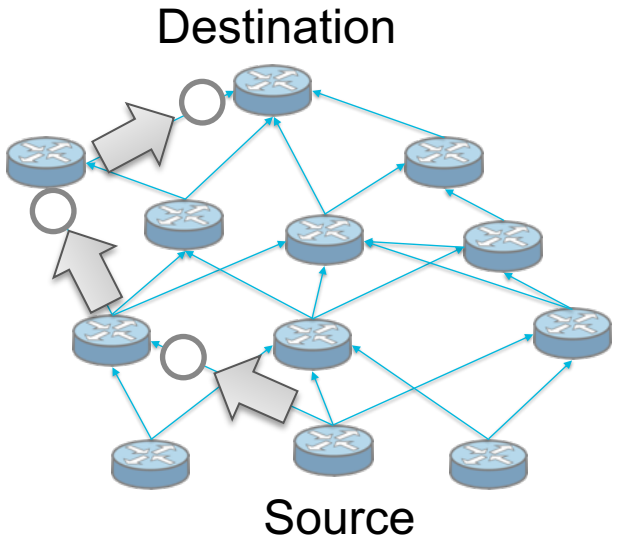


There's no such thing as a Free Lunch!

- Throughput (network capacity)
- Energy consumption

Good news!

- Devices are plugged into a power supply.
- Low traffic rate applications.

Toward Reliable & Available LPWMNs

Scientific Approach

HDR subject!

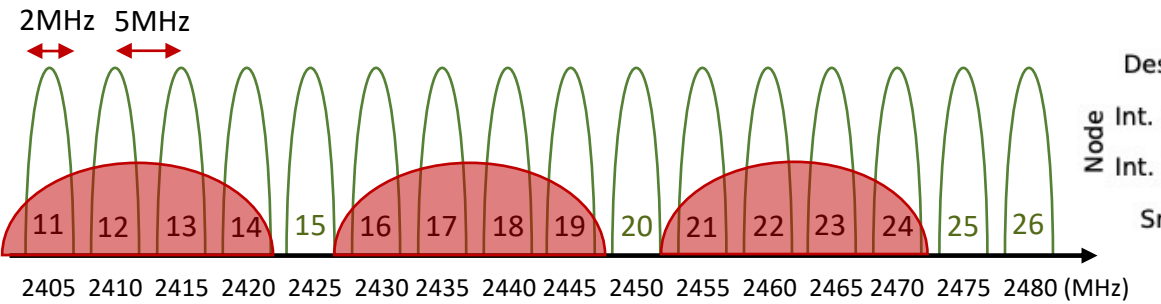
- 1 Postdoc
- 4 PhD students
- Several Interns

Radio Channel Blacklisting Algorithms — **Frequency**

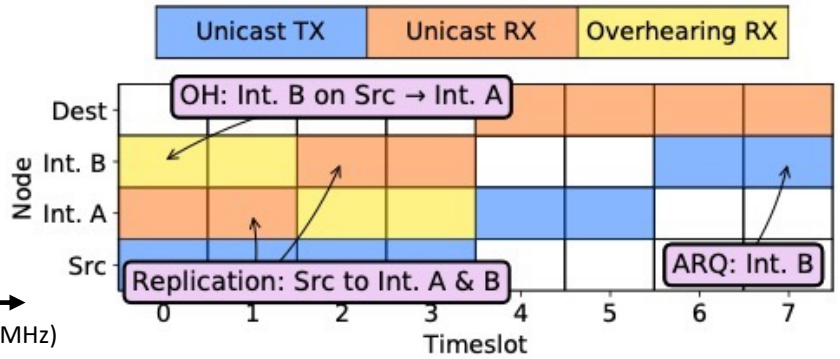
Scheduling Functions — **Temporal**

Multipath Routing Strategies — **Spatial**

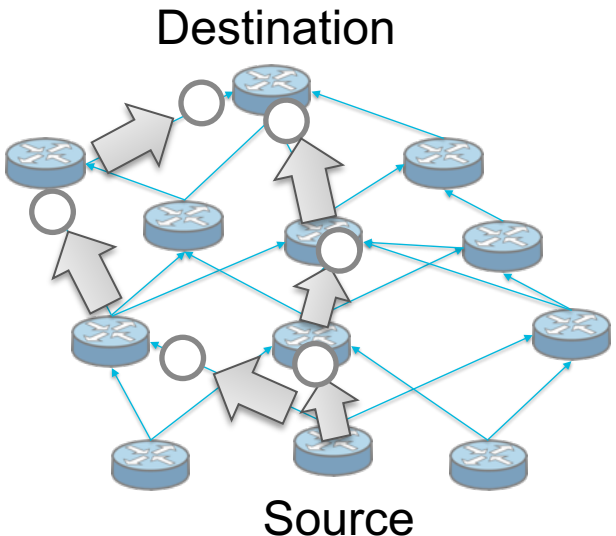
Frequency



Temporal



Spatial



Research Methodology Approach

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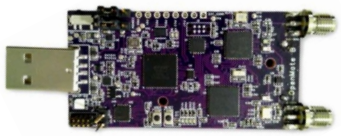
Research Methodology Approach

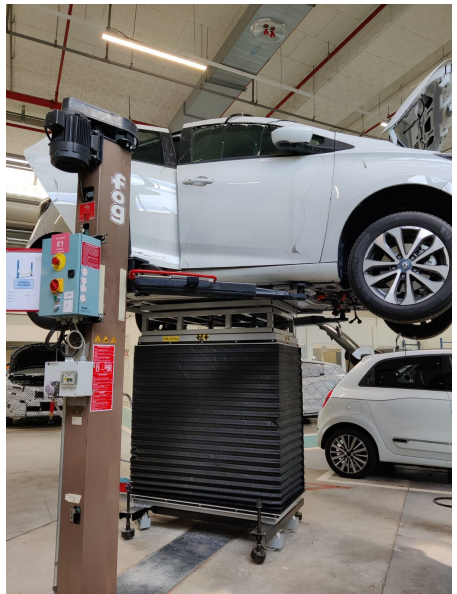
- Academic Research:
  - Analysis.
  - Simulations (6TiSCH simulator, Cooja, **Grid5000**).
  - Experiments (Contiki OS, OpenMotes, **FIT IoT-LAB**).



- Standardization:
  - ROLL, RAW, DetNet, and 6TiSCH WGs.
- Testbeds:
  - OS Electric Vehicle.
  - Renault Fluence Battery Pack.
  - EVs.

- Real-world applications:
  - Wireless BMS with industrial partners (**TI** and **Renault**).

@Technocentre Renault
Project: CIFRE (Renault)



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Research Methodology Approach

Toward Wireless Battery Management System (BMS)

From the desk to the car

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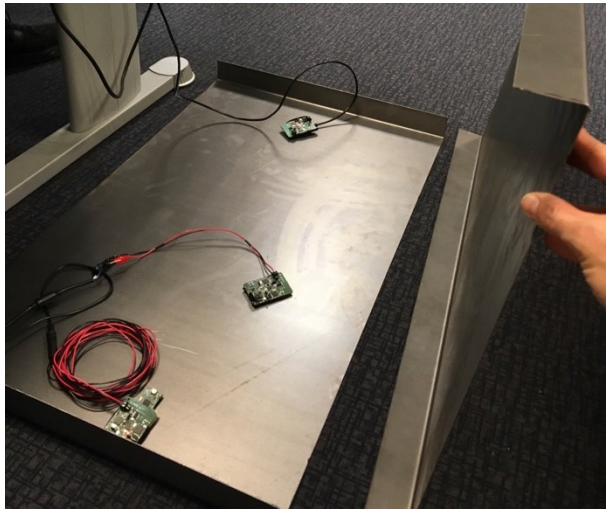
Project: Contrat de Recherche Industriel (Texas Instruments)



@IMT Mines Alès
Project: InterCarnot M.I.N.E.S - TSN

@Technocentre Renault
Project: CIFRE (Renault)

The employed Protocol Stack

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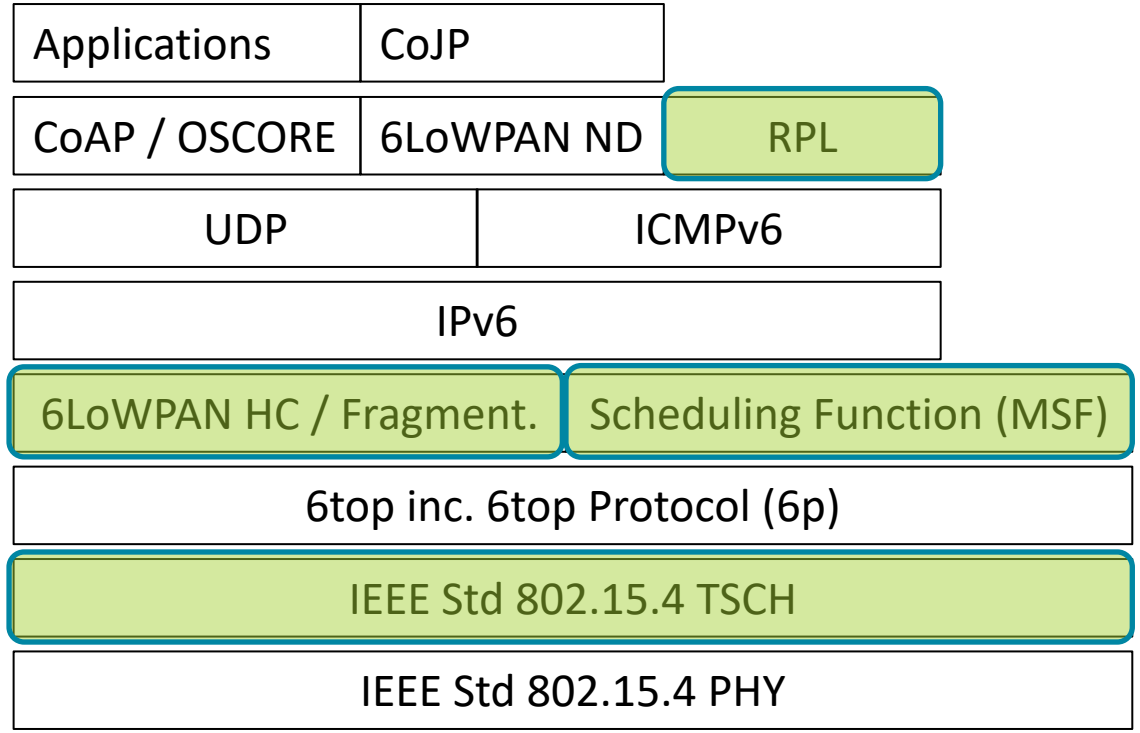
The 6TiSCH Protocol Stack

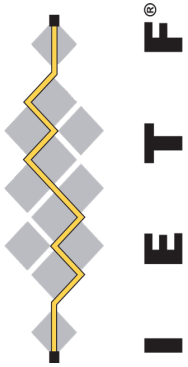
Overview

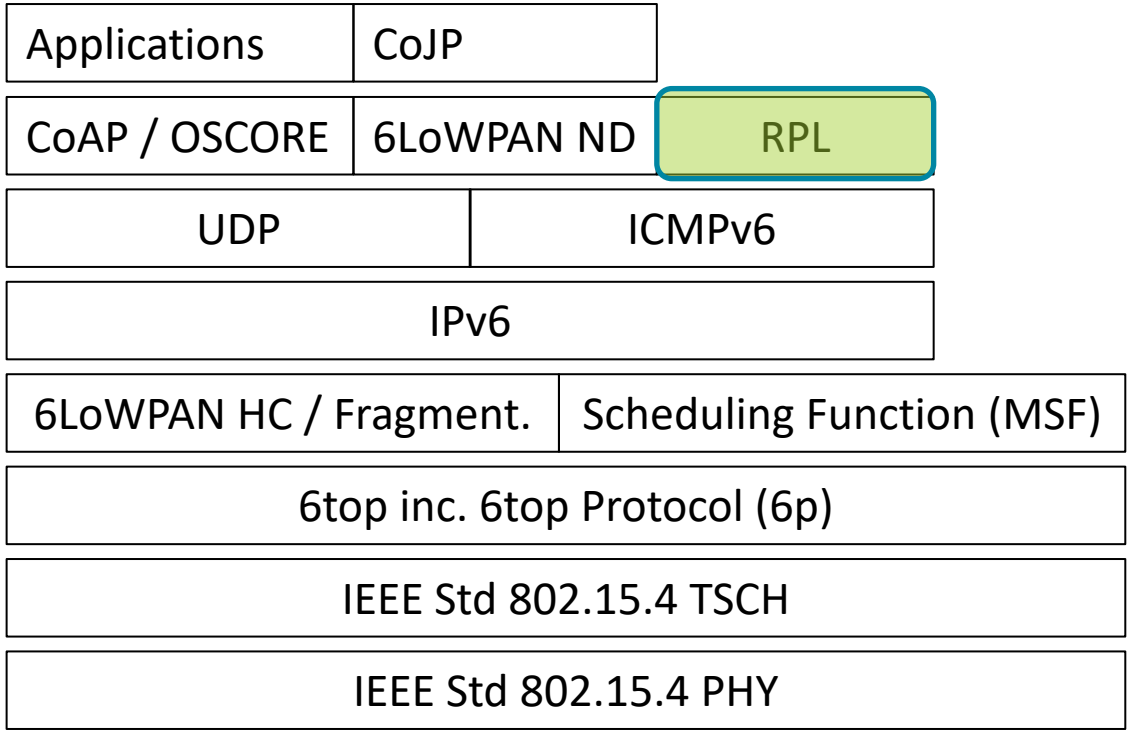


- Routing: RPL
- Resource Allocation: 6P and MSF
- Fragment Forwarding: 6LoWPAN
- Medium Access Control: TSCH

The 6TiSCH Protocol Stack

Overview





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RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks

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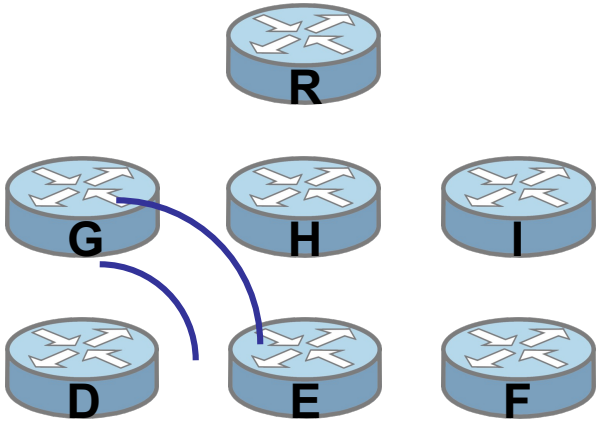
The 6TiSCH Protocol Stack

RFC 6550: RPL

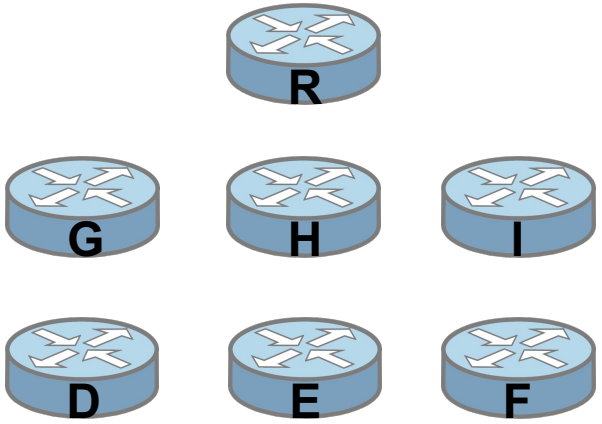
Beyond the radio coverage of one node, it will require a routing protocol



The 6TiSCH Protocol Stack

RFC 6550: RPL

- One of the most adopted routing protocols.
- Link-layer agnostic.
- Proactive routing protocol.



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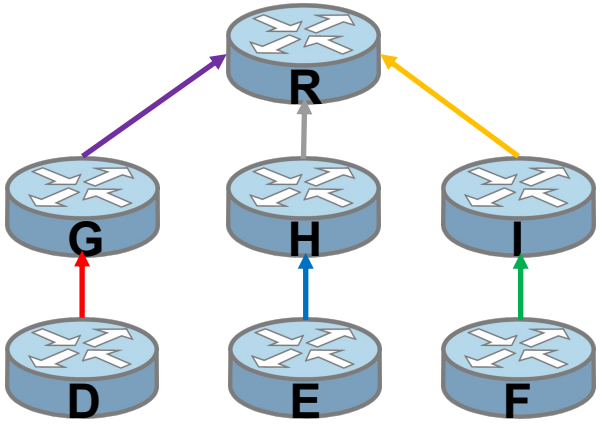

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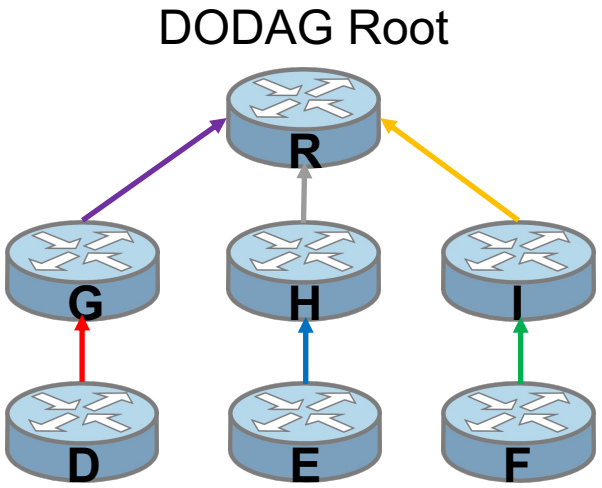

The 6TiSCH Protocol Stack

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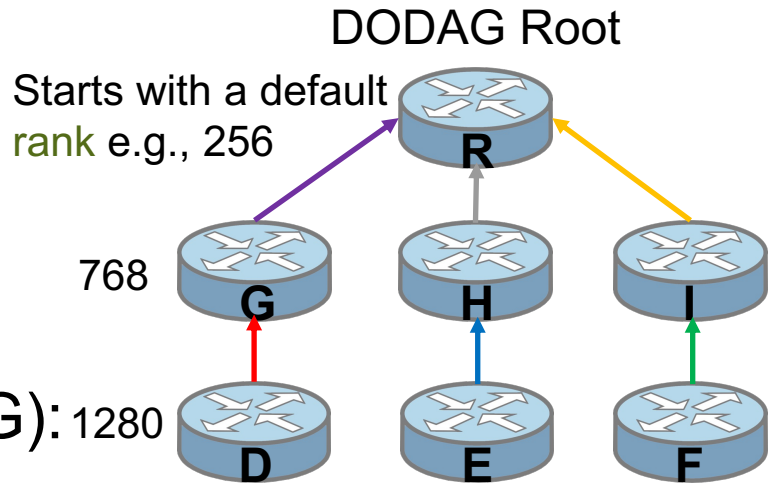

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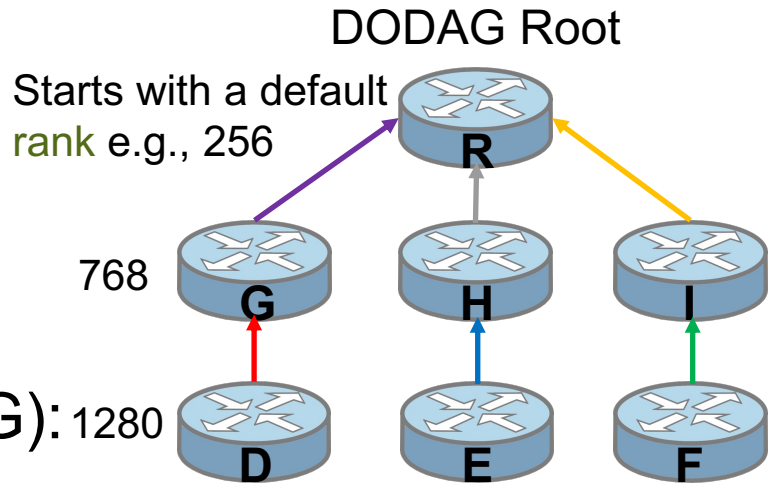

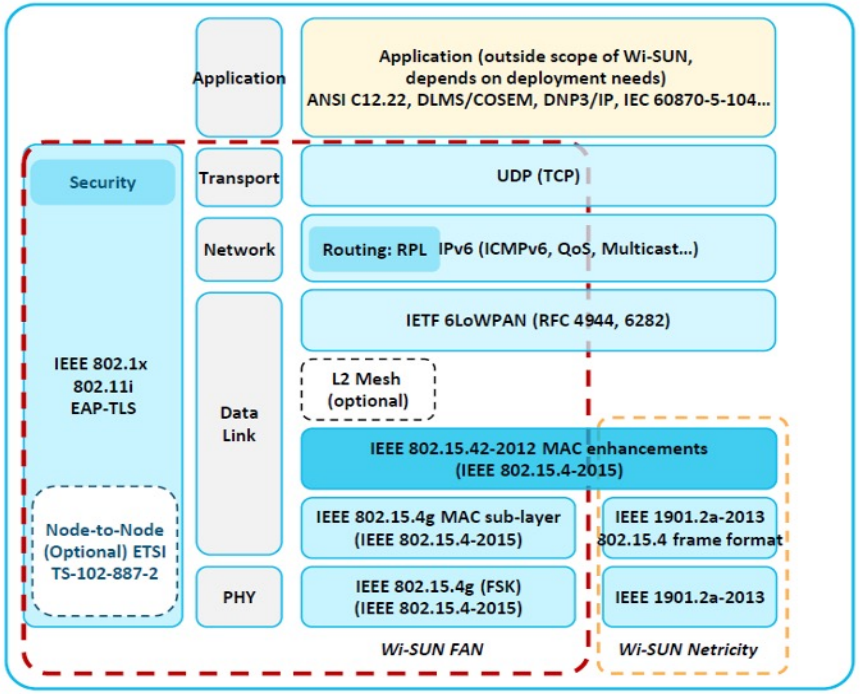

Wi-SUN Protocol Stack

Problem Formulation: Routing Layer

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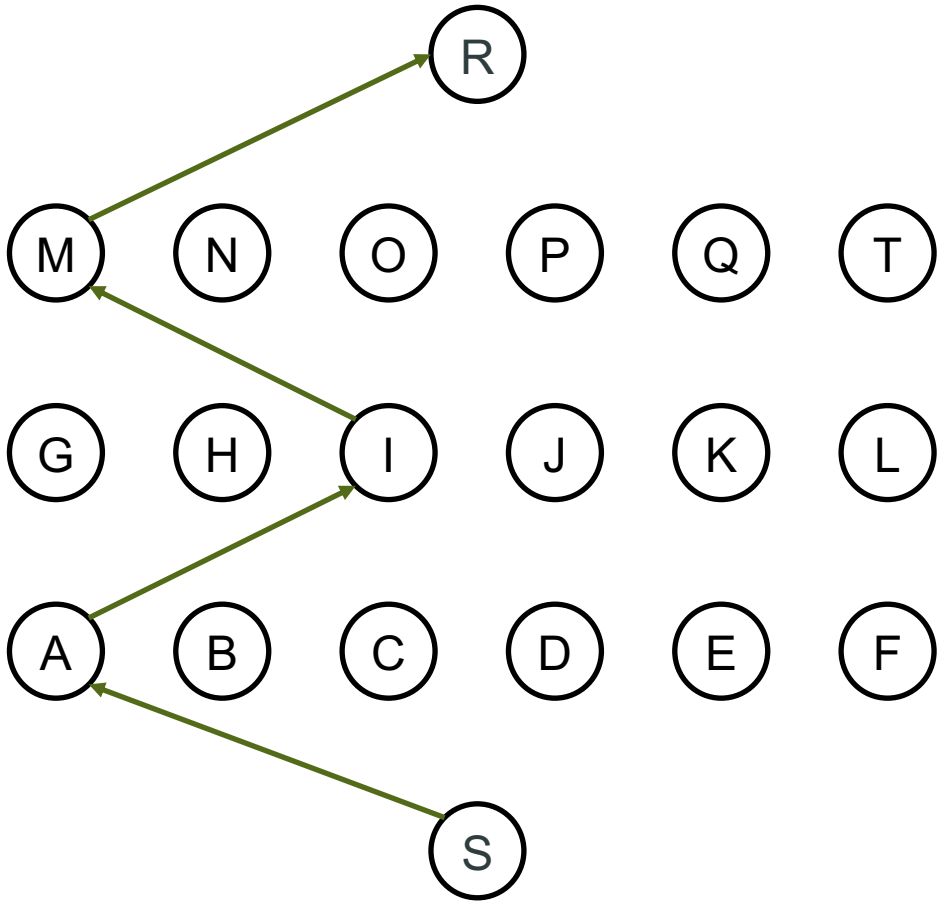
Problem Formulation

An example of a crashed node or bad link quality

Default RPL operation



Preferred Parent (PP)

Problem Formulation

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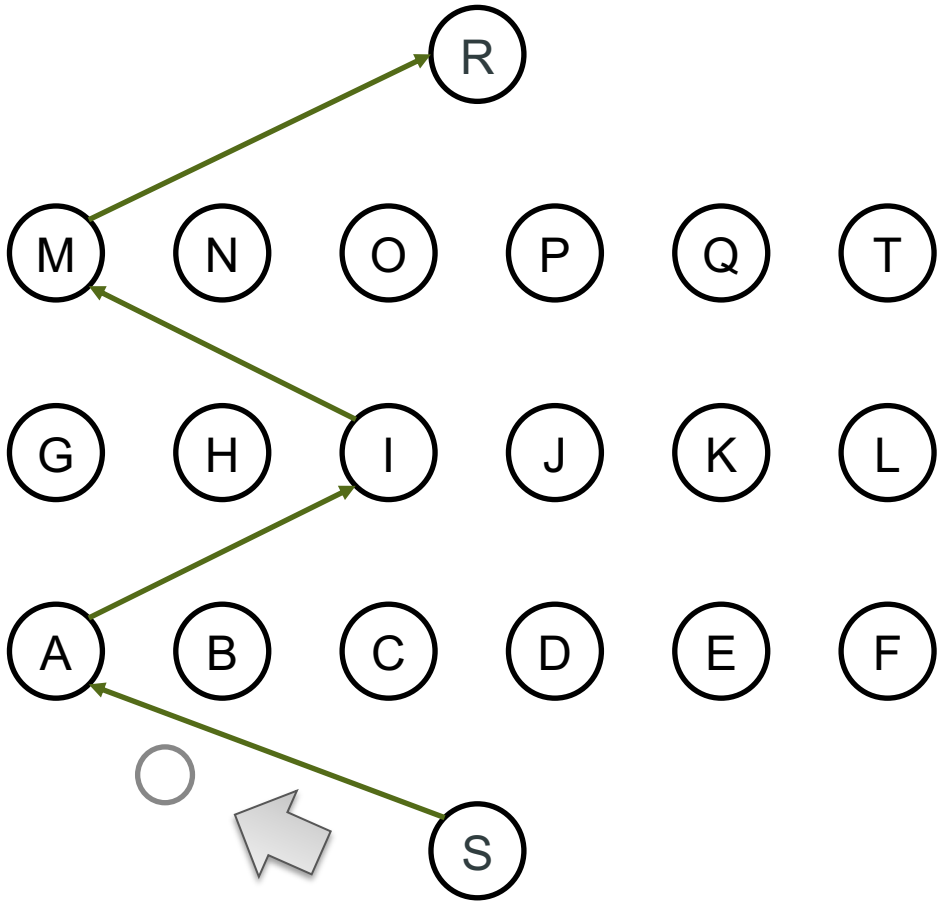

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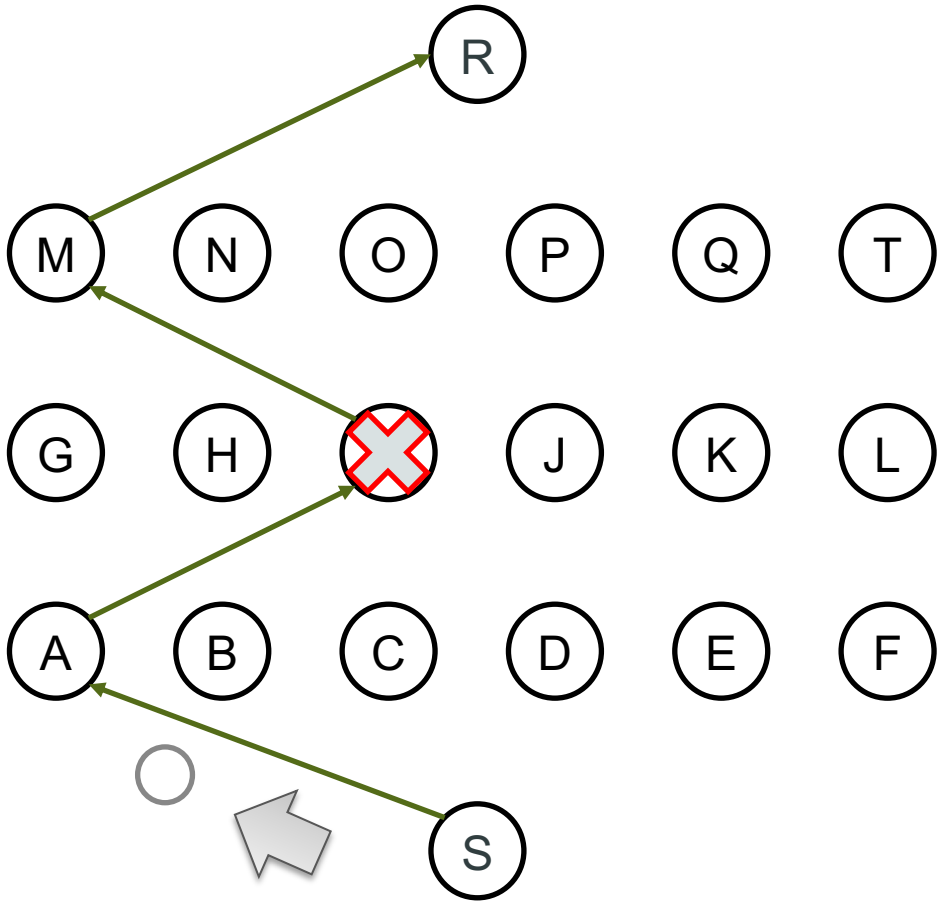

- Node failure
- or poor radio link

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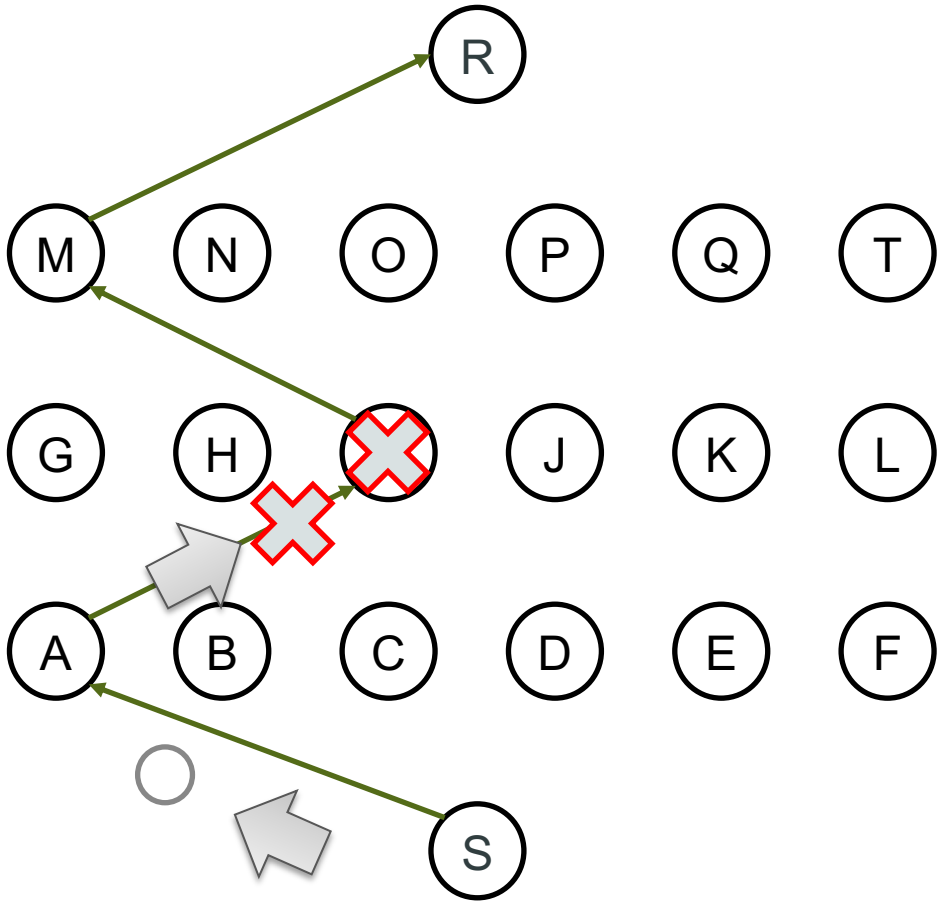

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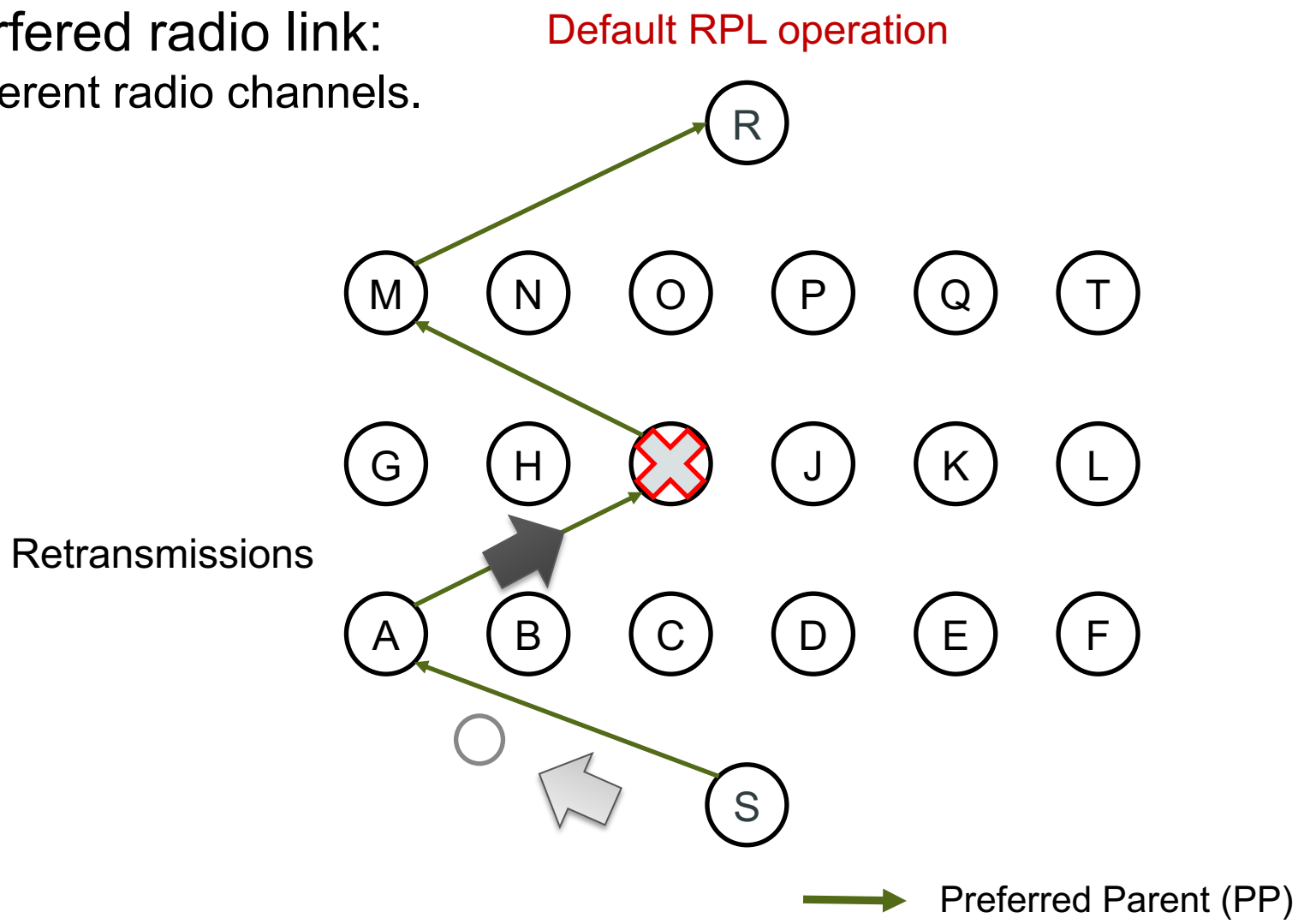

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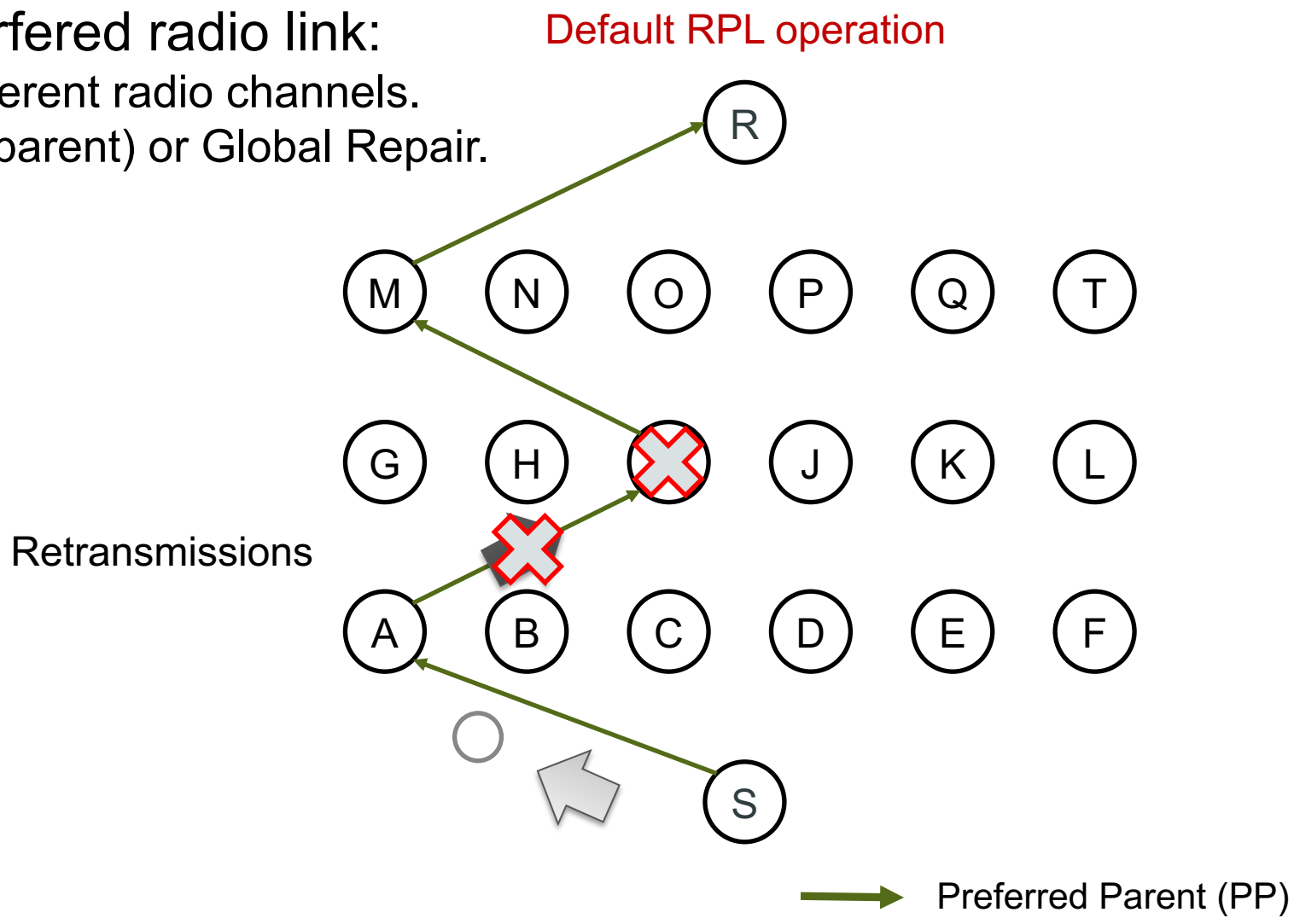

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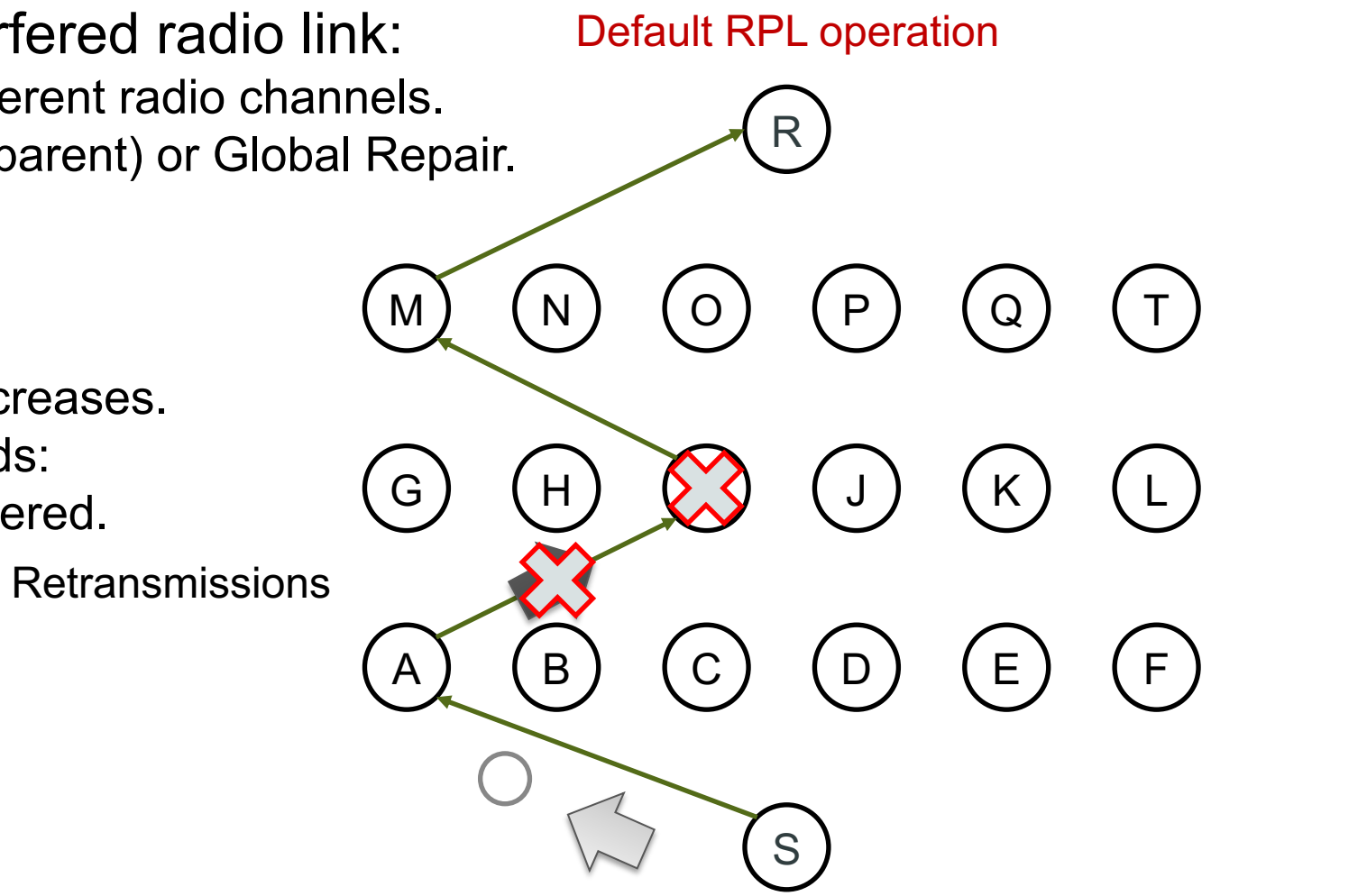
An example of a crashed node or bad link quality

- Crashed node or heavily interfered radio link:
  - TSCH: Retransmissions over different radio channels.
  - RPL: Local (to select alternative parent) or Global Repair.
- Costs:
  - Latency and jitter increase.
  - End-to-end network reliability decreases.
  - Network (unnecessarily) overloads:
    e.g., the Trickle timer will be triggered.



Separation of PSE from PCE

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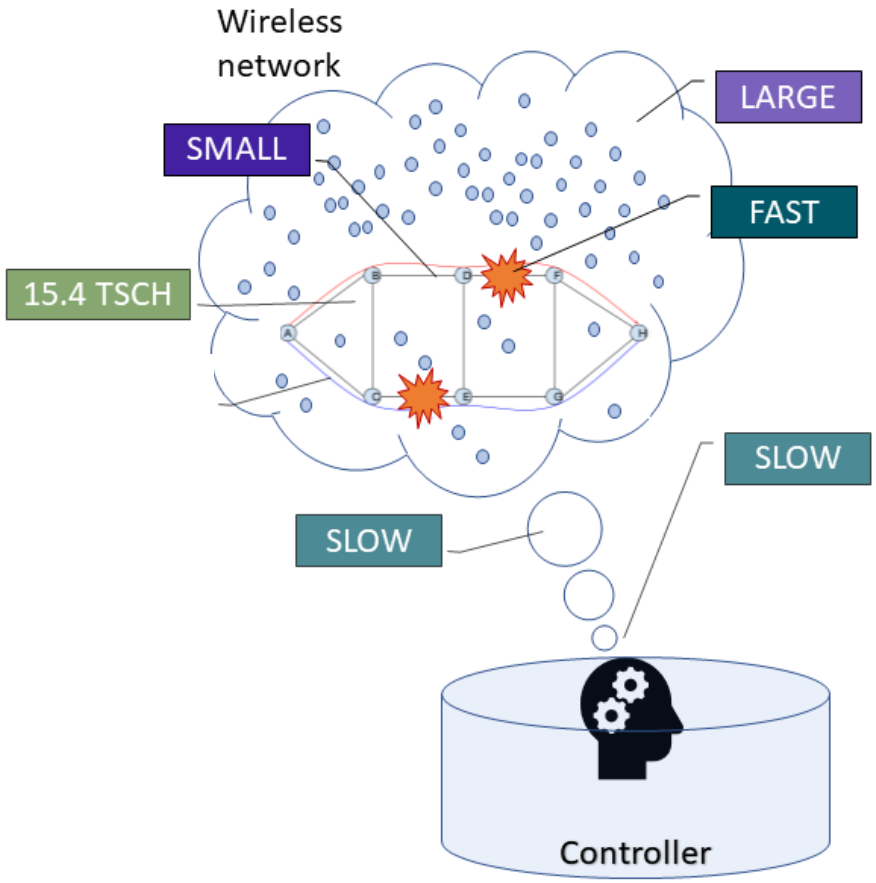
"IETF Reliable and Available Wireless (RAW): Use Cases and Problem Statement",
G. Z. Papadopoulos, F. Theoleyre, P. Thubert and N. Montavont,
In Proc. **AdHoc-Now** - Bari, Italy, October **2020**.

Ongoing Work & Perspectives

Separation of PSE from PCE

- Path Computation Element (Controller):
  - Focus on computing the ***routing paths*** for the whole network.



Ongoing Work & Perspectives

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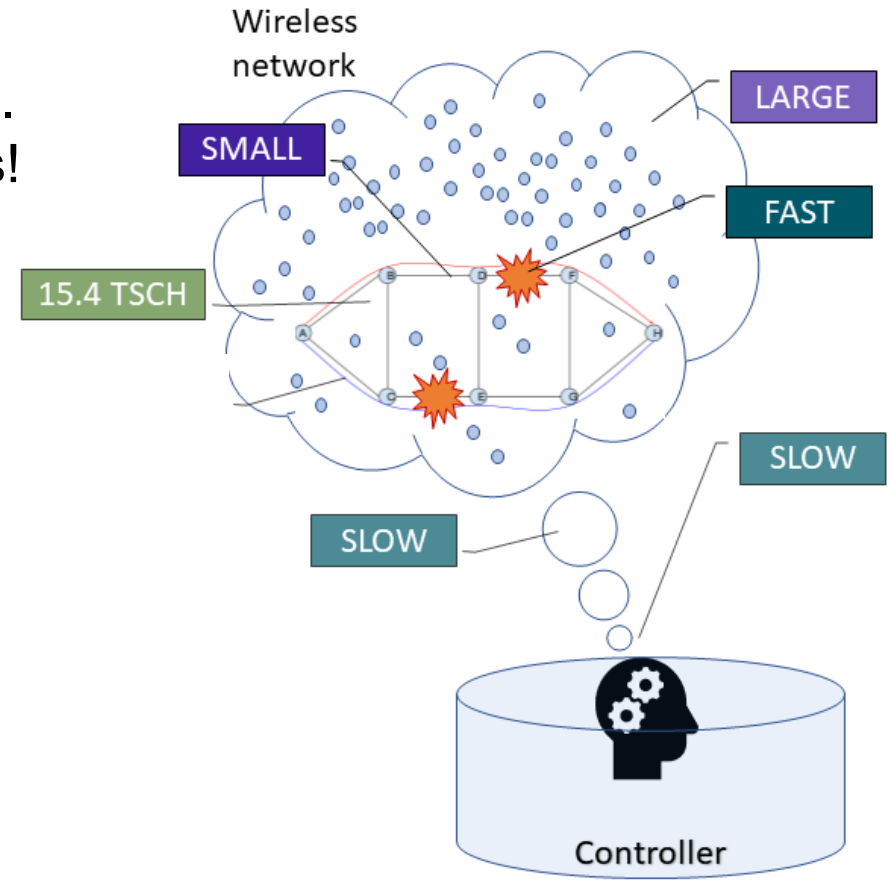
- Path Selection Engine (PSE):
  - Focus on ***forwarding plane*** to make the per-packet decision.
  - Employ either commonly or separately the PAREO Functions!



Ongoing Work & Perspectives

Separation of PSE from PCE

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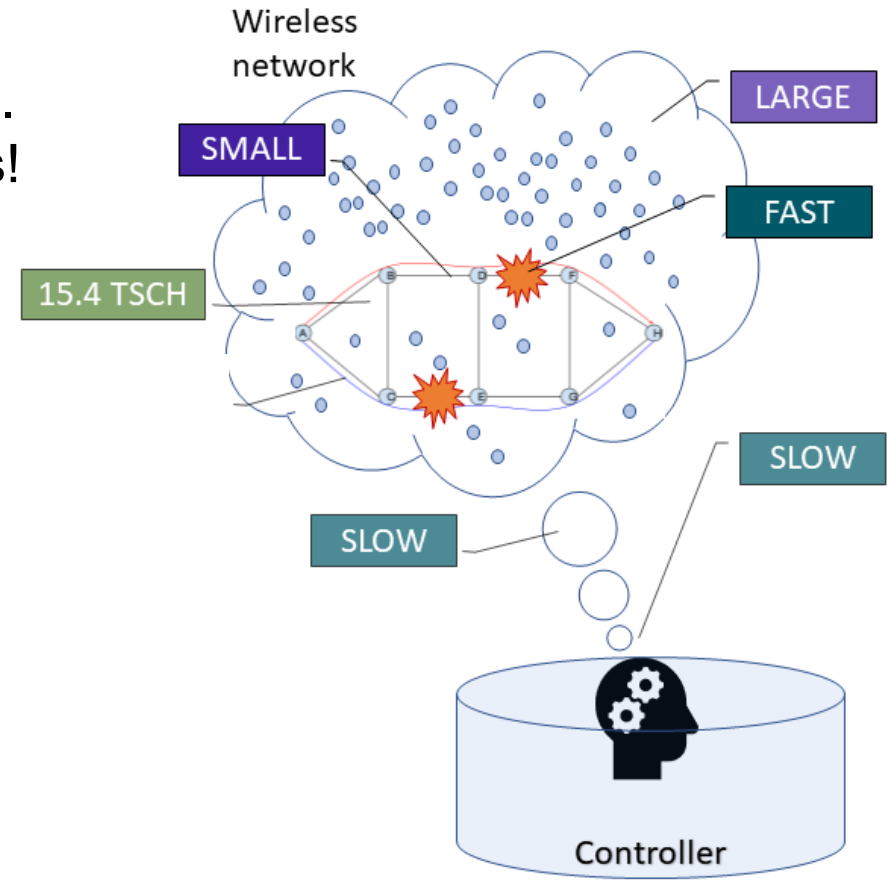
- Path Selection Engine (PSE) [3]:
  - Focus on ***forwarding plane*** to make the per-packet decision.
  - Employ either commonly or separately the PAREO Functions!
- Objective is to *separate*:
  - The **long-term** path computation time scale at which the *paths are recomputed*.
  - From the **short-term** path selection time scale at which the *forwarding decision is taken*.



Step 1: PSE - Forwarding Plane (Meet the PAREO Functions)

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"*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

PAREO Functions

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

- and more such as:
  - Forward Error Correction (FEC) [1], [2]
  - Packet (Re)Ordering (work-in-progress)

[1] “Lightweight XOR based FEC Algorithm for Fragment Forwarding in 6LoWPAN Networks”, C. Ji, A. Bruniaux, V. Kotsiou, G. Z. Papadopoulos and P. Chatzimisios, In Proc. **IEEE GLOBECOM** - Rio de Janeiro, Brazil, December **2022**.

[2] "*Defragmenting the 6LoWPAN Fragmentation Landscape: A Performance Evaluation*" A. Bruniaux, R.-A. Koutsiamanis, G. Z. Papadopoulos and N. Montavont In **MDPI Sensors**, vol. 21(5), pp. 1711, March **2021**.

PAREO Functions

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

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

[1] “Lightweight XOR based FEC Algorithm for Fragment Forwarding in 6LoWPAN Networks”, C. Ji, A. Bruniaux, V. Kotsiou, G. Z. Papadopoulos and P. Chatzimisios, In Proc. **IEEE GLOBECOM** - Rio de Janeiro, Brazil, December **2022**.

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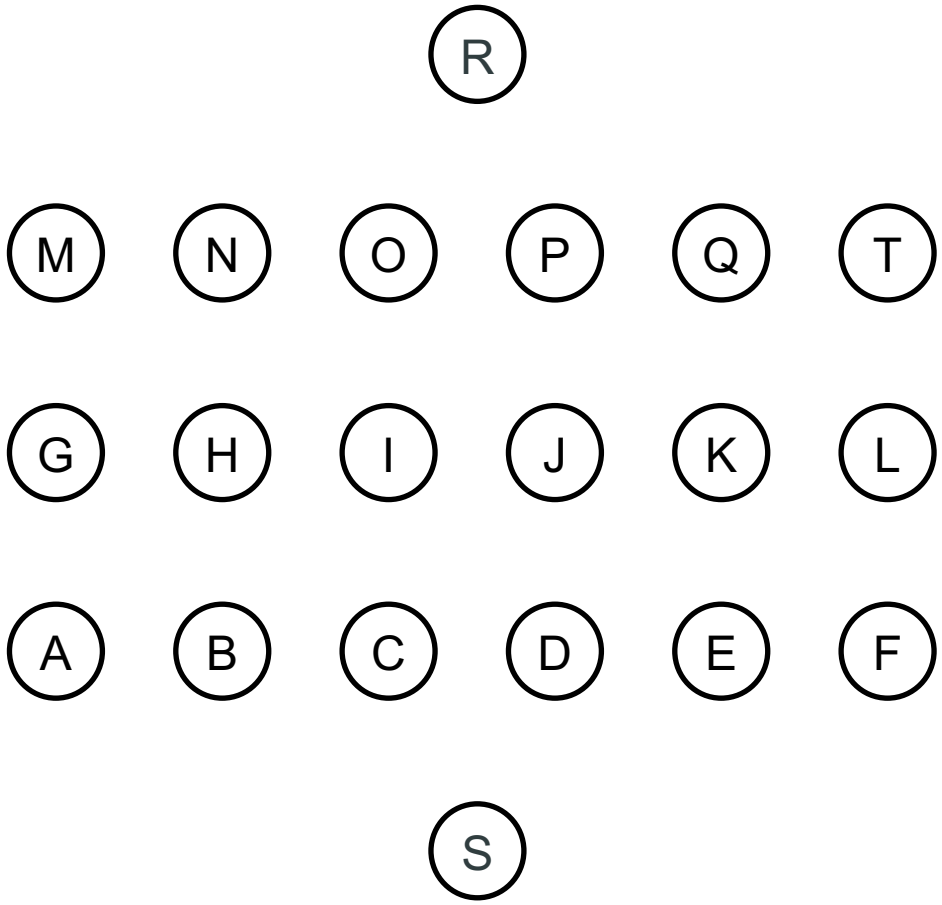
PAREO Functions

Example of a Wireless Topology

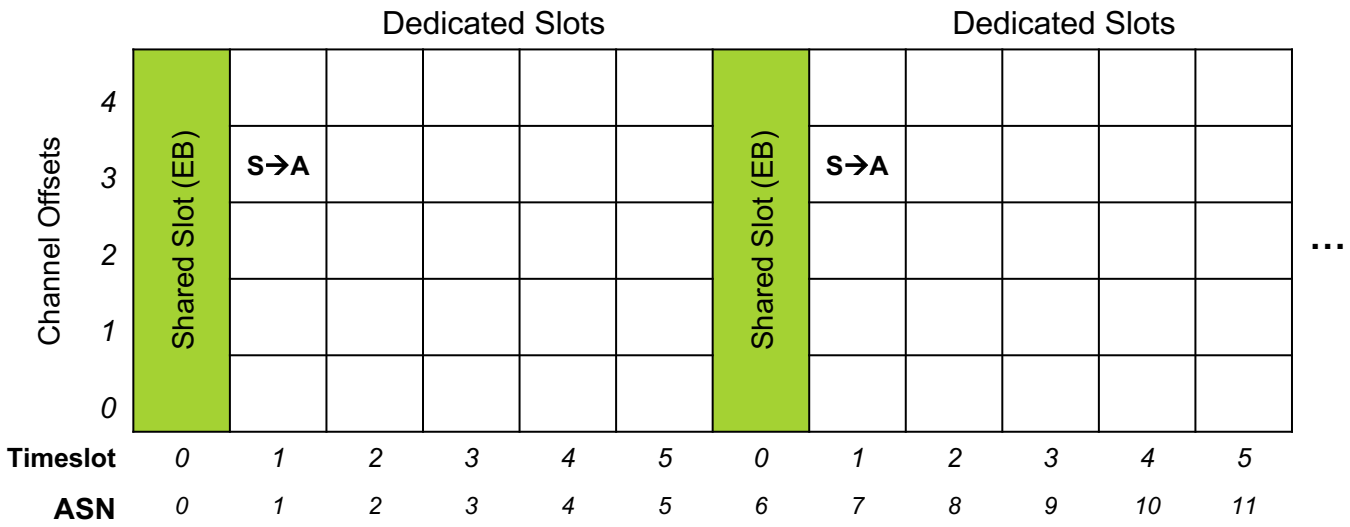
- S is the Source
- R is the Root (destination)
- Relay nodes



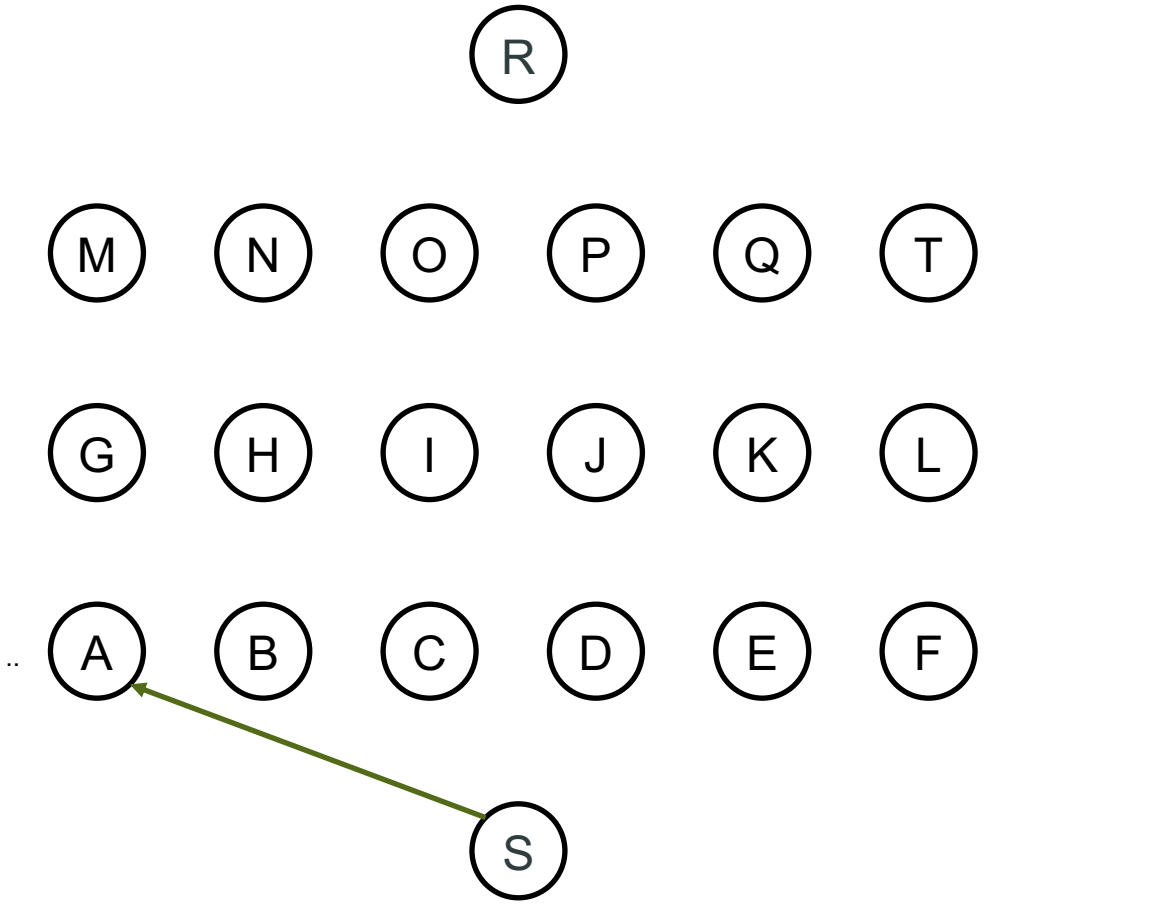
PAREO Functions

Packet Transmission from S to A

- A data packet is sent to the Preferred Parent.



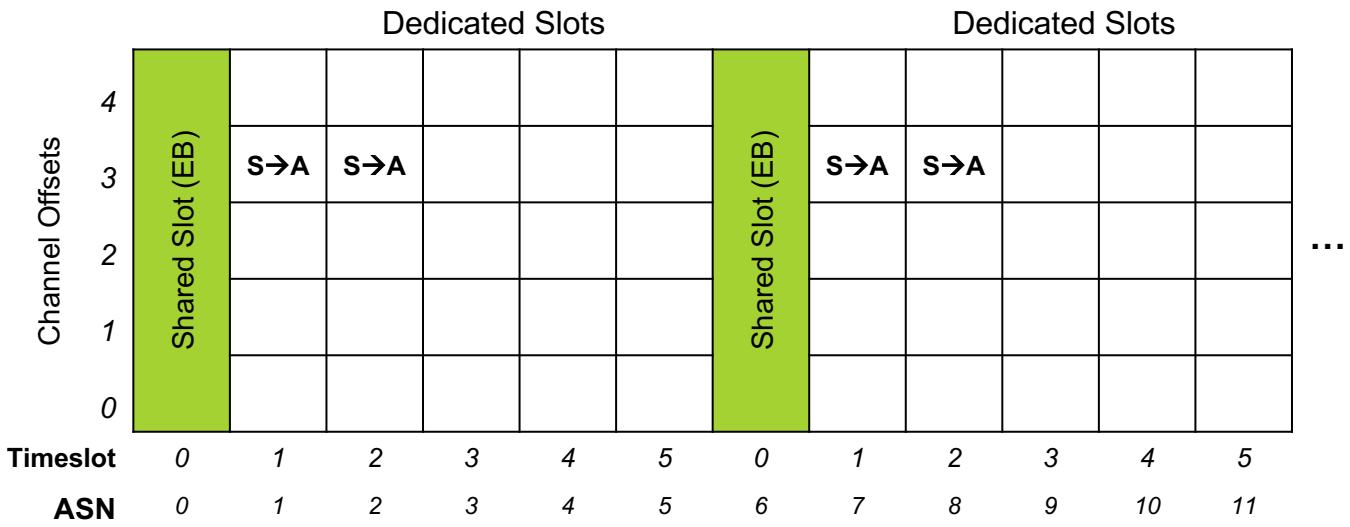
A typical TSCH schedule



PAREO Functions

Automatic Repeat reQuest (ARQ)

- The ARQ function performs the re-transmission of a frame when a previous transmission failed.



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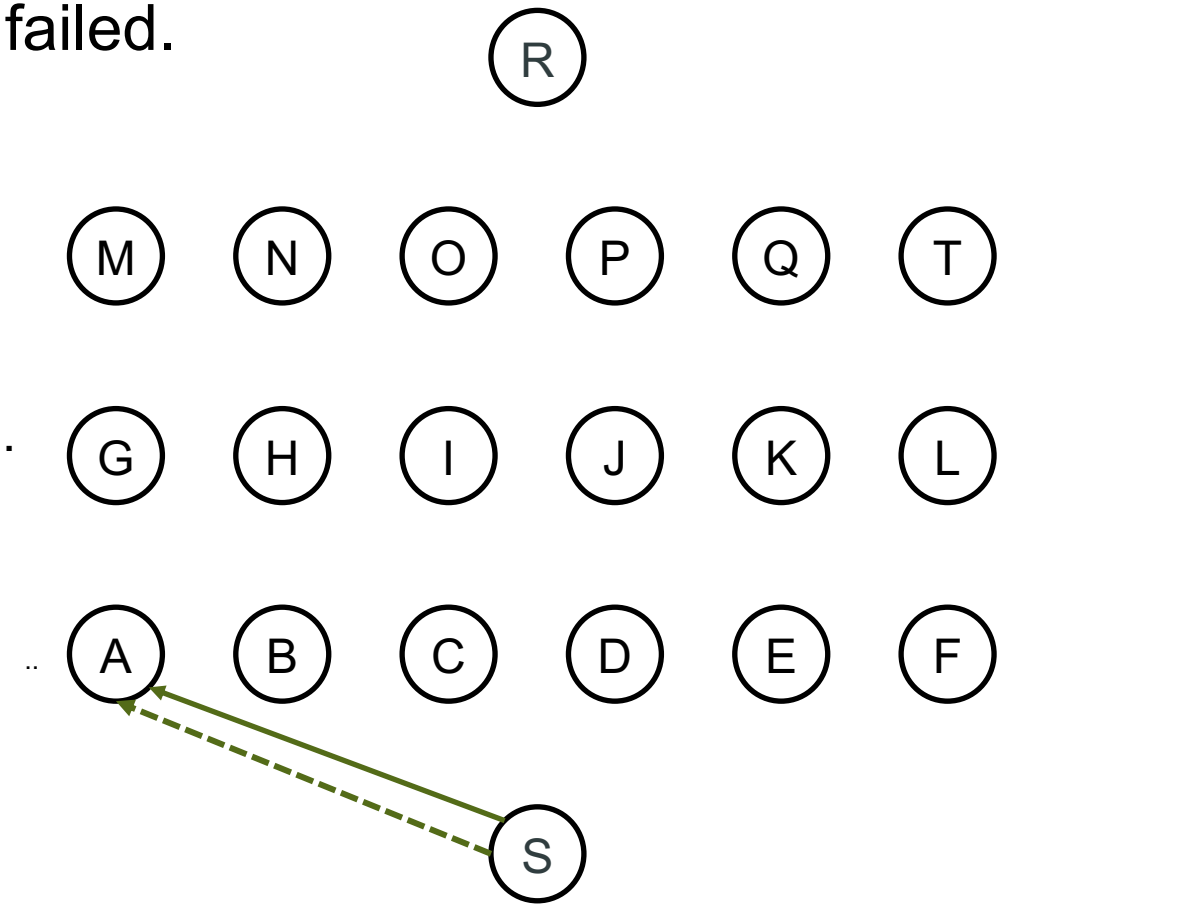
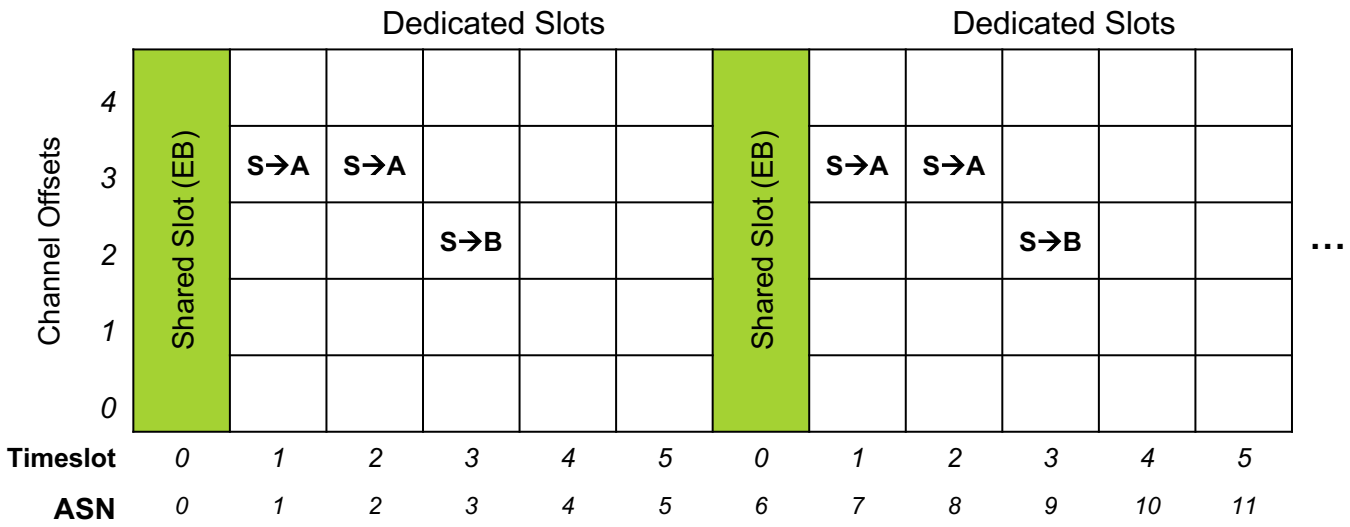


PAREO Functions

Replication

- A data packet is sent to both Preferred & Alternative Parent.



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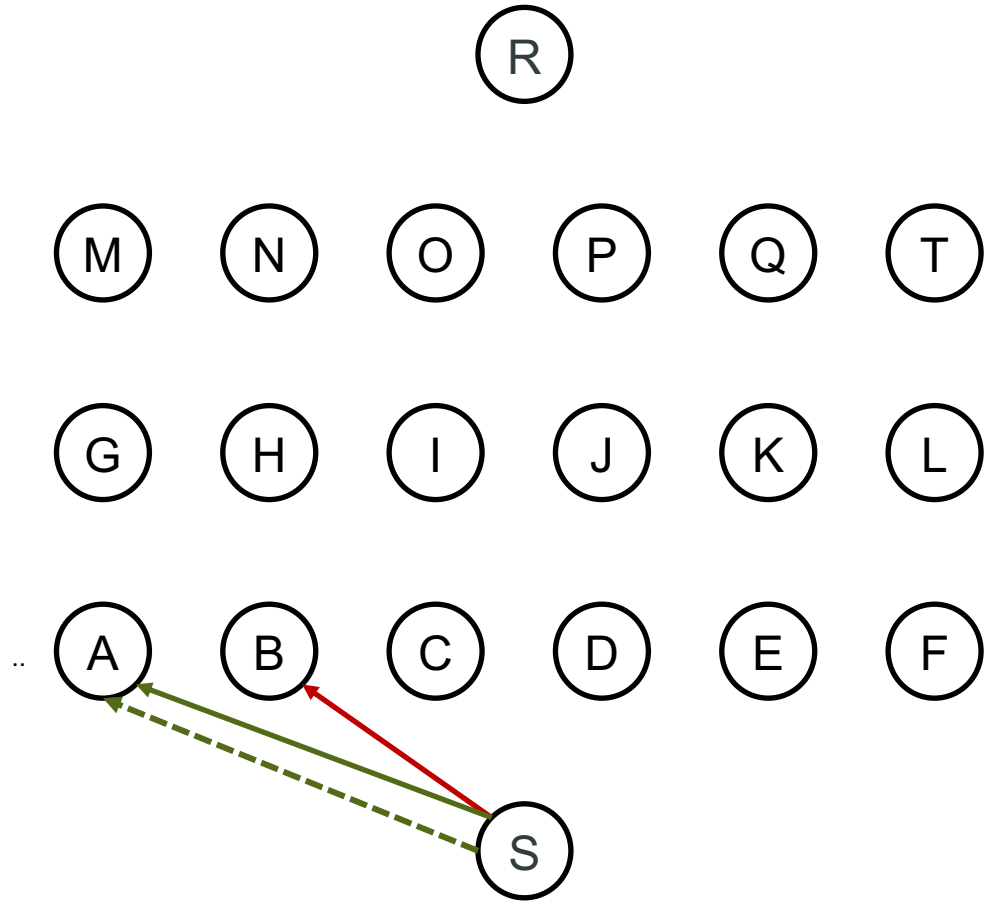
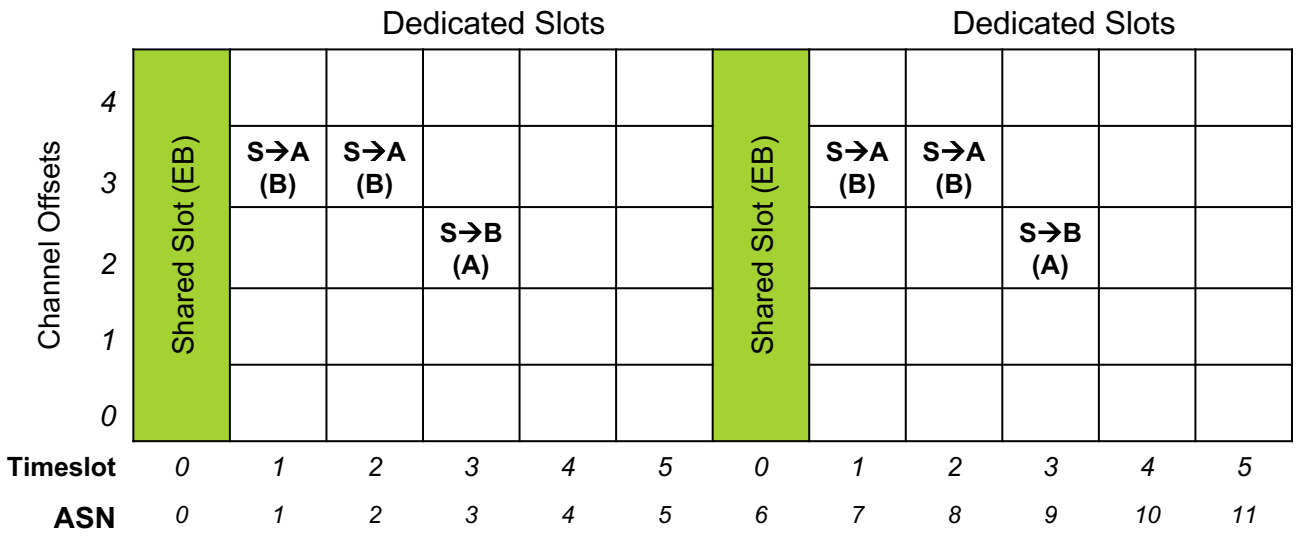


Preferred Parent (PP)
Alternative Parent (AP)

PAREO Functions

Promiscuous Overhearing

- Considering that wireless medium is broadcast by nature.
- Any neighbor of a sender may overhear the transmission.
- Only the actual destination of the frame must ACK.



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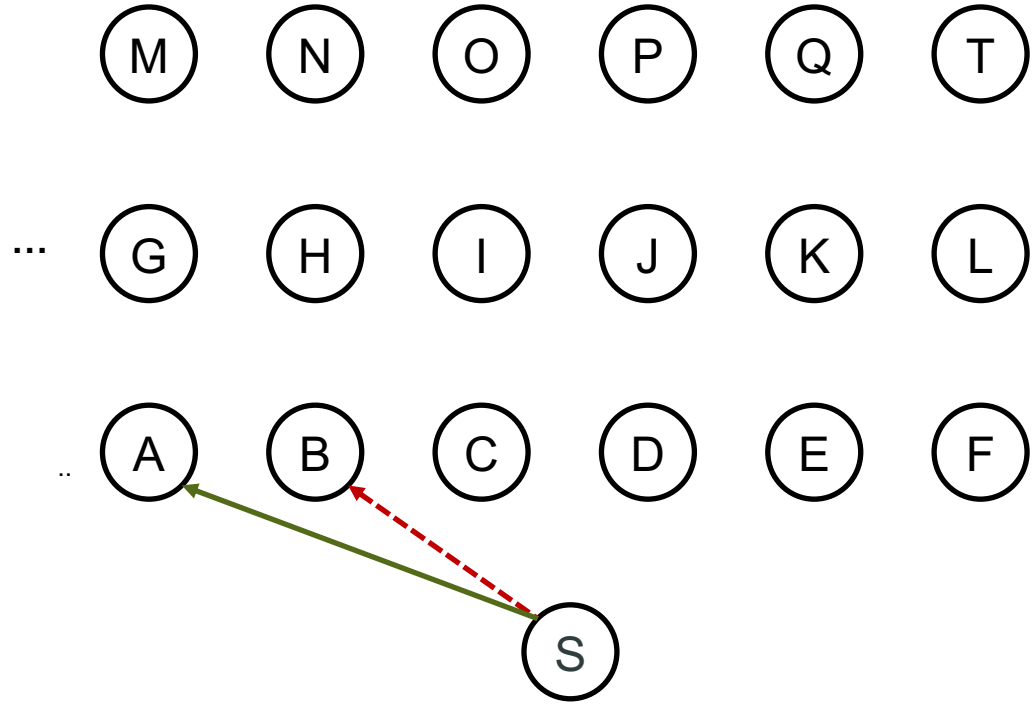


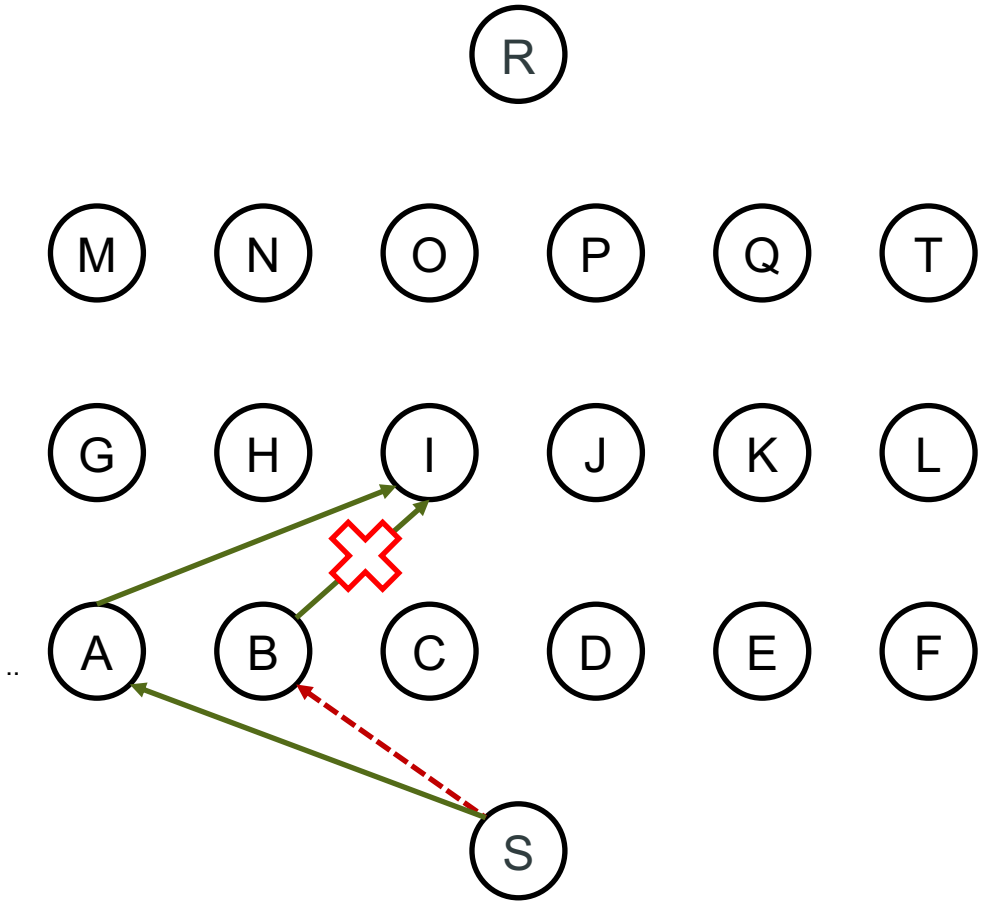
PAREO Functions

Elimination

- A node discards the duplicated data packets.

Channel Offsets	Shared Slot (EB)	Dedicated Slots					Shared Slot (EB)	Dedicated Slots				
4						B→I						B→I
3		S→A (B)	S→A (B)					S→A (B)	S→A (B)			
2				S→B (A)						S→B (A)		
1					A→I						A→I	
0												
Timeslot		0	1	2	3	4	5	0	1	2	3	4	5
ASN		0	1	2	3	4	5	6	7	8	9	10	11

A typical TSCH schedule



Preferred Parent (PP)

Alternative Parent (AP)

Step 2: PCE – Routing Plane (Alternative Parent Selection)

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IETF®

"*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

Common Ancestor (CA)

- One possible option is to *select* the *Alternative Parent* as the *one having Common Ancestor*.

Alternative Parent Selection

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- One possible option is to *select* the *Alternative Parent* as the *one having Common Ancestor*.
- Many different variations/enhancements we have proposed over the years:
  - 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**.
  - 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," In Proc. **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** - Paris, France, May 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**.
  - M. Kersalé, G. Z. Papadopoulos, J. M. Del Fiore, P. Thubert and N. Montavont, "Vers les Réseaux Industriels Déterministes," In Proc. **CoRes 2017**.

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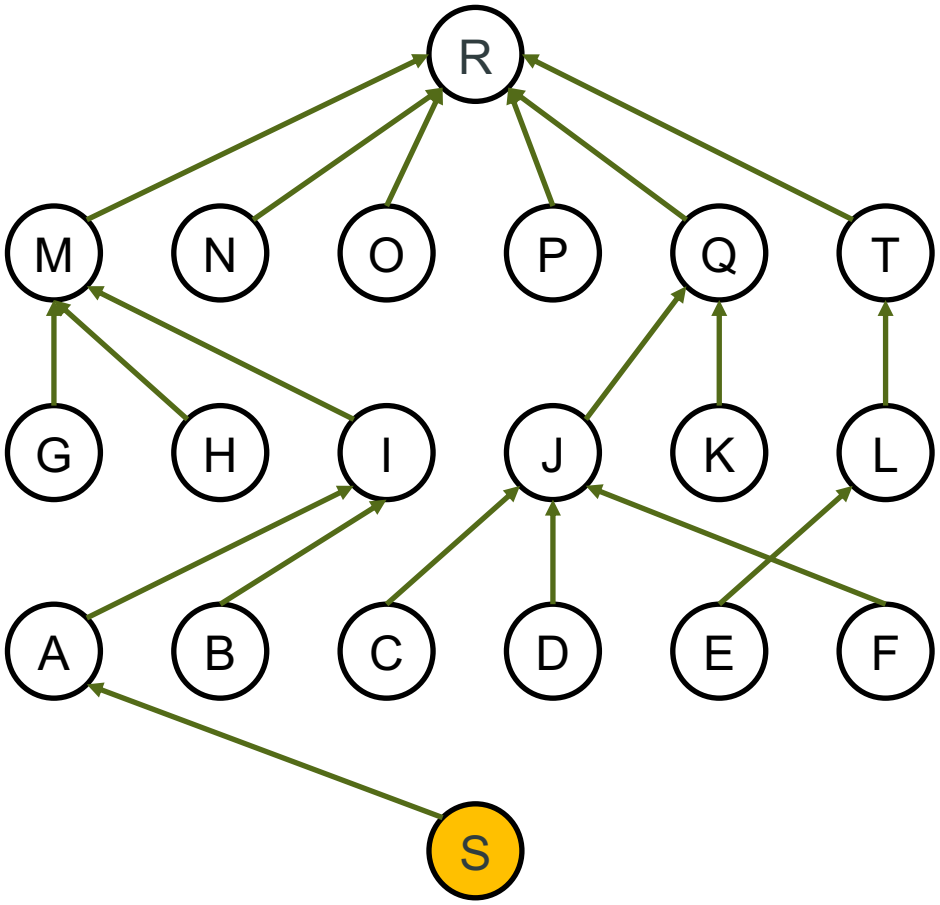
The **default DODAG** Topology



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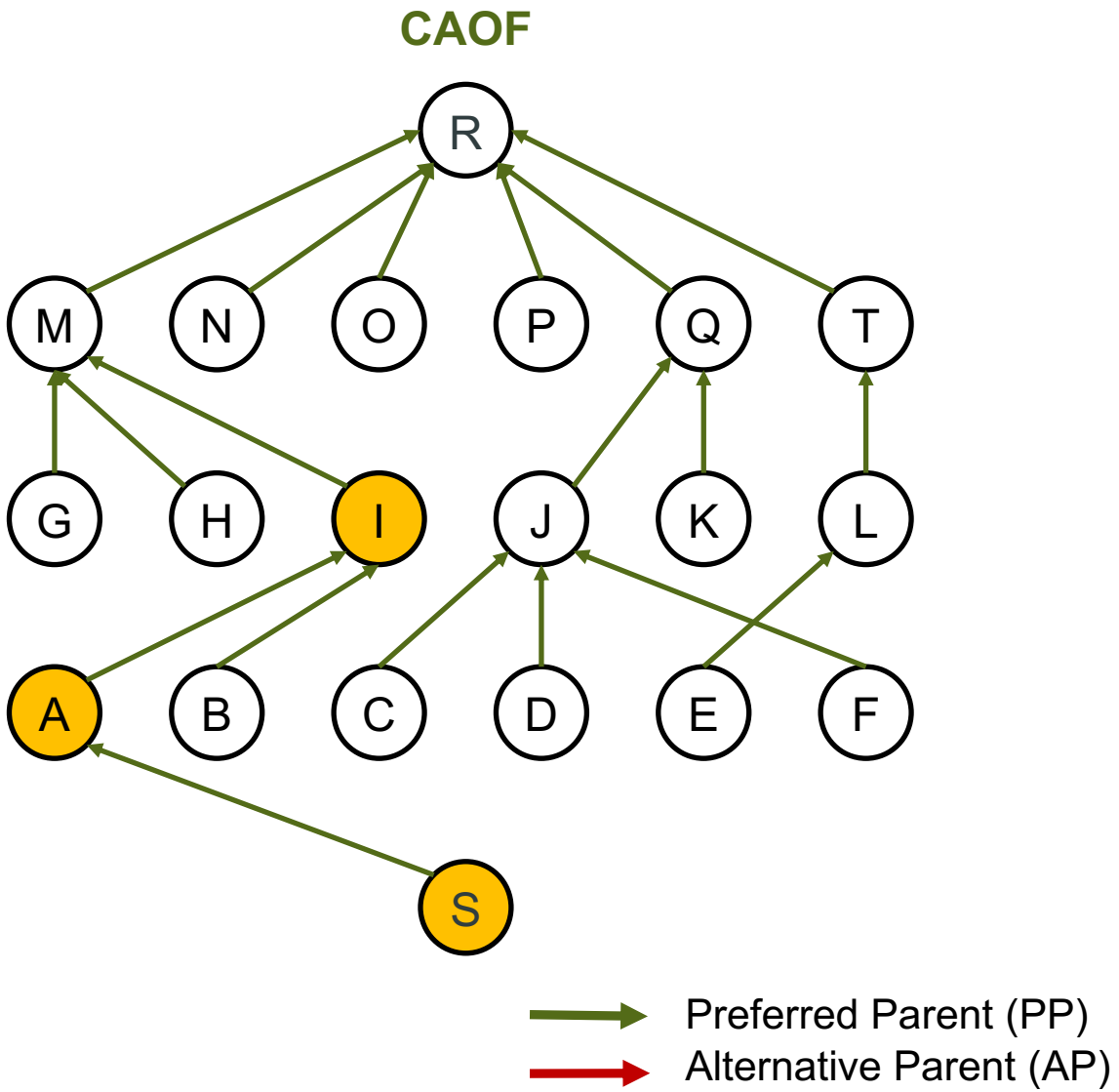

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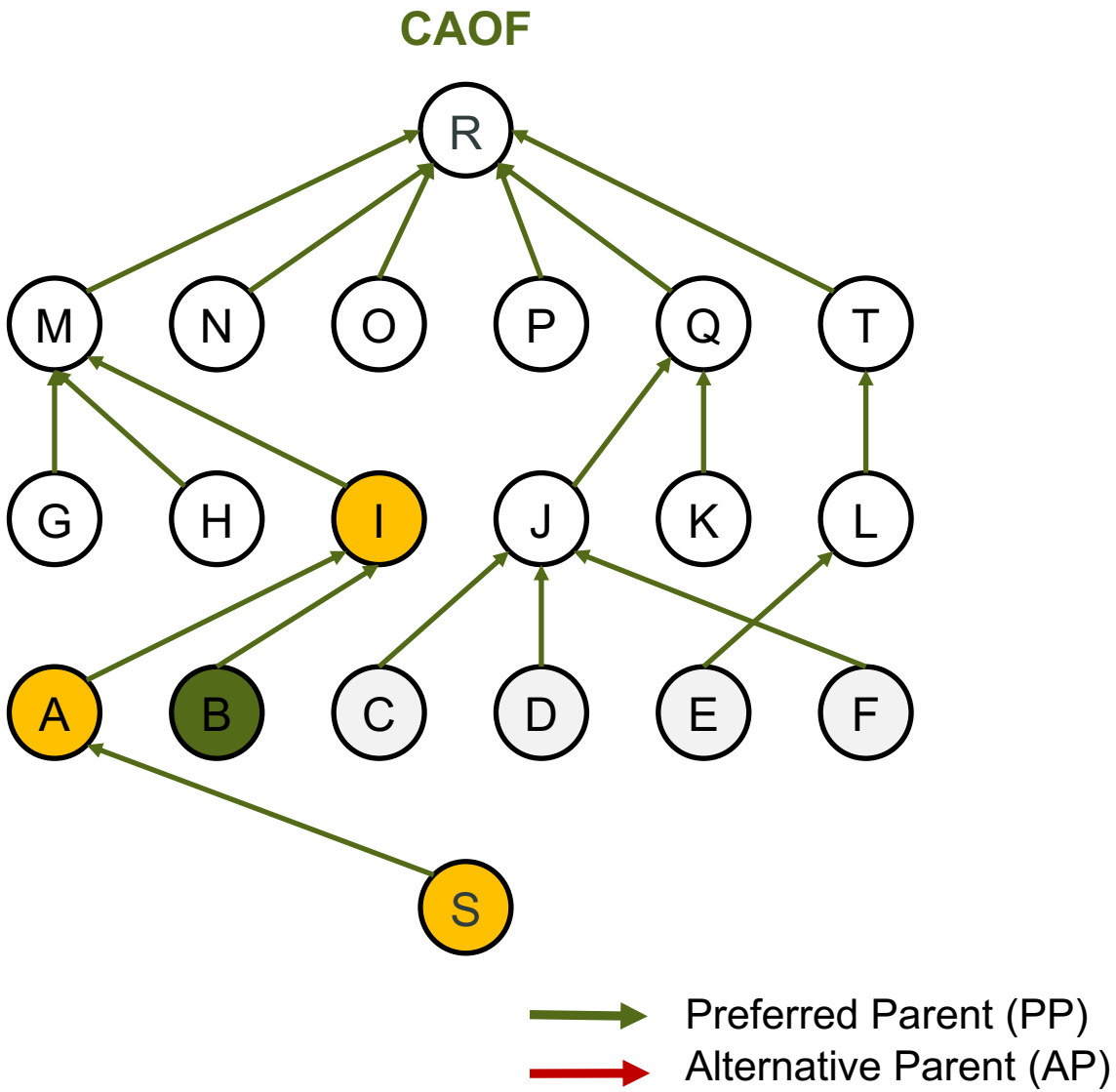

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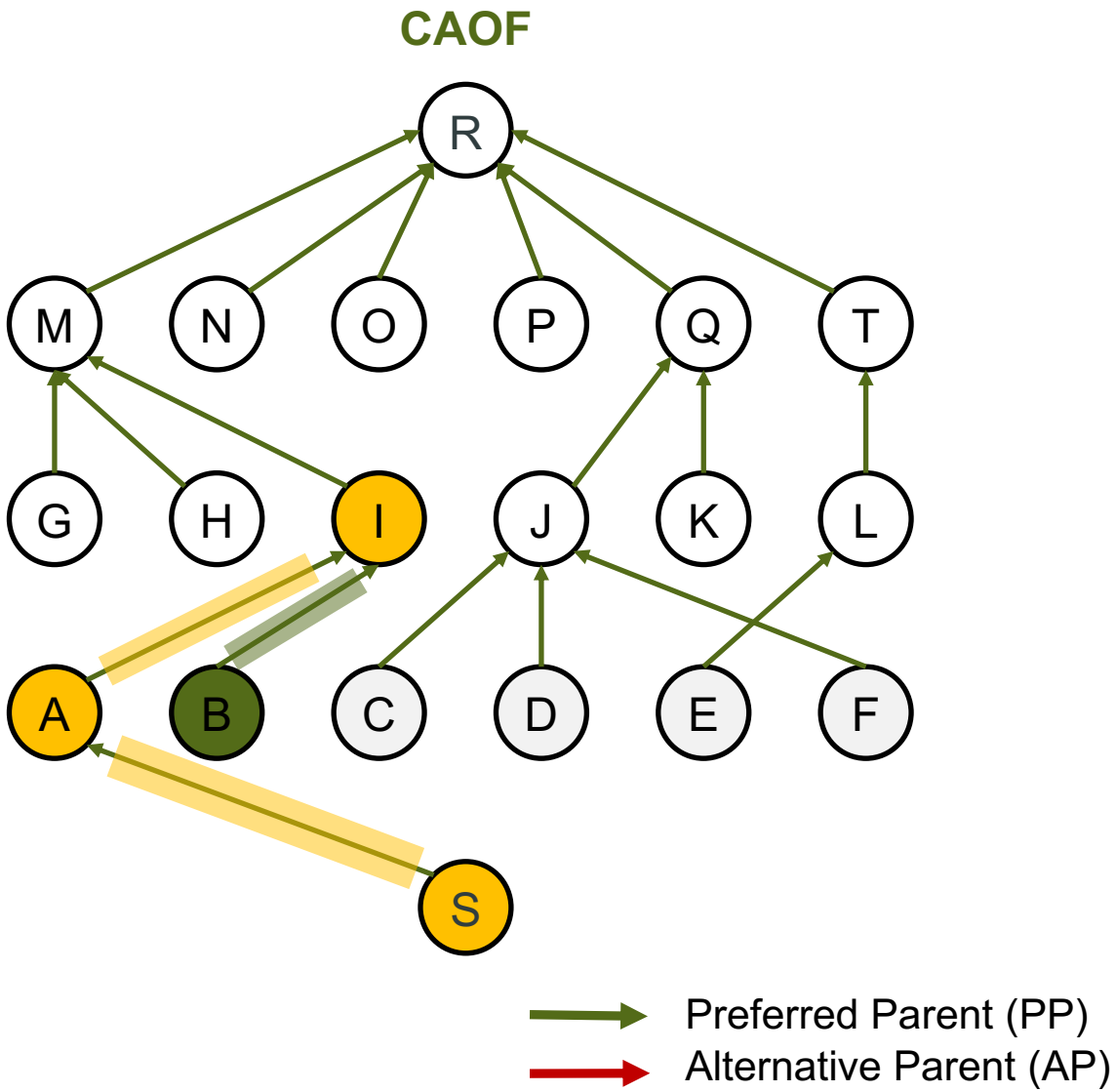

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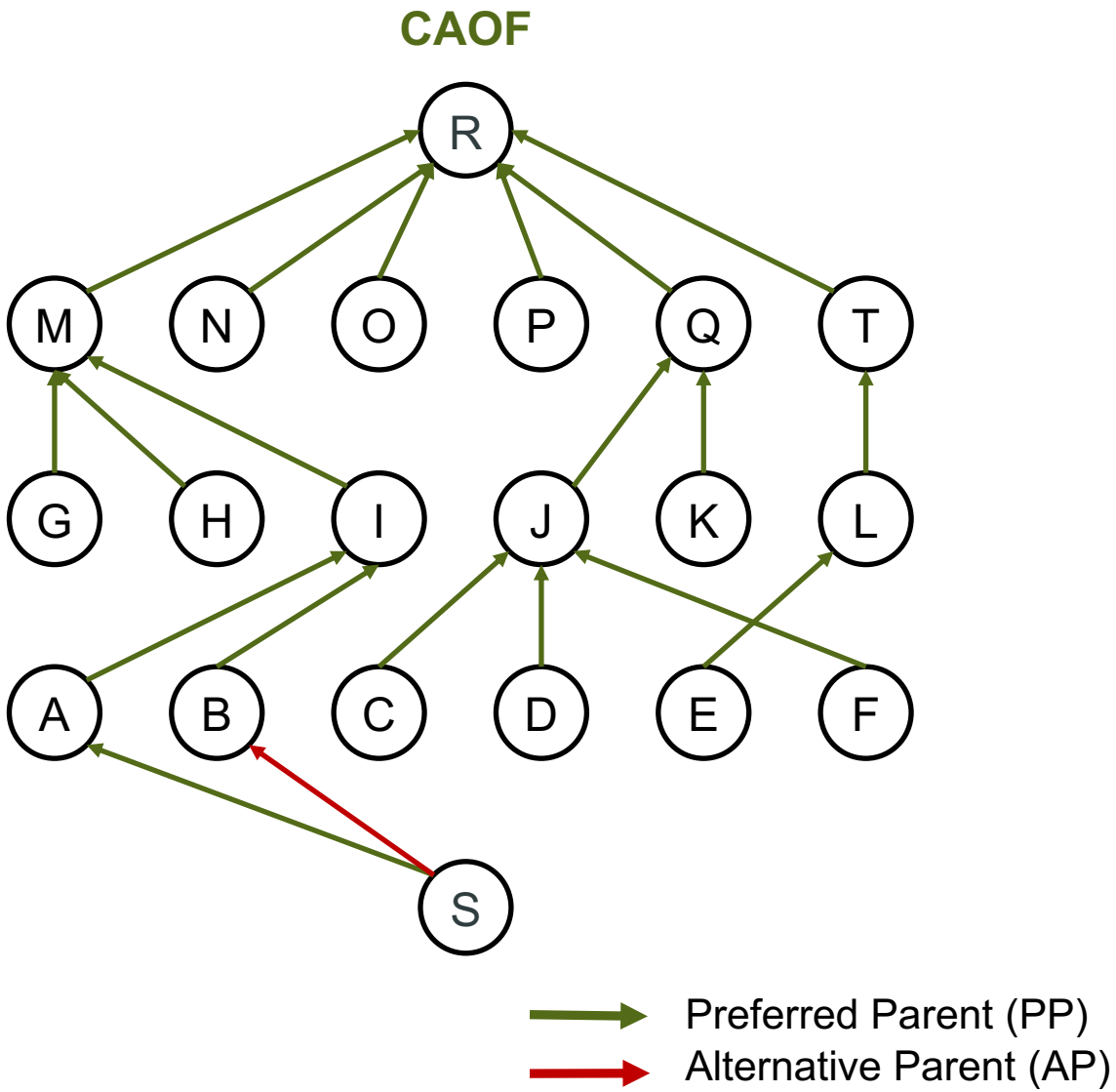
  - Ladder (or DNA) pattern.



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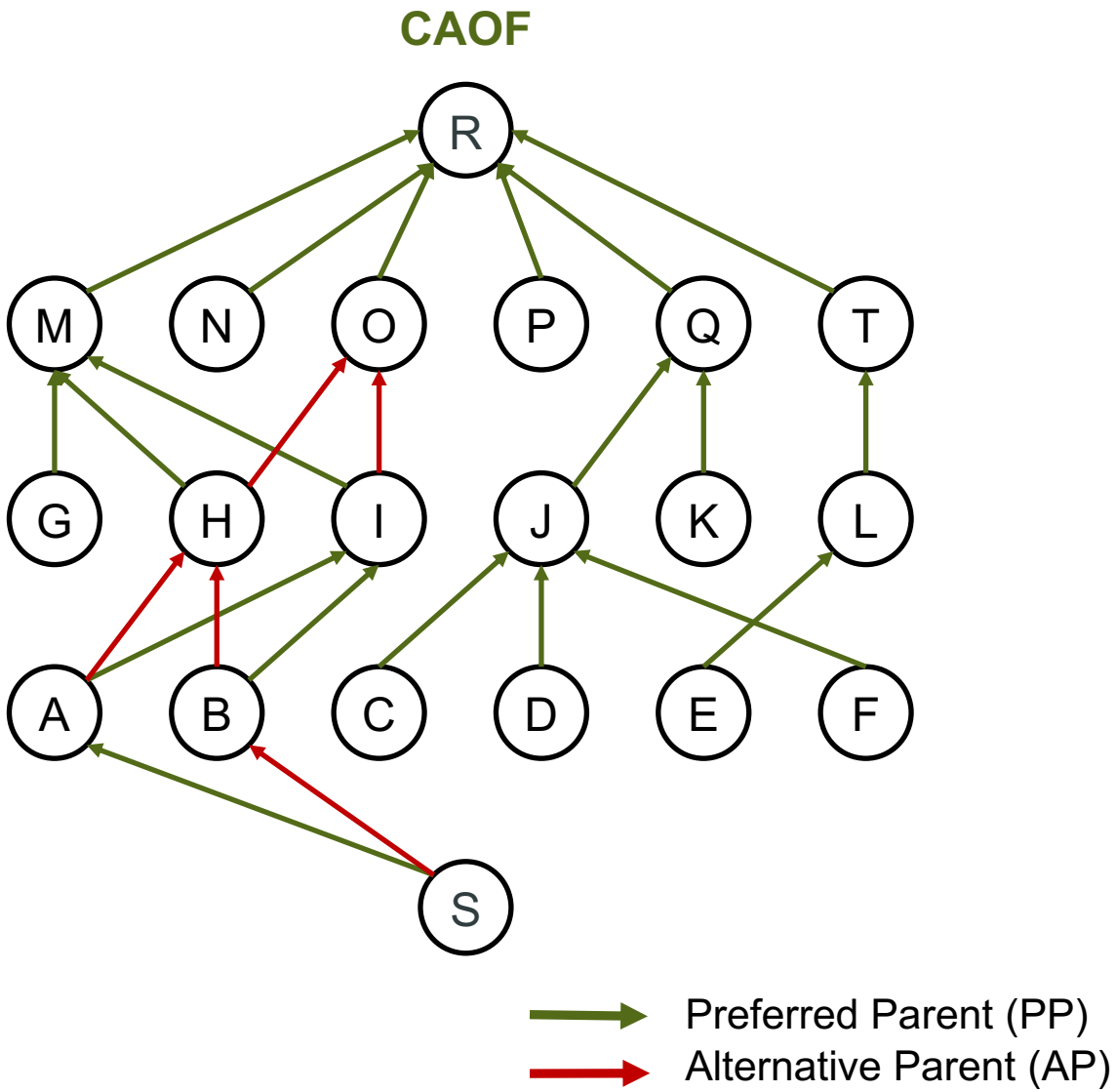
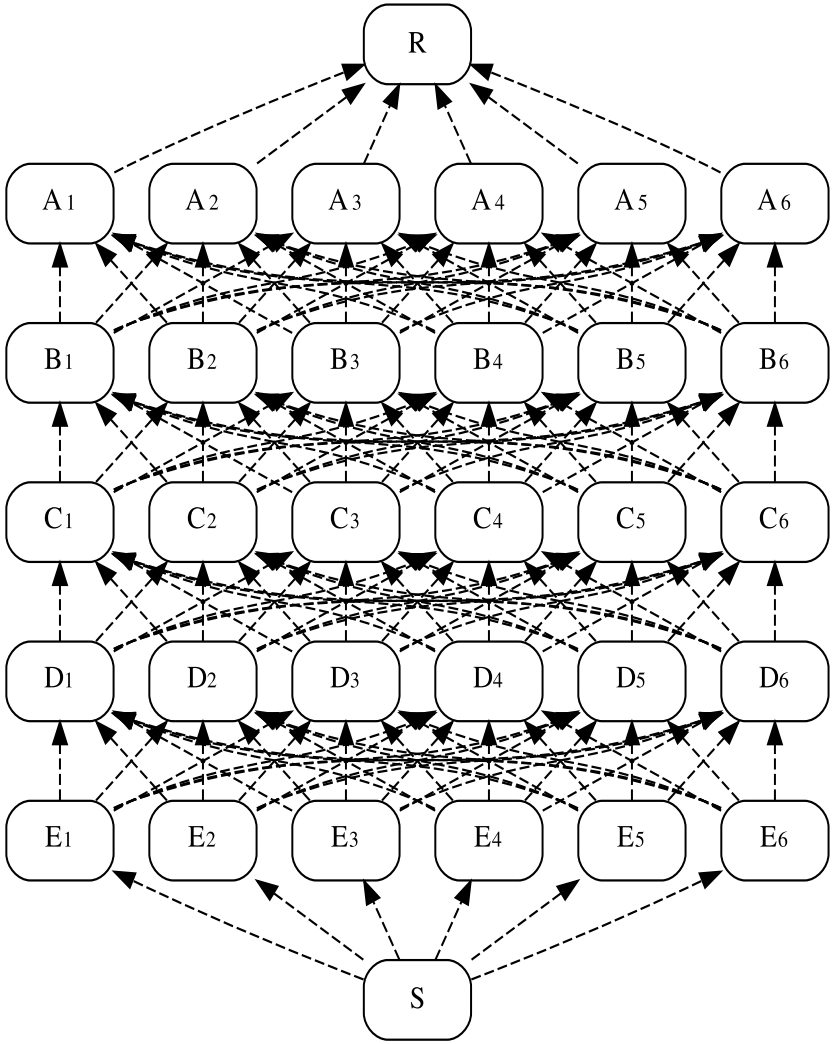


Simulation Setup

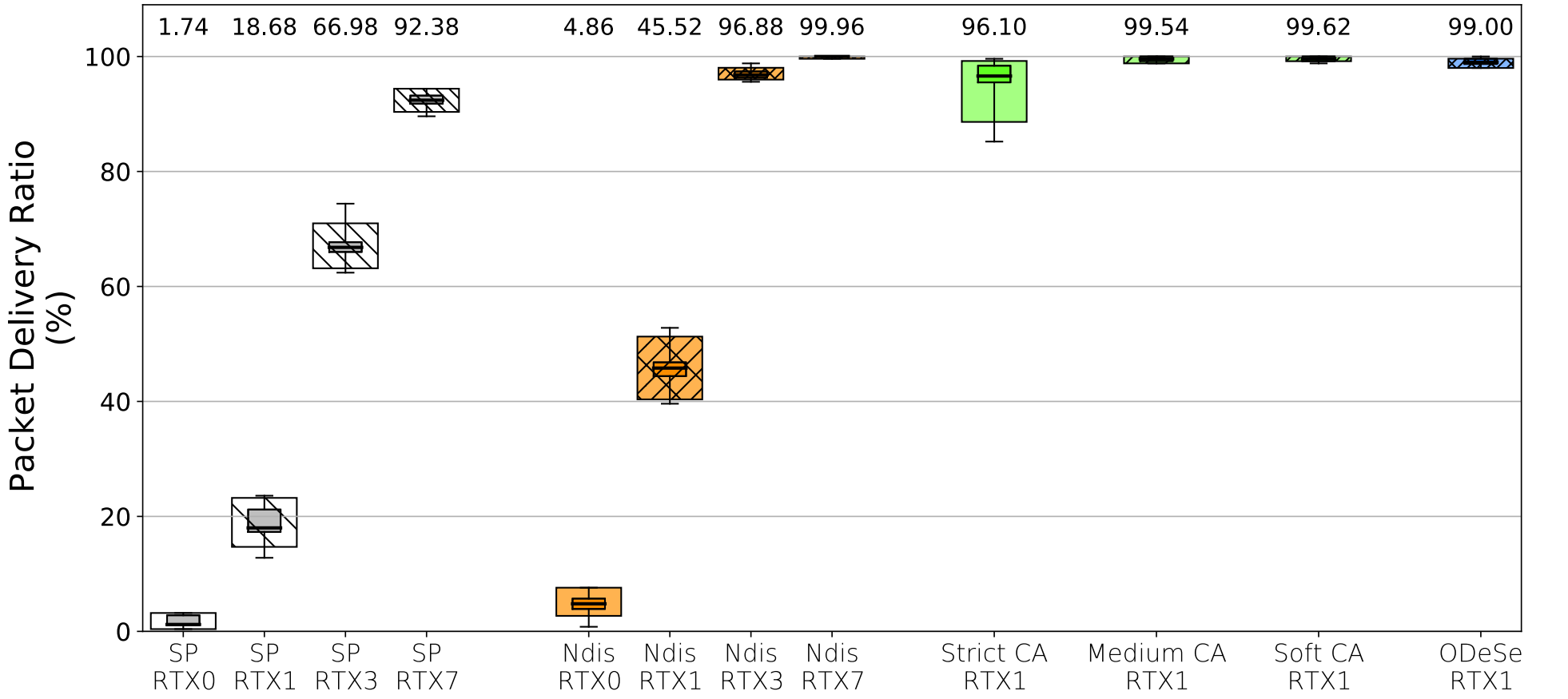
Contiki OS & Cooja, Single-path, n-Disjoint, CA, ODeSe

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	



Performance Evaluation

50% Link Quality : End-to-end Packet Delivery Ratio (6 hops)



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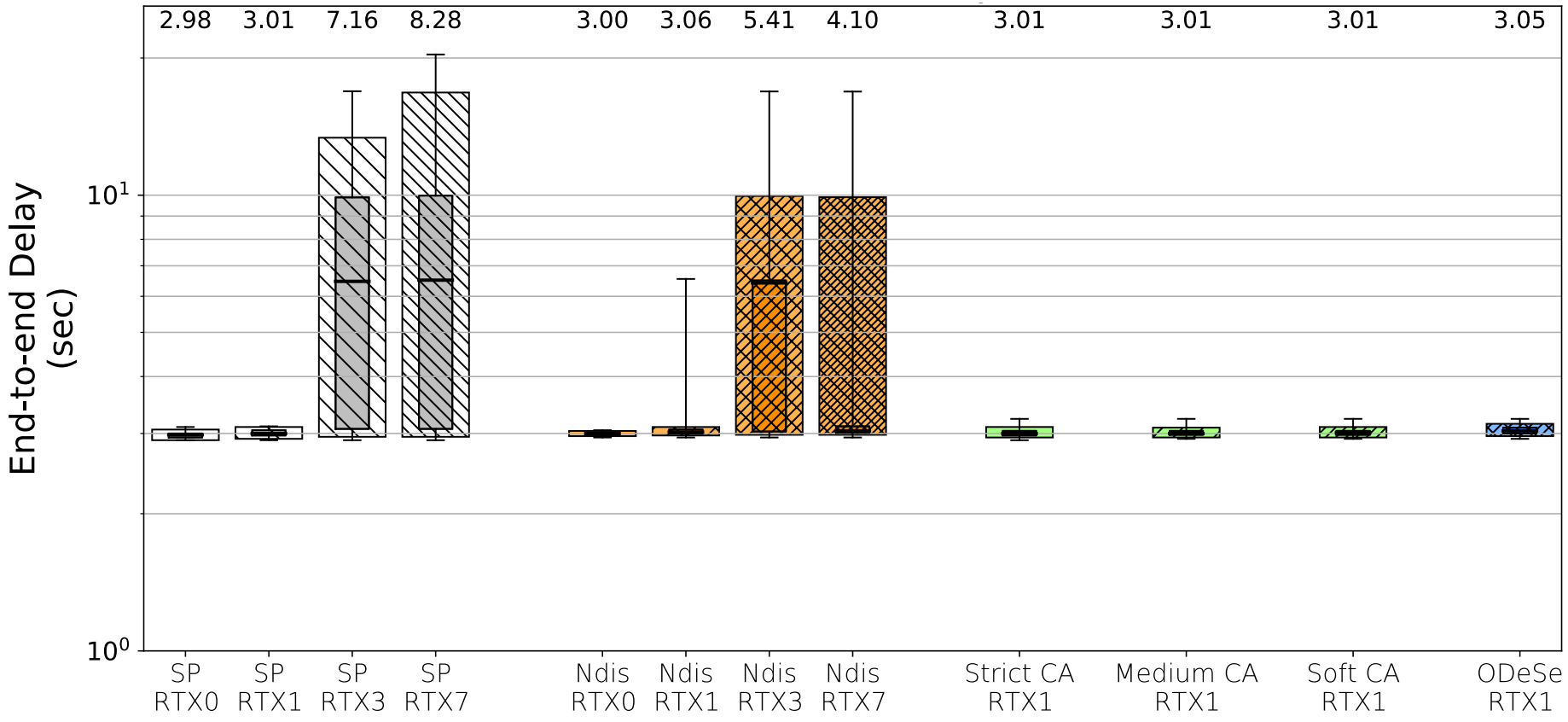
Single-path (with retransissions) **Multi-path: 3 disjoint paths (+ retrans.)** **Multi-paths (CAOF)**

Performance Evaluation

50% Link Quality : End-to-end latency

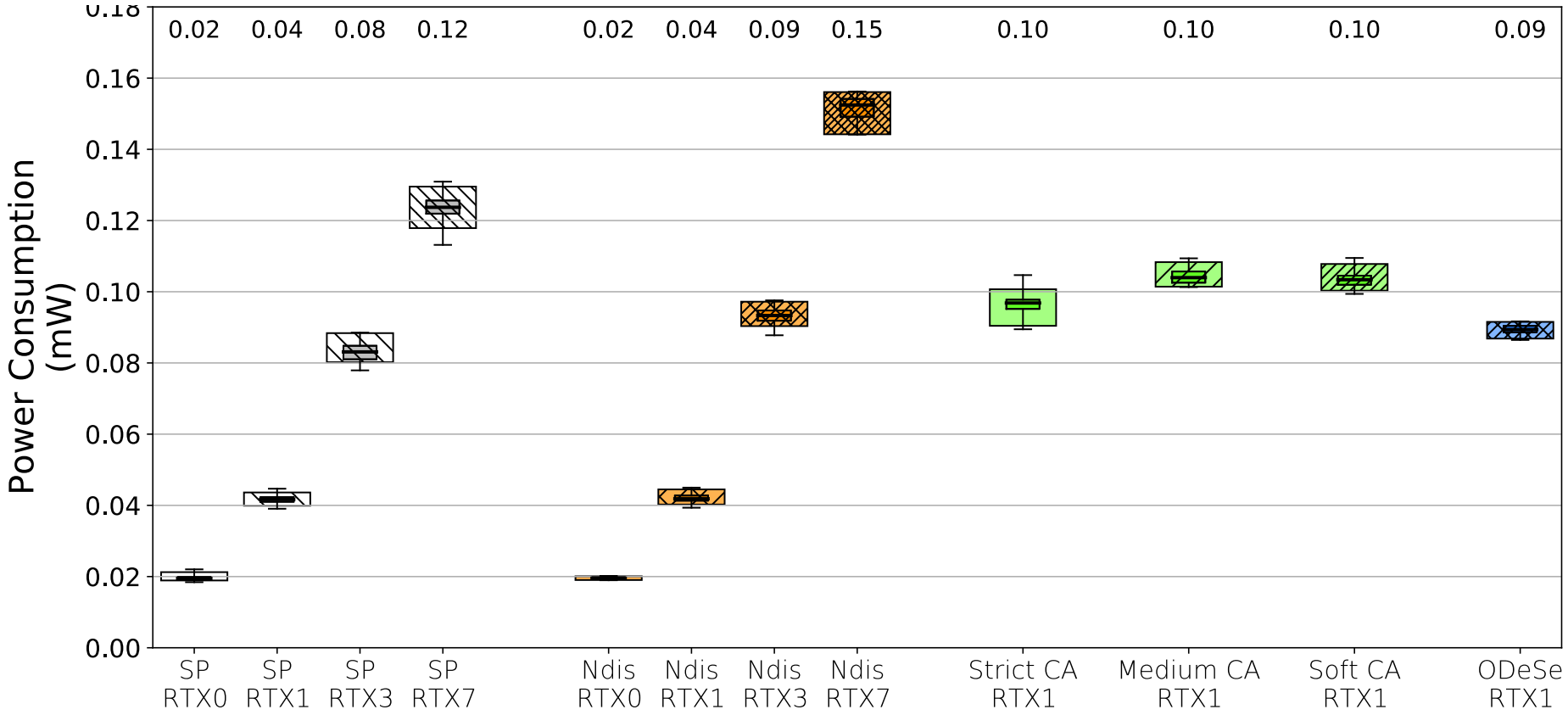


Single-path, 0 rtx
Single-path, 1 rtx
Single-path, 3 rtx
Single-path, 7 rtx
N-disjoint 3P, 0 rtx
N-disjoint 3P, 1 rtx
N-disjoint 3P, 4 rtx
N-disjoint 3P, 7 rtx
Strict CA
Medium CA
Soft CA
ODeSe

Single-path (with retransissions) **Multi-path: 3 disjoint paths (+ retrans.)** **Multi-paths (CAOF)**

Performance Evaluation

50% Link Quality : Power consumption per algorithm



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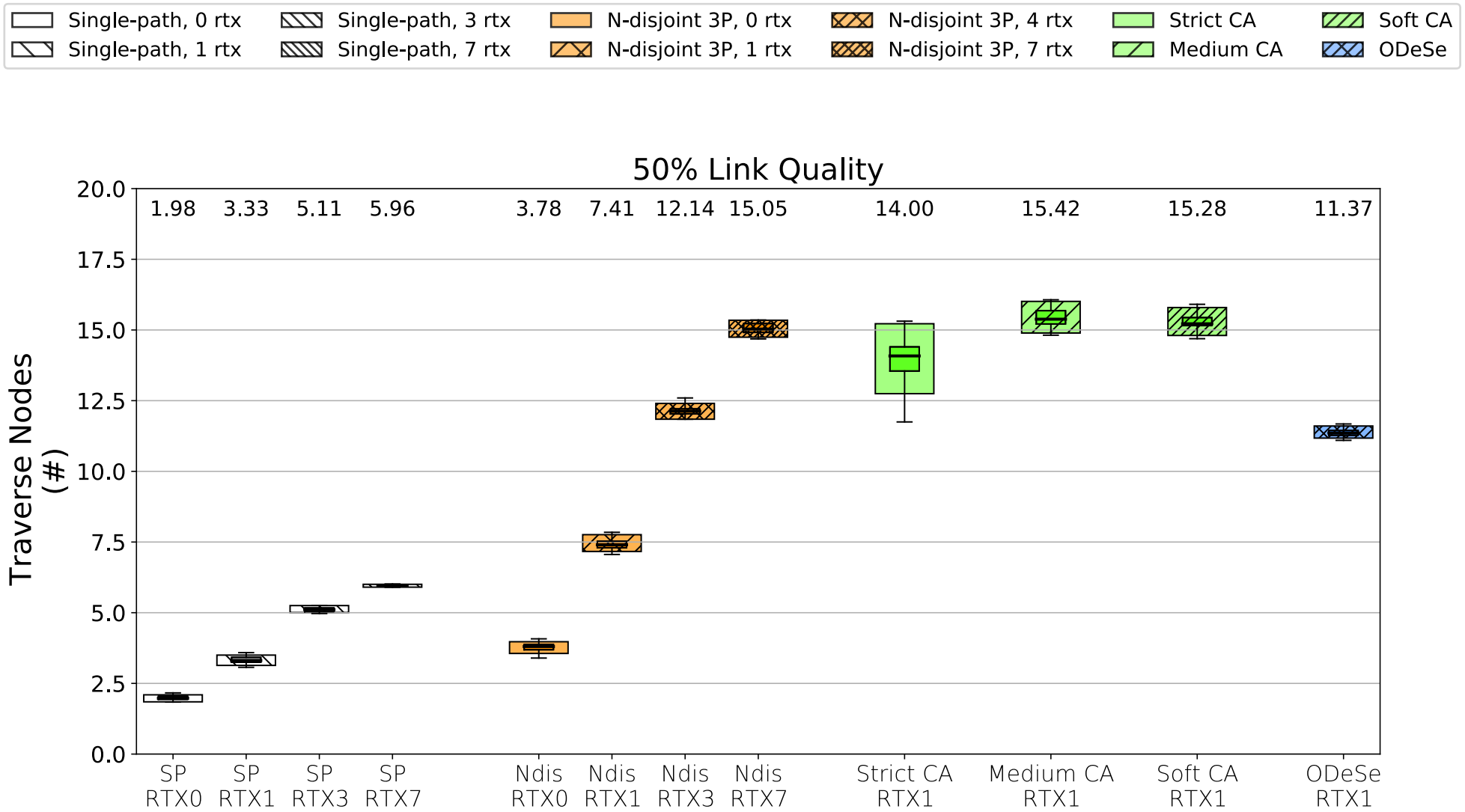
Strict CA
Medium CA
Soft CA
ODeSe

Single-path (with retransissions) **Multi-path: 3 disjoint paths (+ retrans.)** **Multi-paths (CAOF)**

Simulation Results

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



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Key Takeaways

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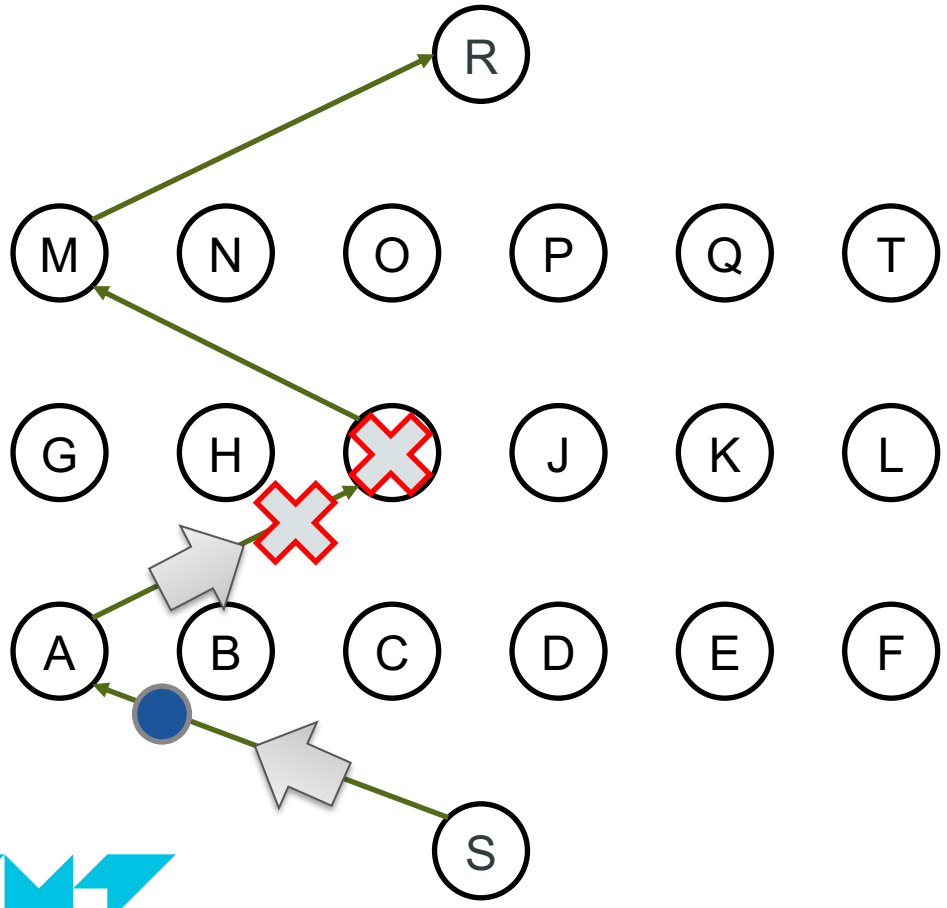
Key Takeaways

Why PAREO and Multi-path approaches?

Key Takeaways

Why PAREO and Multi-path approaches?

Default RPL
(single-path) operation



Preferred Parent (PP)

Key Takeaways

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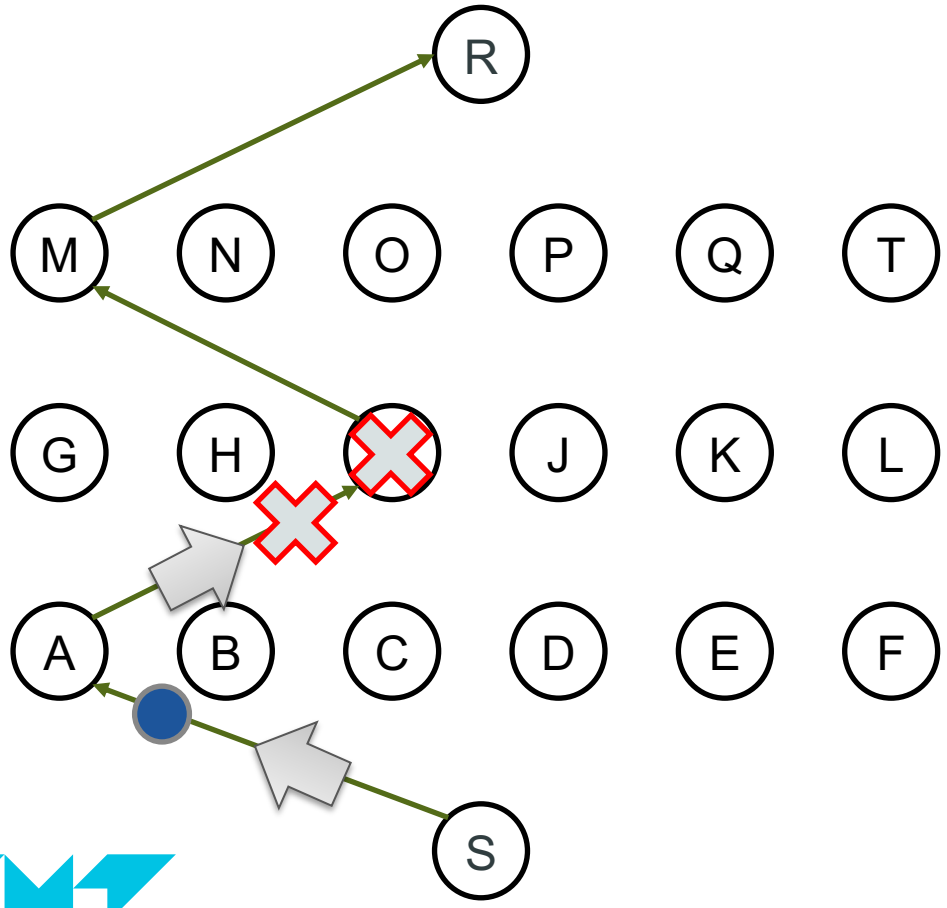
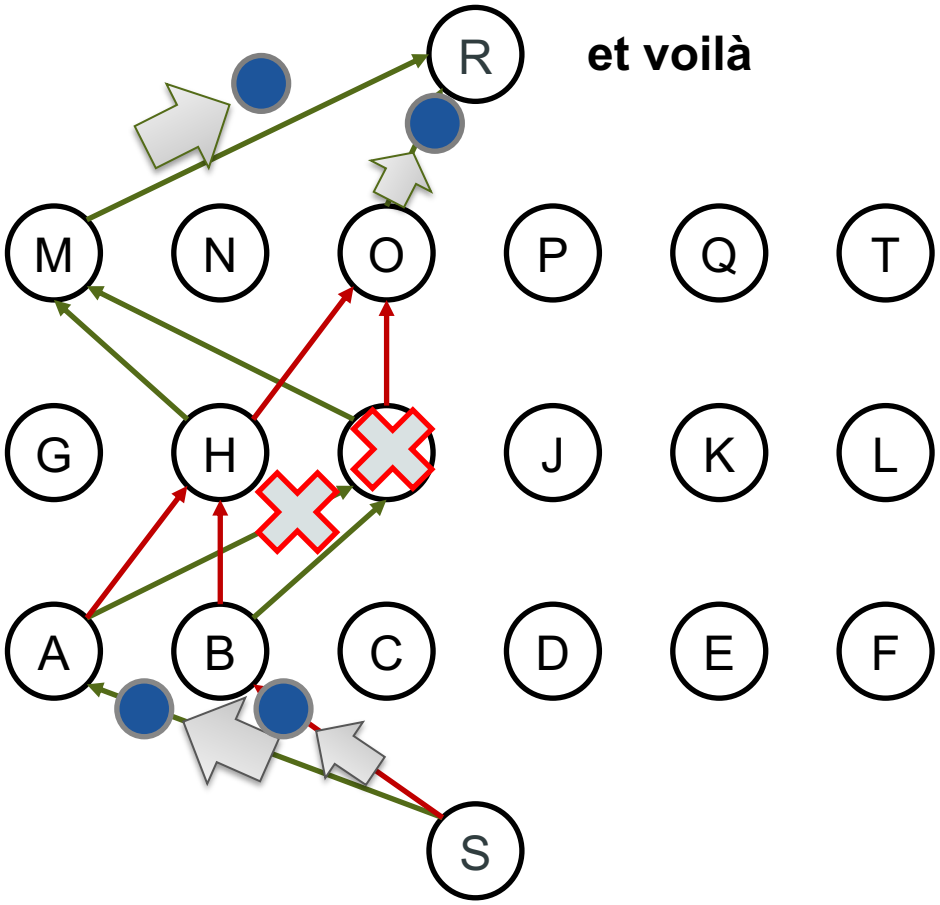


PAREO + CAOF
(multi-path) operation



Preferred Parent (PP)
Alternative Parent (AP)

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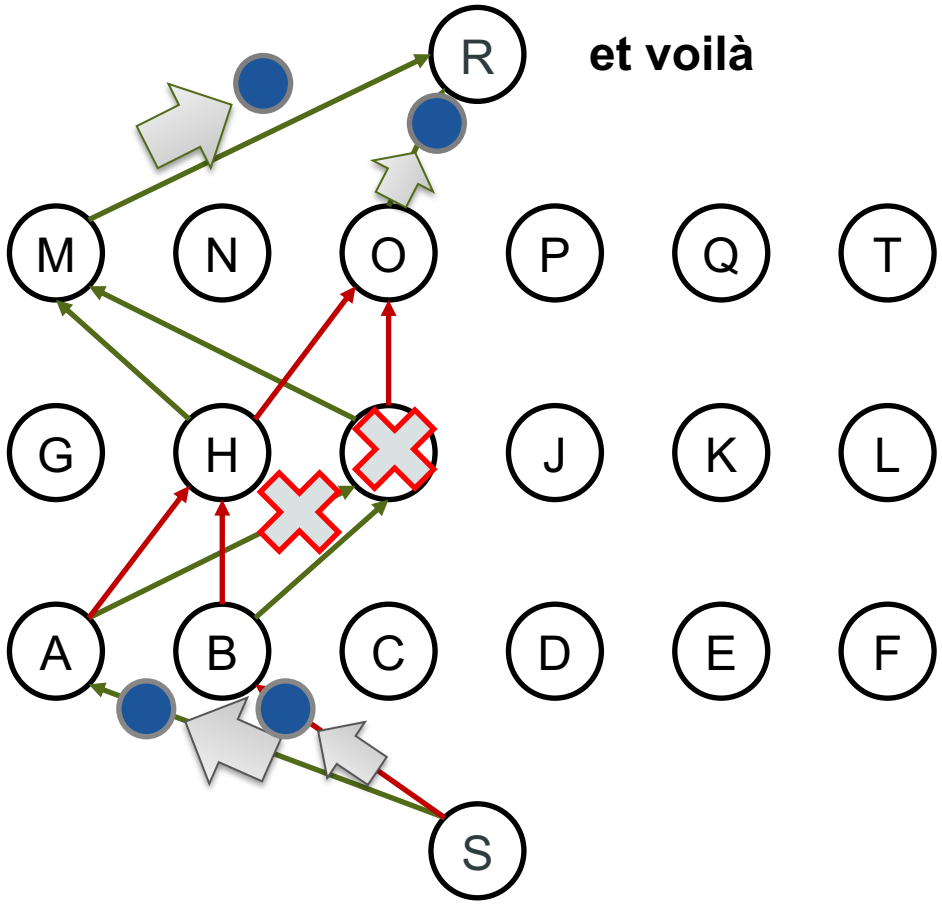
Key Takeaways

Why Common Ancestor pattern?

PAREO + CAOF
(multi-path) operation



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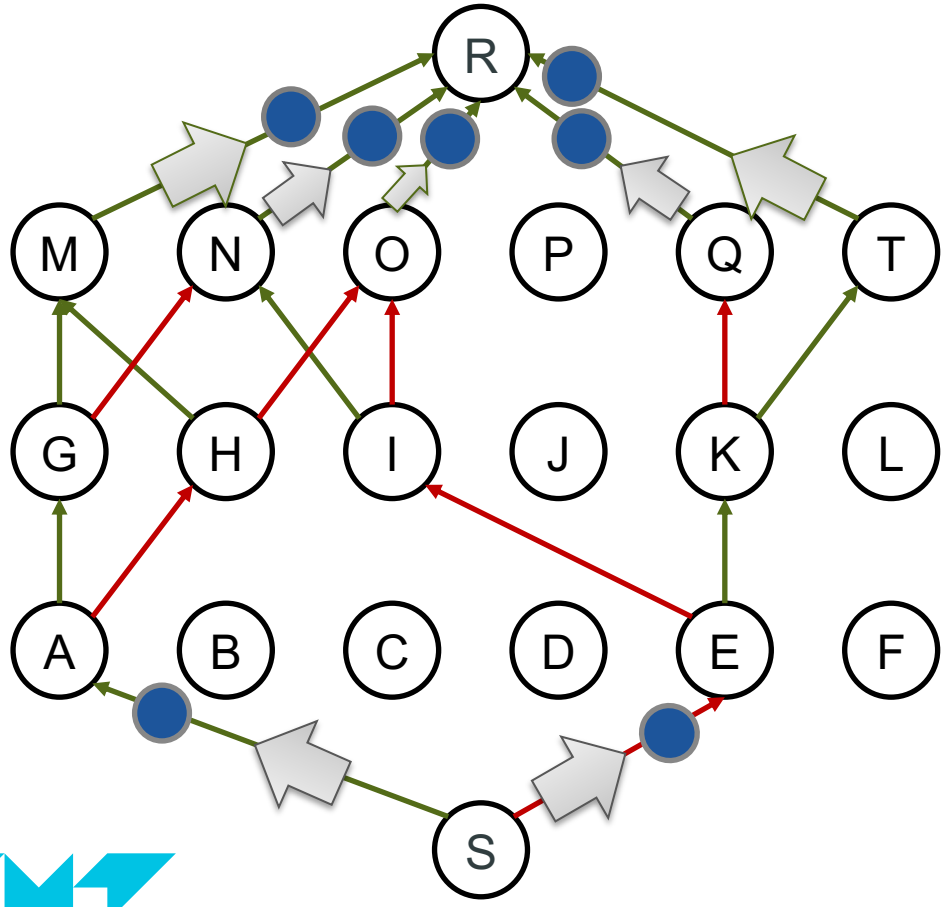

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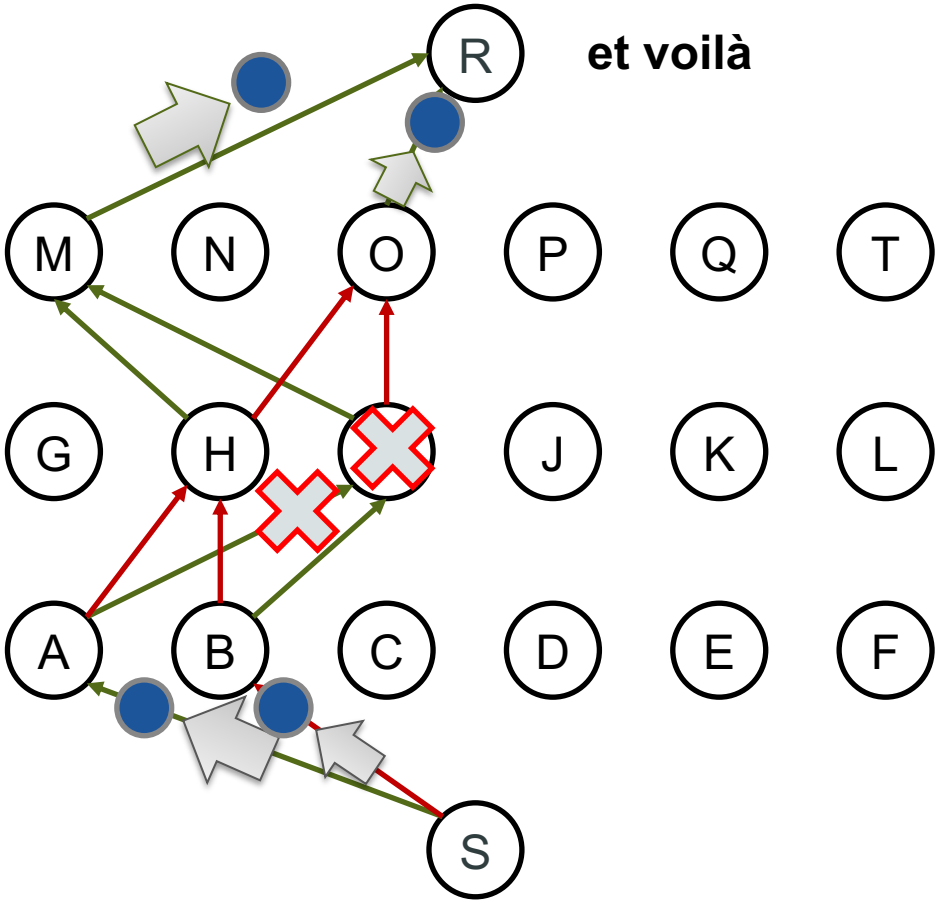

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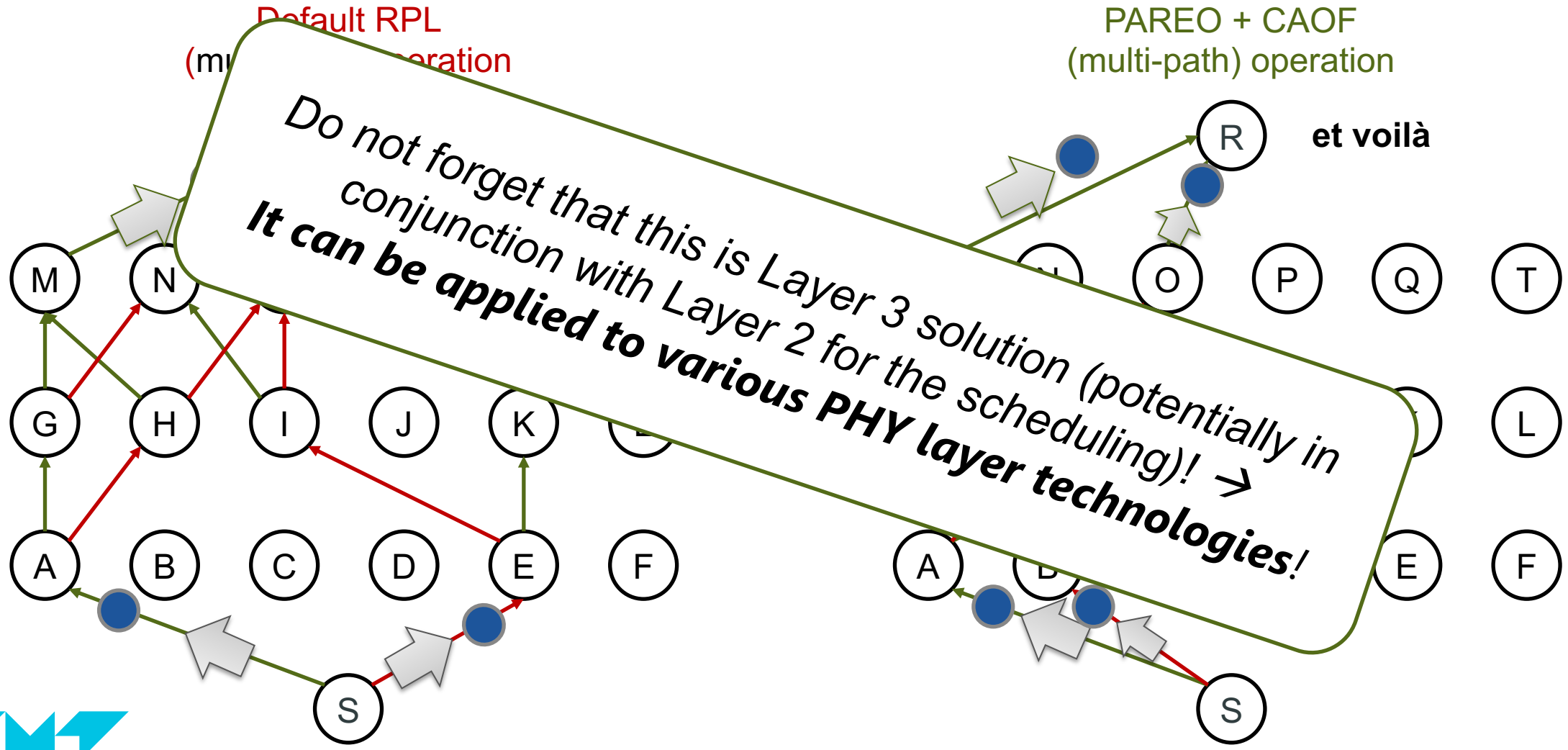


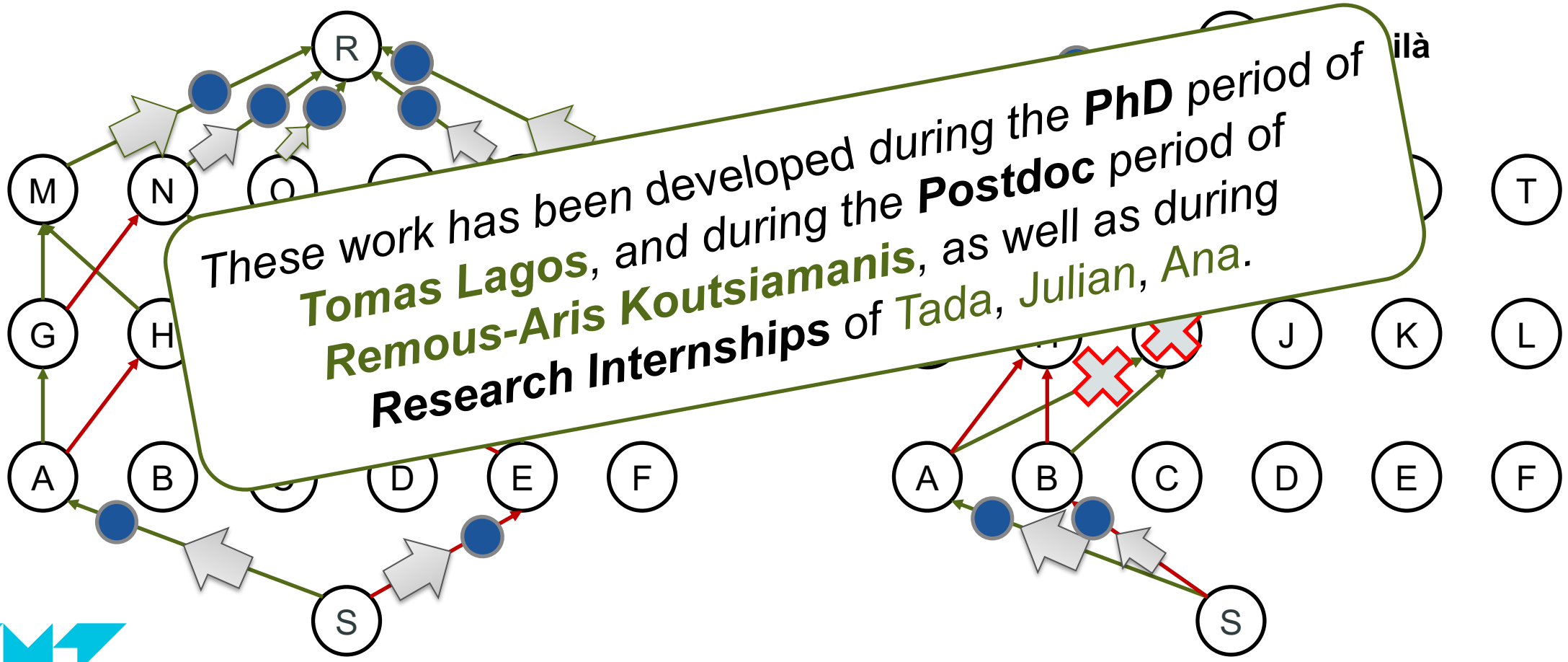
Do not forget that this is Layer 3 solution (potentially in conjunction with Layer 2 for the scheduling)! →
It can be applied to various PHY layer technologies!

Preferred Parent (PP)
Alternative Parent (AP)

Key Takeaways

Default RPL
(multi-path) operation

PAREO + CAOF
(multi-path) operation



These work has been developed during the **PhD** period of **Tomas Lagos**, and during the **Postdoc** period of **Remous-Aris Koutsiamanis**, as well as during **Research Internships** of Tada, Julian, Ana.

Preferred Parent (PP)
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Ongoing Work & Perspectives

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Ongoing Work & Perspectives

1. PAREO Functions

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

- and more such as:
  - Forward Error Correction (FEC) [1], [2]
  - Packet (Re)Ordering (**work-in-progress**) → Juan-Cruz Pinero

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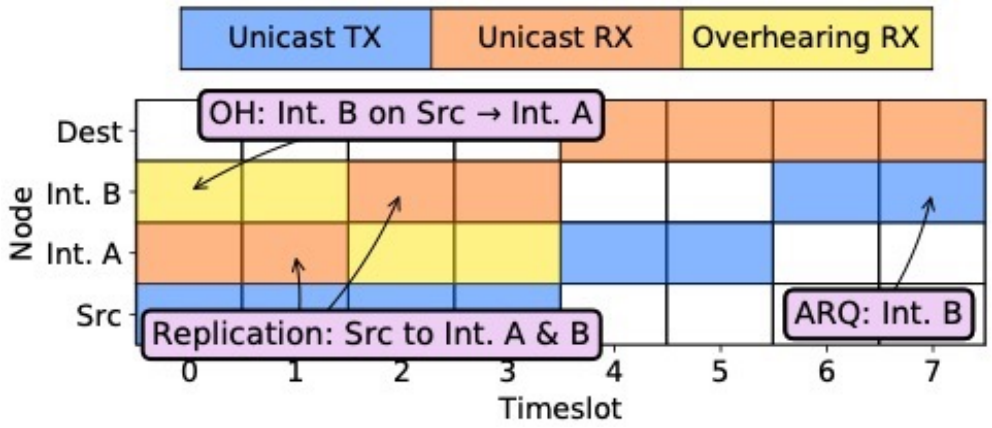
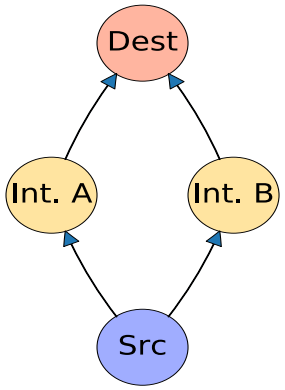
Ongoing Work & Perspectives

2. Toward a Centralized Routing Approach

- To achieve Reliable and Available properties:
  - Routing: Multi-path (RPL) → Distributed / Adaptive!
  - Resource Allocation: (Controller-based schedule) → Centralized / STATIC!





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In Proc. **MSN 2020**.

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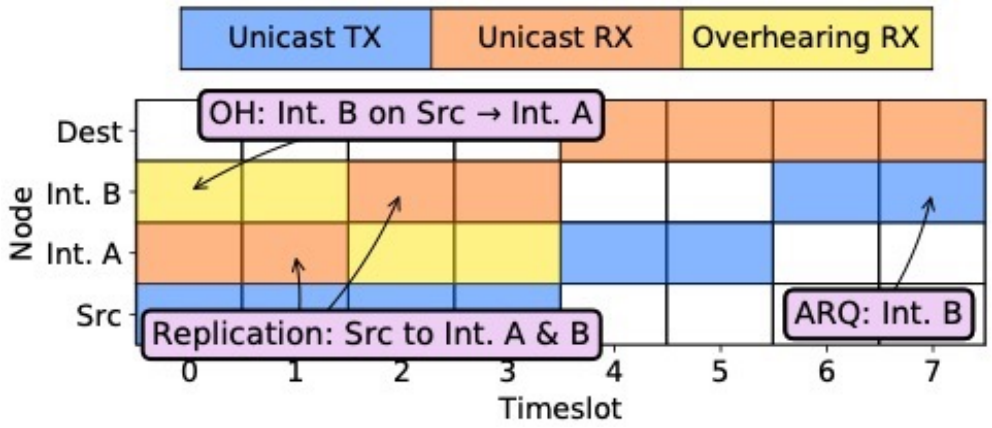

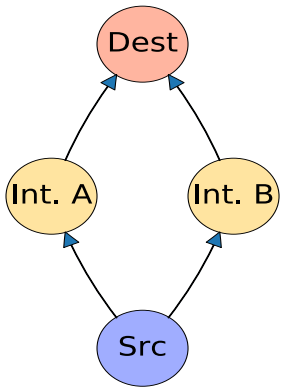

- Towards fully centralized and adaptive entity (Controller):
  - Both for Routing and Scheduling, and why not even for Radio Channel Blacklisting decisions!

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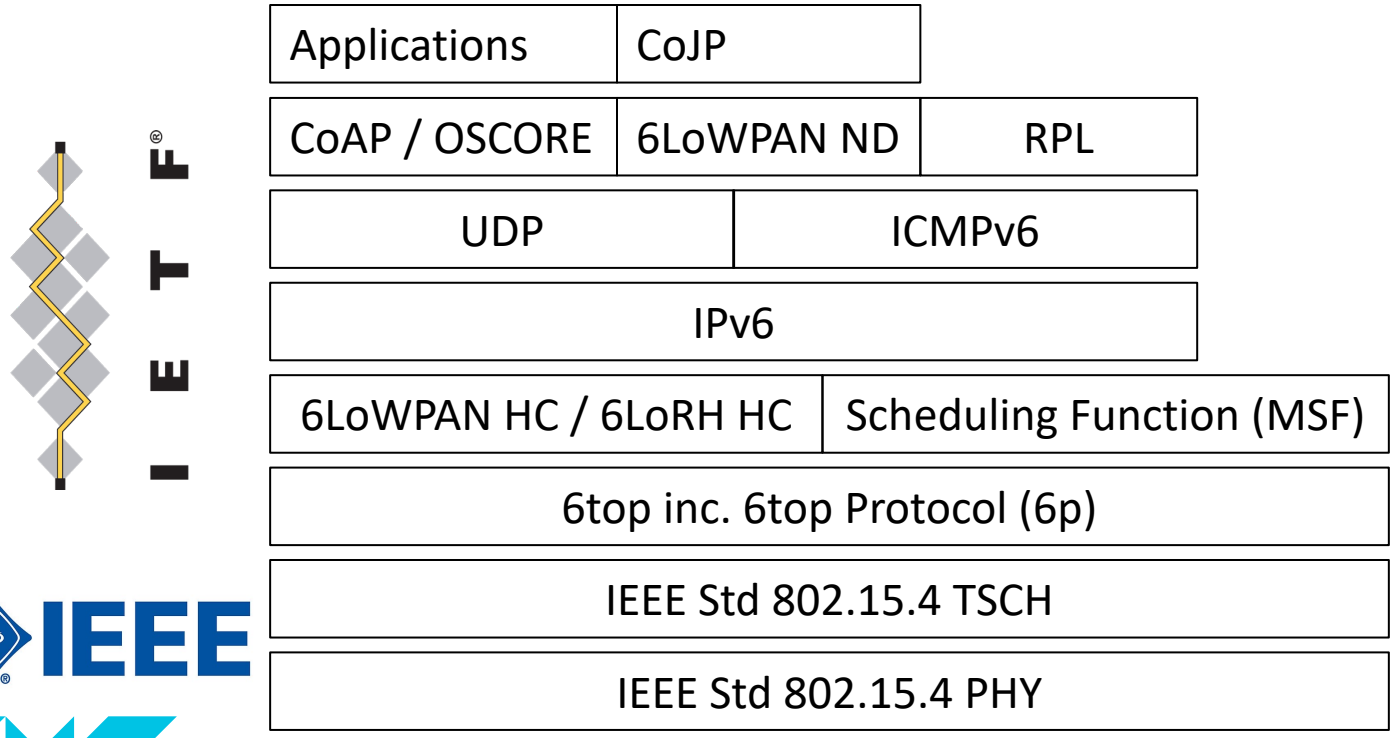
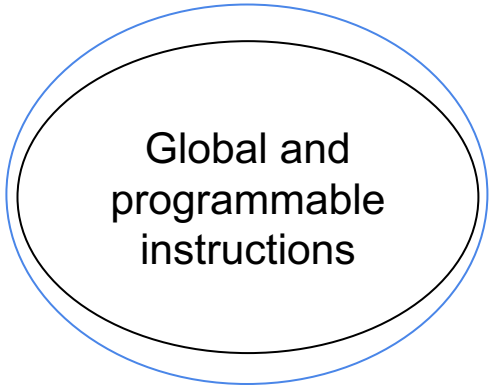
Ongoing Work & Perspectives

3. Reprogrammable Stack

- What about the modularity of the employed Stack?
- The **whole behavior** of a node can be **programmable**.

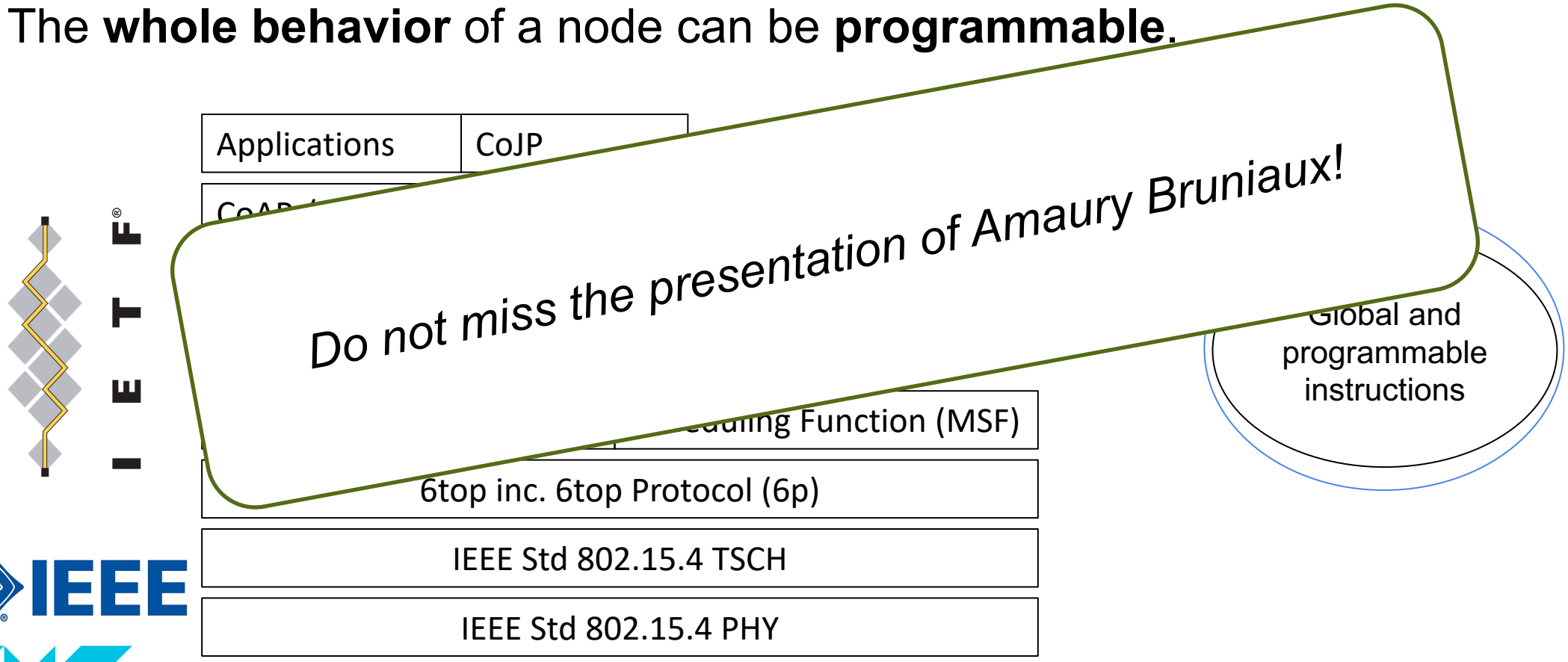




Ongoing Work & Perspectives

3. Reprogrammable Stack

- What about the modularity of the employed Stack.
- The **whole behavior** of a node can be **programmable**.



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Miscellaneous

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Scientific Contributions

Towards Reliable and Available Low-Power Wireless Mesh Networks

- C. Ji, A. Bruniaux, V. Kotsiou, G. Z. Papadopoulos and P. Chatzimisios, “Lightweight XOR based FEC Algorithm for Fragment Forwarding in 6LoWPAN Networks”, In Proc. **IEEE GLOBECOM** - Rio de Janeiro, Brazil, December **2022**.
- 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**.
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- 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**.
- G. Z. Papadopoulos, F. Theoleyre, P. Thubert and N. Montavont, “IETF Reliable and Available Wireless (RAW): Use Cases and Problem Statement”, In Proc. **AdHoc-Now** - Bari, Italy, October **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**.
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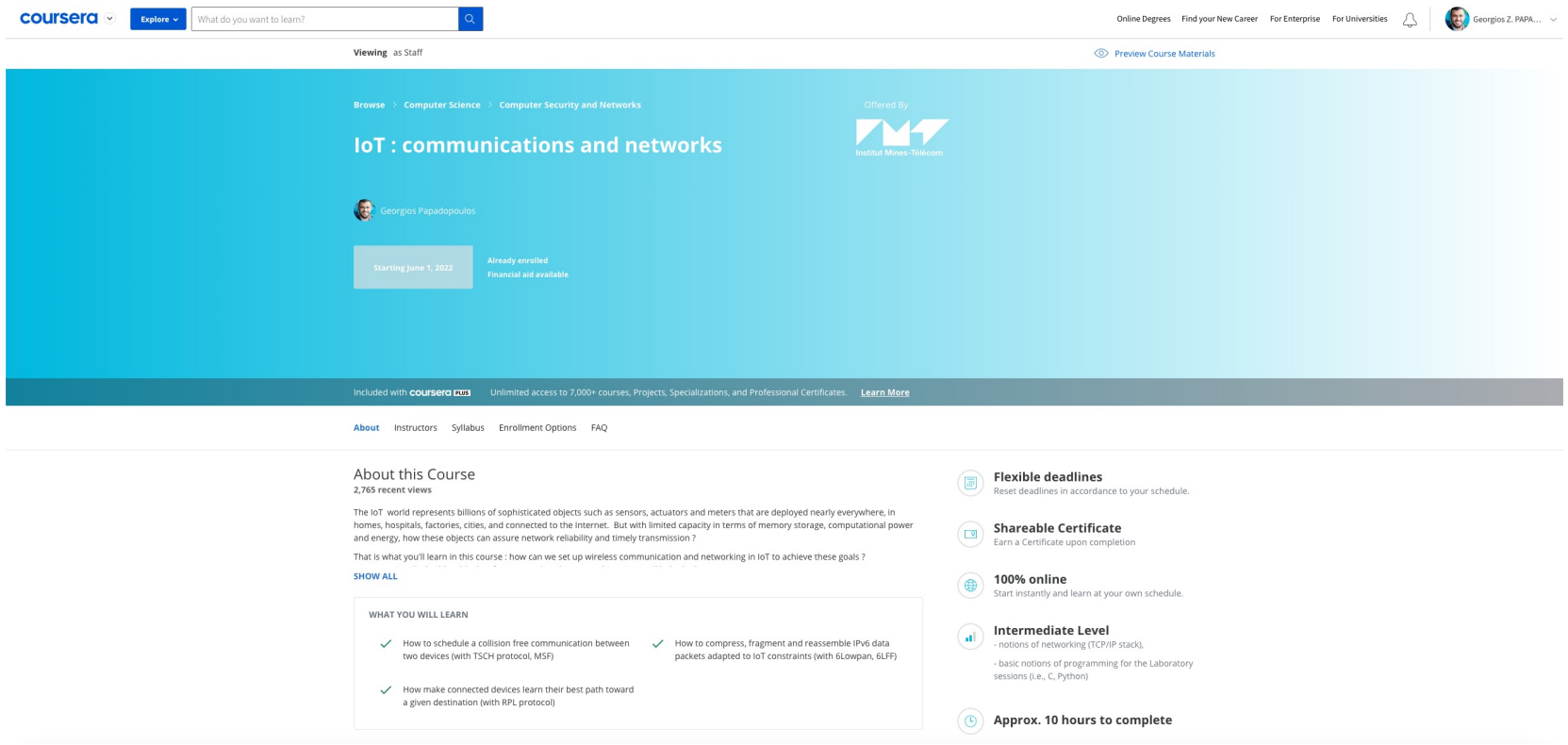
- G. Z. Papadopoulos, T. Matsui, P. Thubert, G. Texier, T. Watteyne and N. Montavont, "Leapfrog Collaboration: Toward Determinism and Predictability in Industrial-IoT applications,” in Proc. **IEEE ICC 2017**.
- T. Matsui, G. Z. Papadopoulos, P. Thubert, T. Watteyne, N. Montavont, "Poster: 4th Industrial 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**.

Education

MOOC: IoT Communications and Networks

Coordination de MOOC : coursera

- **09**/2022 - *: “IoT Communications and Networks” (> 1000 enrolments).
- Link: https://www.coursera.org/learn/iot-communication-network



Education

MOOC: IoT Communications and Networks

- Outline of the MOOC:
  - Week 1: Welcome & MAC Methods (i.e., TSCH)
  - Week 2: 6TiSCH
  - Week 3: IPv6 & 6LoWPAN
  - Week 4: RPL
- Educational Team:
  - Remous-Aris Koutsiamanis
  - Nicolas Montavont
  - Georgios Z. Papadopoulos
  - Géraldine Texier
- Interviews from the industrial community:
  - Pascal Thubert, Cisco Systems
  - Thomas Watteyne, Analog Devices, Falco
  - Rémi Dubaele, ENEDIS

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(if I missed someone, it was not intended!)

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  - Philippe Fabian
  - Alex Marquet
  - Remous-Aris Koutsiamanis
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  - Cristian Bautista
  - Juan Sebastian Molina
  - Amaury Bruniaux
  - Fabián Antonio Rincon Vija
  - Guillaume Le Gall
  - Renzo Efraín Navas
  - Tomas Lagos Jenschke
  - Vasilios Kotsiou
- Research Interns:
  - Juan Cruz Piñero
  - Jeremy Dubrulle (*PhD visit)*
  - Matthieu Silard
  - Ega Fosso
  - Mohamed Lamine Koma
  - Amaury Bruniaux
  - Dimitris Sourailidis
  - Matias Sambrizzi
  - Ana Czarnitzki Estrin
  - Fernando Iglesias
  - David Hauweele (*PhD visit*)
  - Juan Navarro Gutierrez
  - Sergio Aguilar Romero (*PhD visit*)
  - H. Dakdouk, E. Tarazona
  - A. Ouya, C. Bouette, B. Martinez De Aragon
  - Eduardo Ingles Sanchez
  - Agustin Picard
  - Cristian Alderete
  - Chenyang Ji
  - Maurine Kersale
  - Julian Martin Del Fiore
  - Tadanori Matsui
  - Alexandros Mavromatis
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  - SRCD Department/IMT Atlantique
  - F. Theoleyre, T. Noel, J. Montavont, A. Gallais
  - Patrick Savelli, B. Cousin
  - Bruno Quoitin
  - Periklis Chatzimisios
  - Carles Gomez
  - Xenofon Fafoutis, Atis Elsts
  - George Oikonomou, Theo Tryfonas
  - M. Gidlund, A. Mahmood
  - Dan Garcia-Carrillo, A. Skarmeta
  - R. Alami, R. Féraud
  - D. Dujovne, I. Alvarez-Hamelin
  - D. Zorbas, C. Douligeris
- Industrial Partners:
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  - Dominique Poissonnier, TI
  - Samuel Cregut, Renault
  - Dominique Barthel, Orange

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Reliable and Available Low-Power Wireless Mesh Networks

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cnrs GDR Groupement de recherche
RSD
Réseaux et Systèmes Distribués

Backup Slides

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Mandjet Platform

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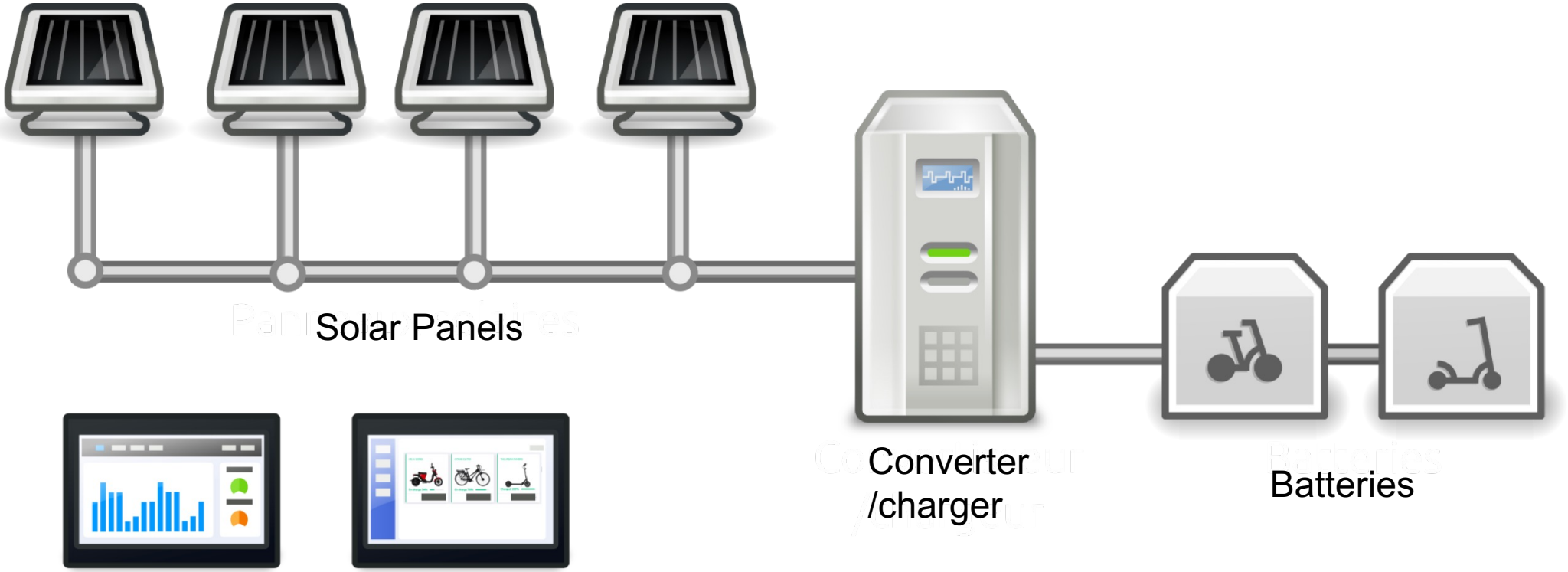
Architecture



Real time visualisation of consumption and production

EV Renting system

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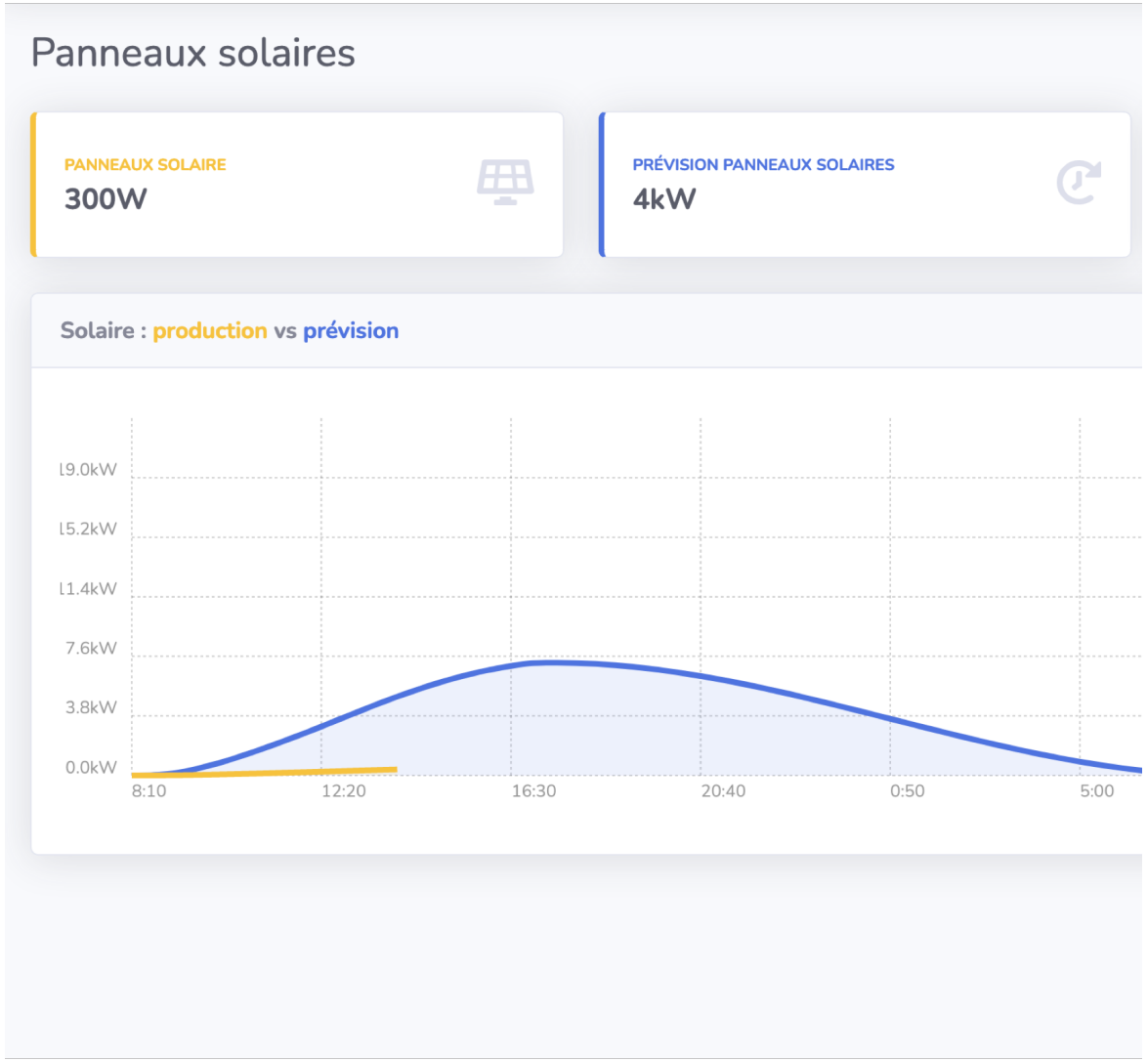
Mandjet Platform

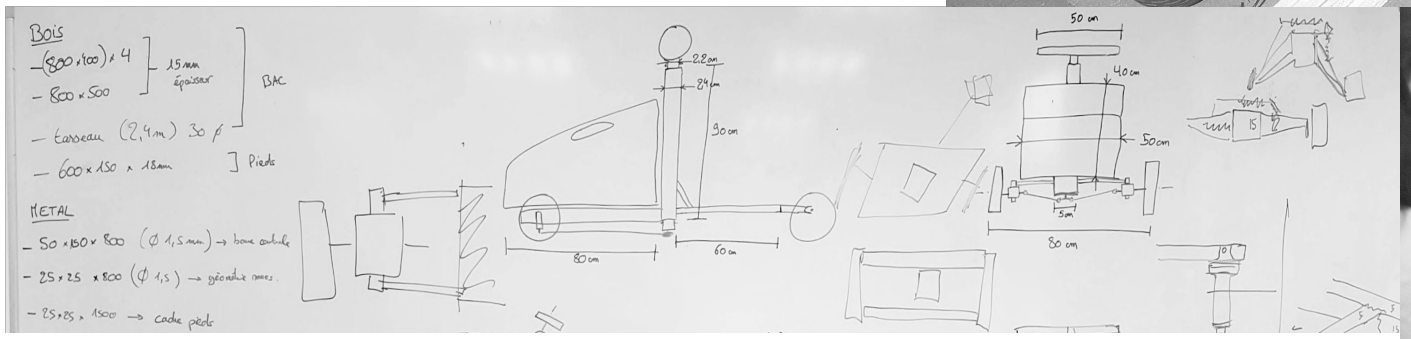
1. Research

- Adaptation and interoperability protocols for smart grids:
  - e.g., 6LoWPAN, SCHC.
- Alignment of electricity consumption and production.



Mandjet Platform

2. Education



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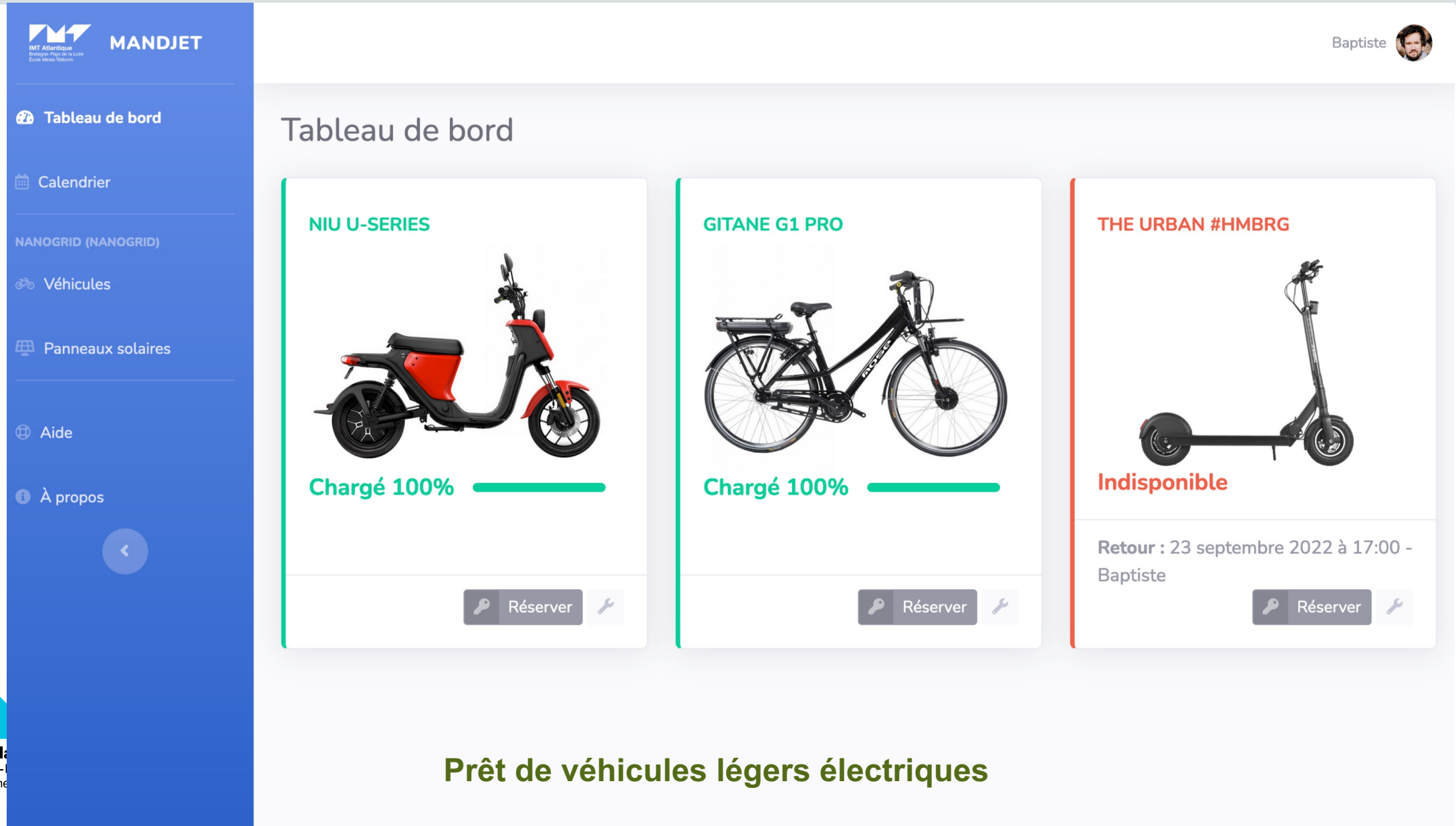
Mandjet Platform

3. Transformation écologique et sociale (TES)



Prêt de véhicules légers électriques

Alternative Parent Selection: CAOF Strategies

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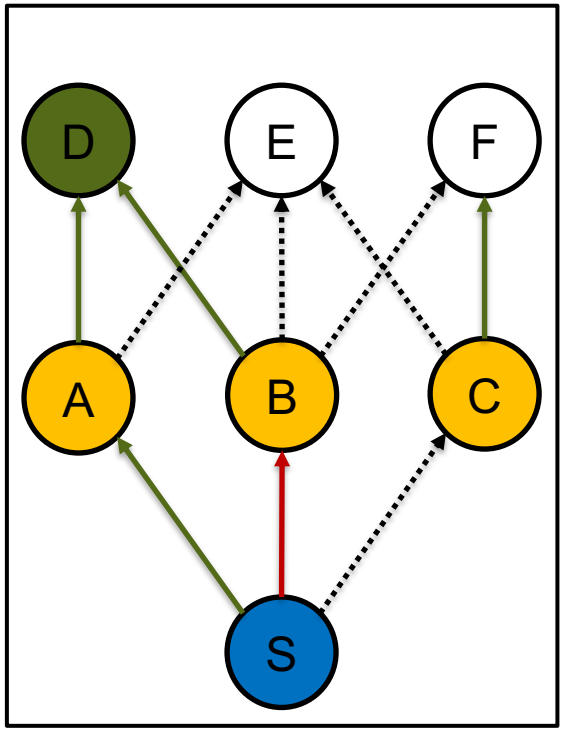
Alternative Parent Selection

Common Ancestor Strategies

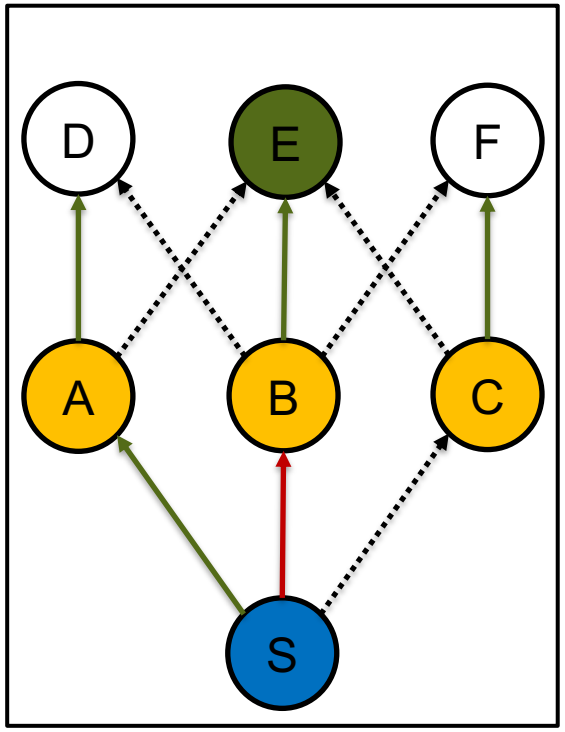
Strict CA



Common Preferred Parent

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

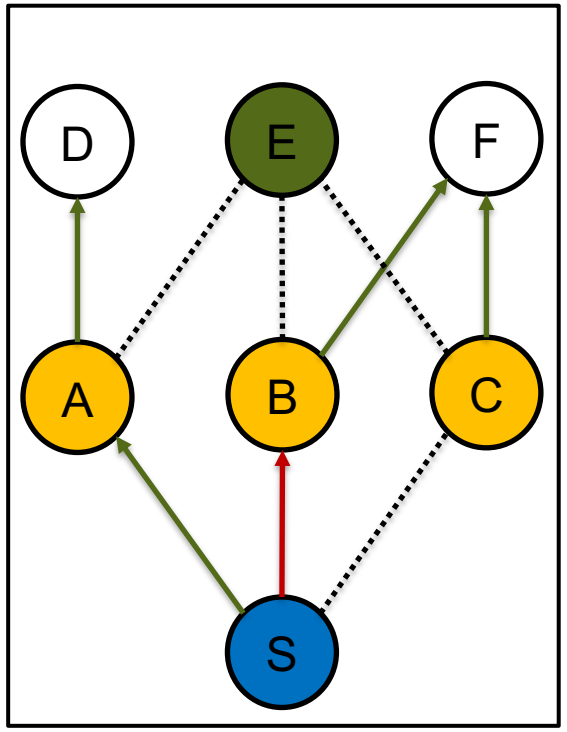
Medium CA



PP in the PS of the AP

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

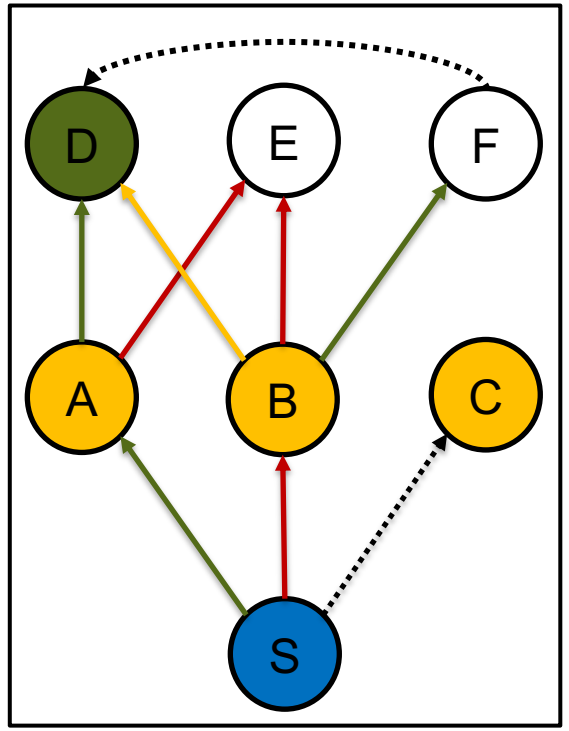
Soft CA



Any Common Parent in the PSs

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

ODeSe



PP Adaptation

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Preferred Parent (PP)
Alternative Parent (AP)
Temporary Parent (TP)
Parent Set (PS)