Optimal Selection and Adaptation of a Flexible Functional Split in Softwarized 5G Radio Access Networks

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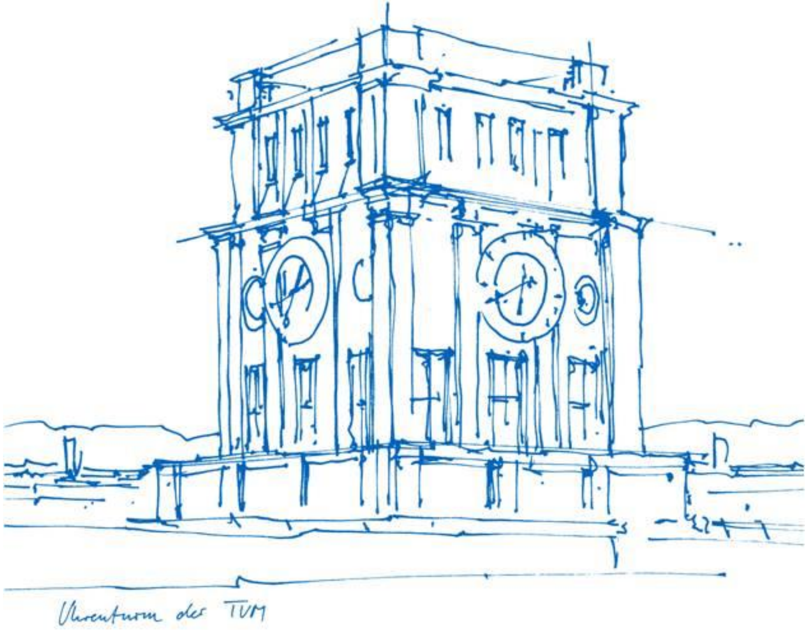
21. März 2022



Outline

- **Chapter I — *Motivation, Objective, and Challenges***
- **Chapter II — *The Dynamic Functional Split Selection Problem***
- **Chapter III — *Modeling the Cost of Flexible Communication Networks***
- **Chapter IV — *Optional Functional Split Selection in 5G Radio Access Networks***
- **Chapter V — *Implementation of an Adaptive Functional Split***
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- **Chapter VII — *Conclusions and Outlook***

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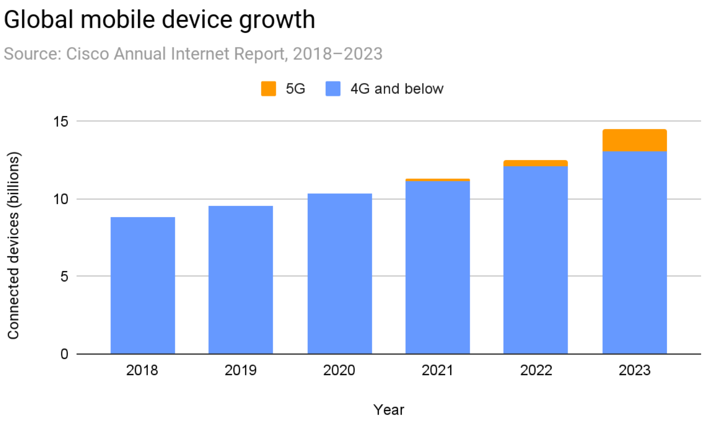
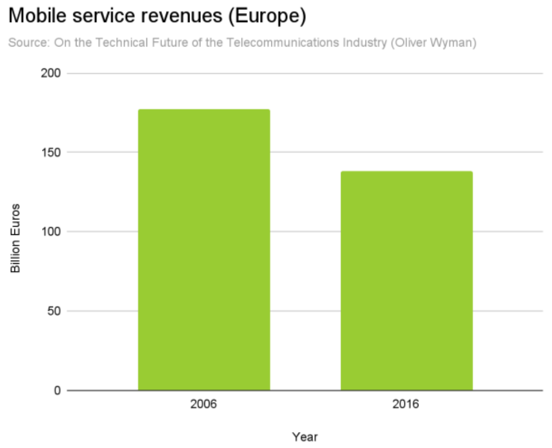
Mobile demand is growing, revenue is not!

- **Mobile devices** will grow from **8.8 billion** in 2018 to **13.1 billion** in 2023 [Cis20]
  - **1.4 billion** 5G devices in 2023
- Mobile operators report **less revenue** [GAO17]
  - European operators earned **177 G€** in 2006 and **138 G€** in 2016



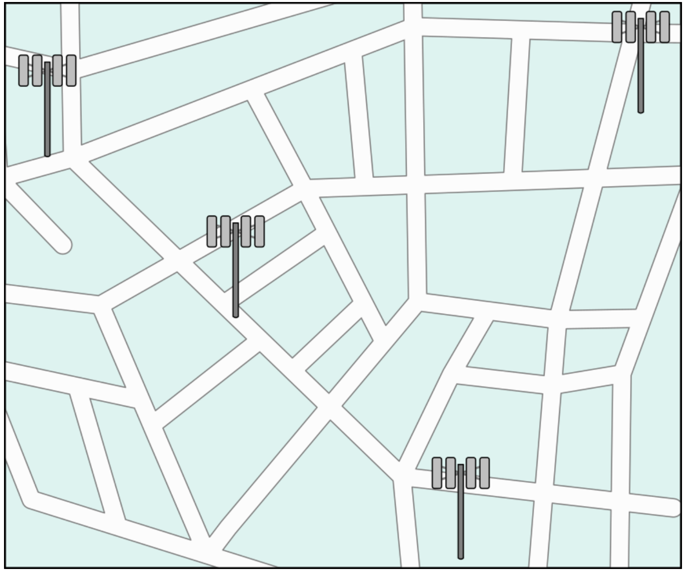


[Cis20] Cisco public. *Cisco annual internet report (2018–2023)*. White Paper (2020).

[GAO17] R. A. Gustav A. Oertzen. *On the Technical Future of the Telecommunications Industry*. White Paper. Oliver Wyman, (2017).

Efficiency is key for profitability

- Operators need to be **efficient** at using the resources of Radio Access Networks (RAN)



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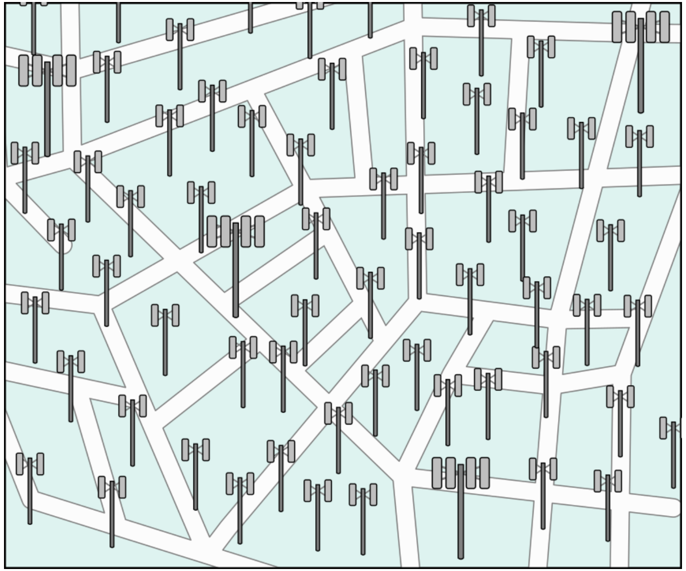
- **Increasing cell density** is required for improving **resource efficiency** [KS17]
  - Better **coverage**
  - Less **power consumption**
  - LOS conditions enable **high-frequency bands**



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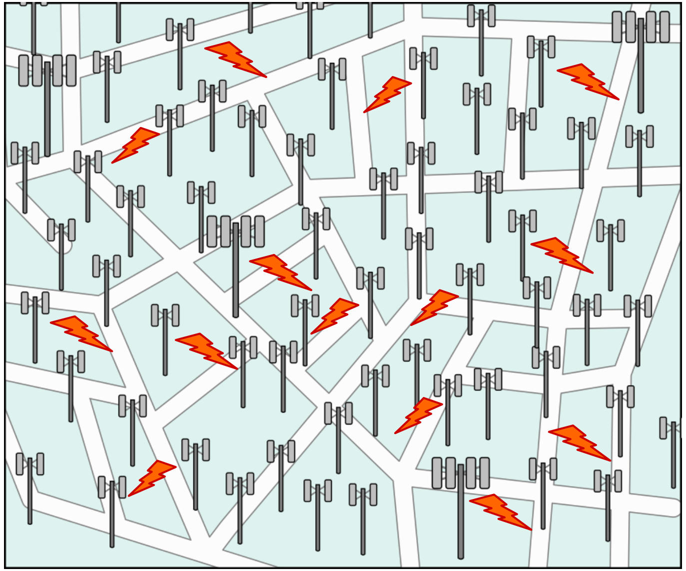
- **However…**
  - ...**inter-cell interference** becomes worse
  - ...the **deployment** and **operating costs** are unclear



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Network softwarization to the rescue!

- **Possible solution:** exploit **network softwarization** technologies
  - **Network Function Virtualization** (NFV)
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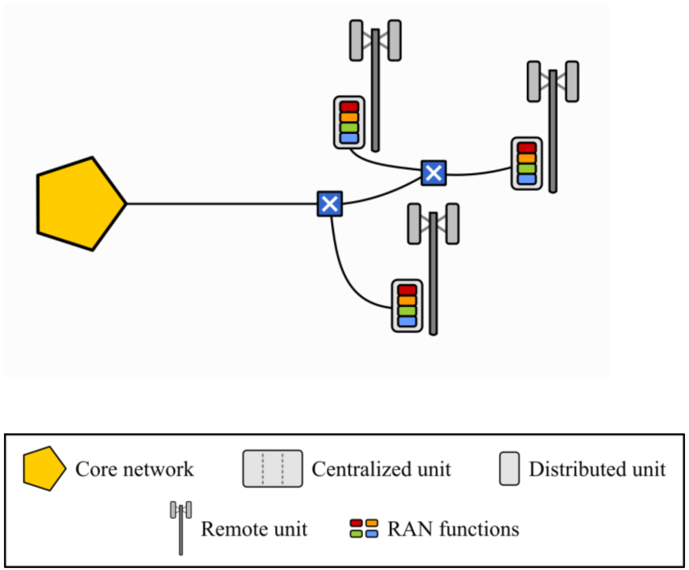
Distributed RAN



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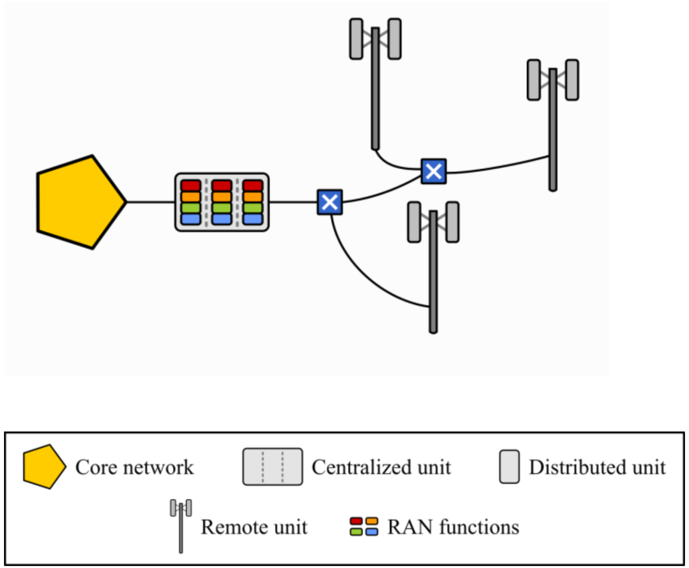
- **Softwarization** enables **function centralization** [Che+14a]
  - Less **operating** and **deployment cost**
  - Enhanced **interference mitigation techniques**

Centralized RAN



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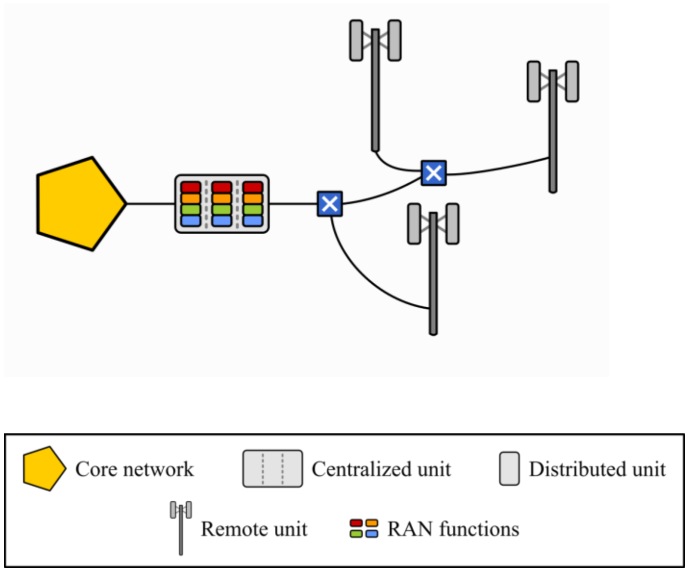

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Full centralization is not feasible

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  - Usually **not available!** [Che+16a]

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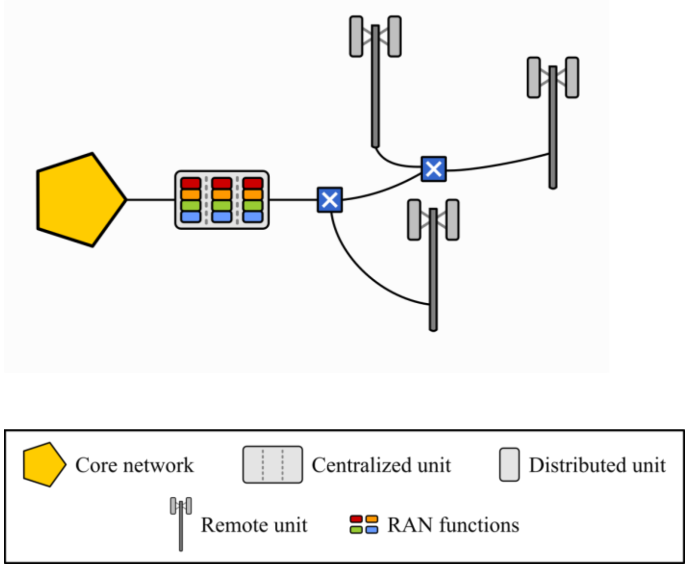

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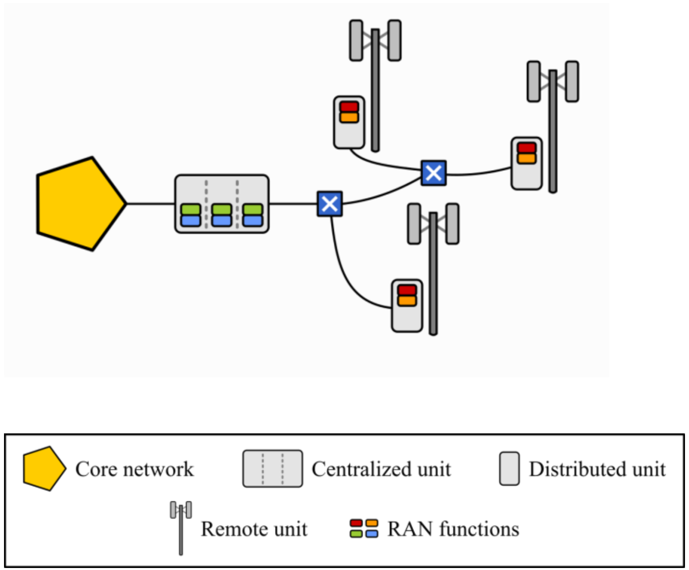

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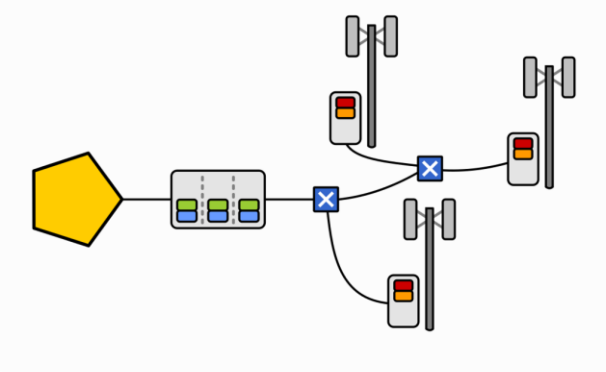

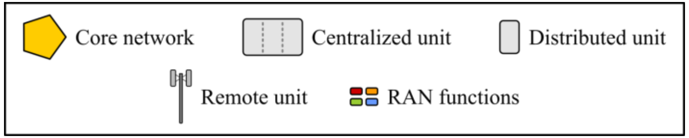

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  - User **location** and **mobility**
  - User **traffic**

- **Static functional splits** cannot cope with dynamicity

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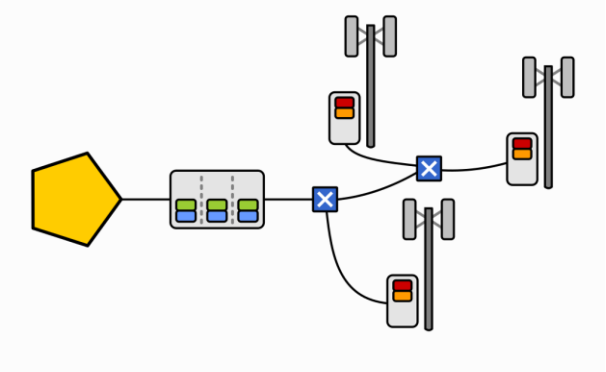

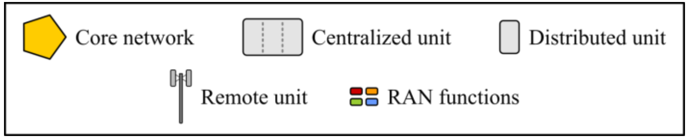

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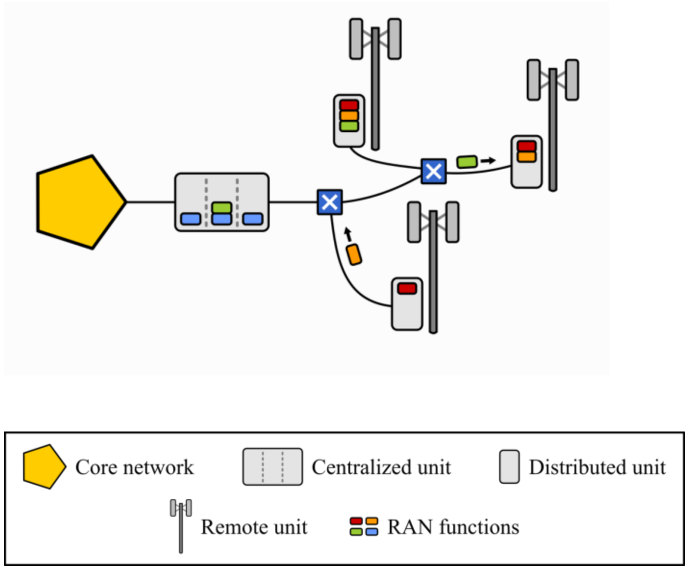
- **Our solution:**
  - Select the **functional split** dynamically
  - Adapt **functional split** during runtime

Dynamically centralized RAN



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- Find the **right functional split** for each **instant**
  - How to obtain the **optimal functional split**? ➔ *Ch. II and IV*

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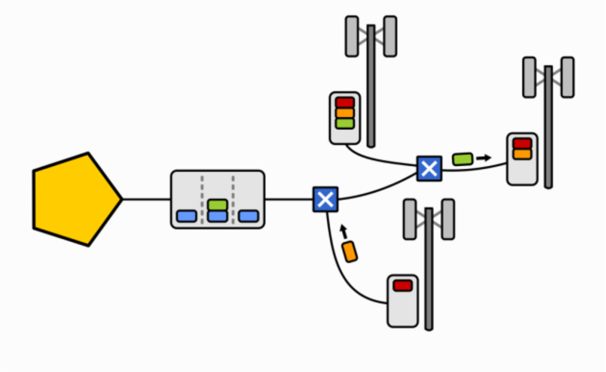

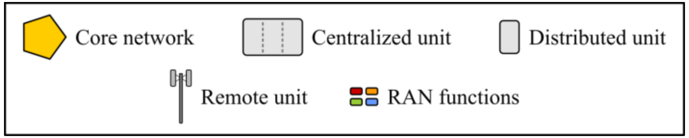

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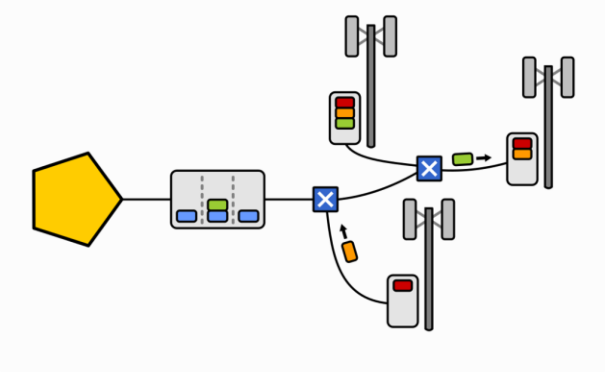

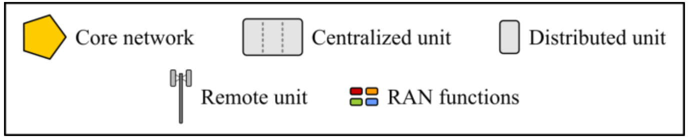

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  - Is it **feasible** with current technology? ➔ *Ch. V*

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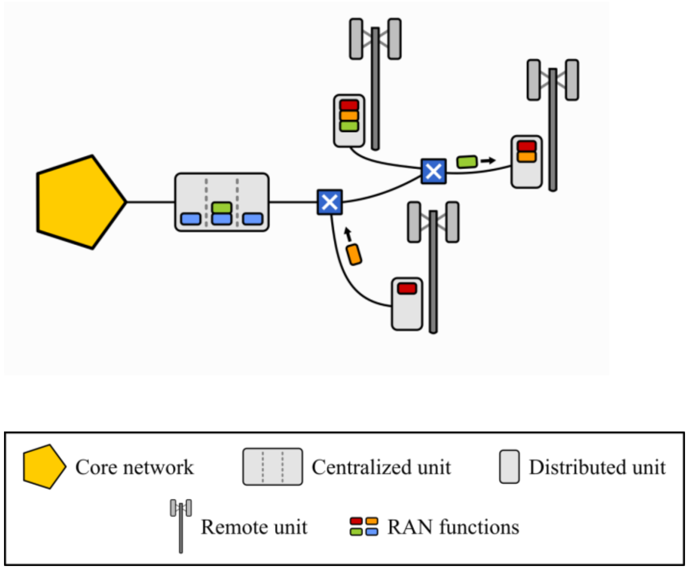

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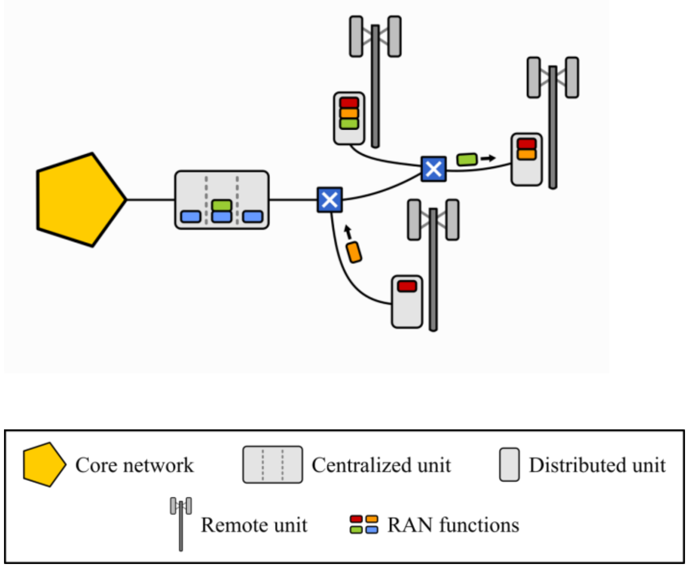
- **Optimal** functional split may change **too frequently**
  - When **should we adapt** to maximize revenue? ➔ *Ch. VI*

Dynamically centralized RAN



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Selecting the optimal functional split

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  - …reduce **the operating cost**
  - …be **implemented** in current RANs

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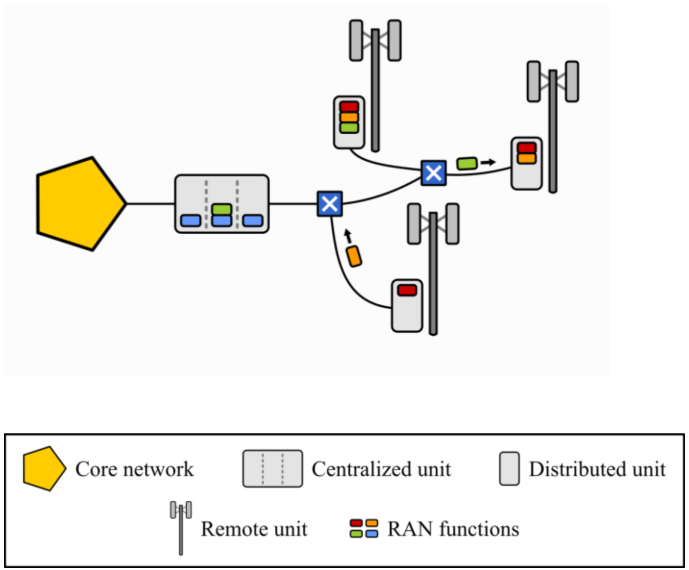

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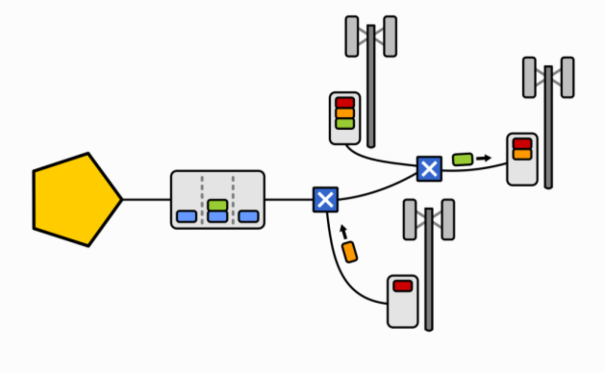
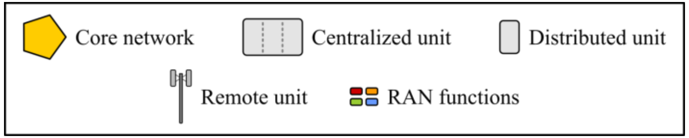
- How many **options** are there?

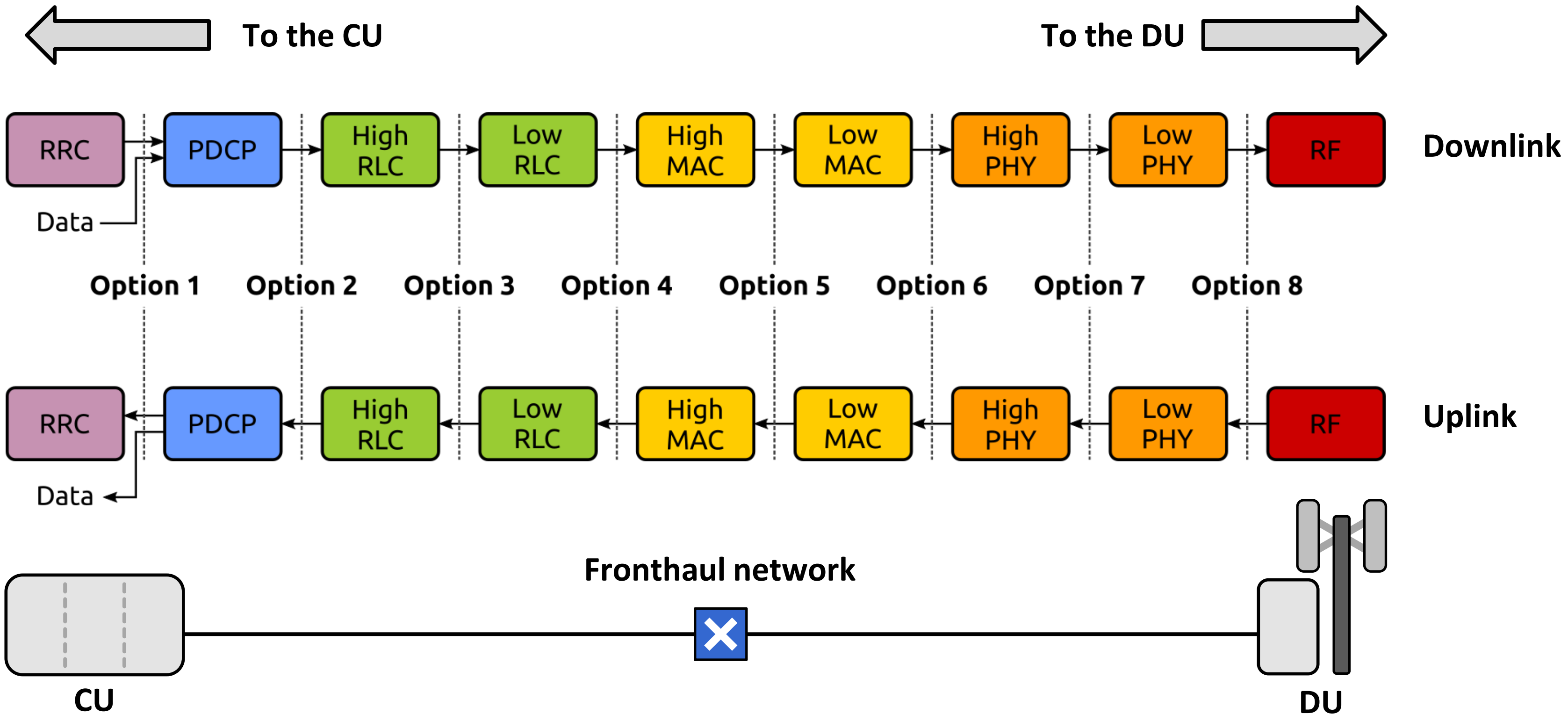
- What **advantages** and **disadvantages** do they have?

Dynamically centralized RAN





5G functional split options



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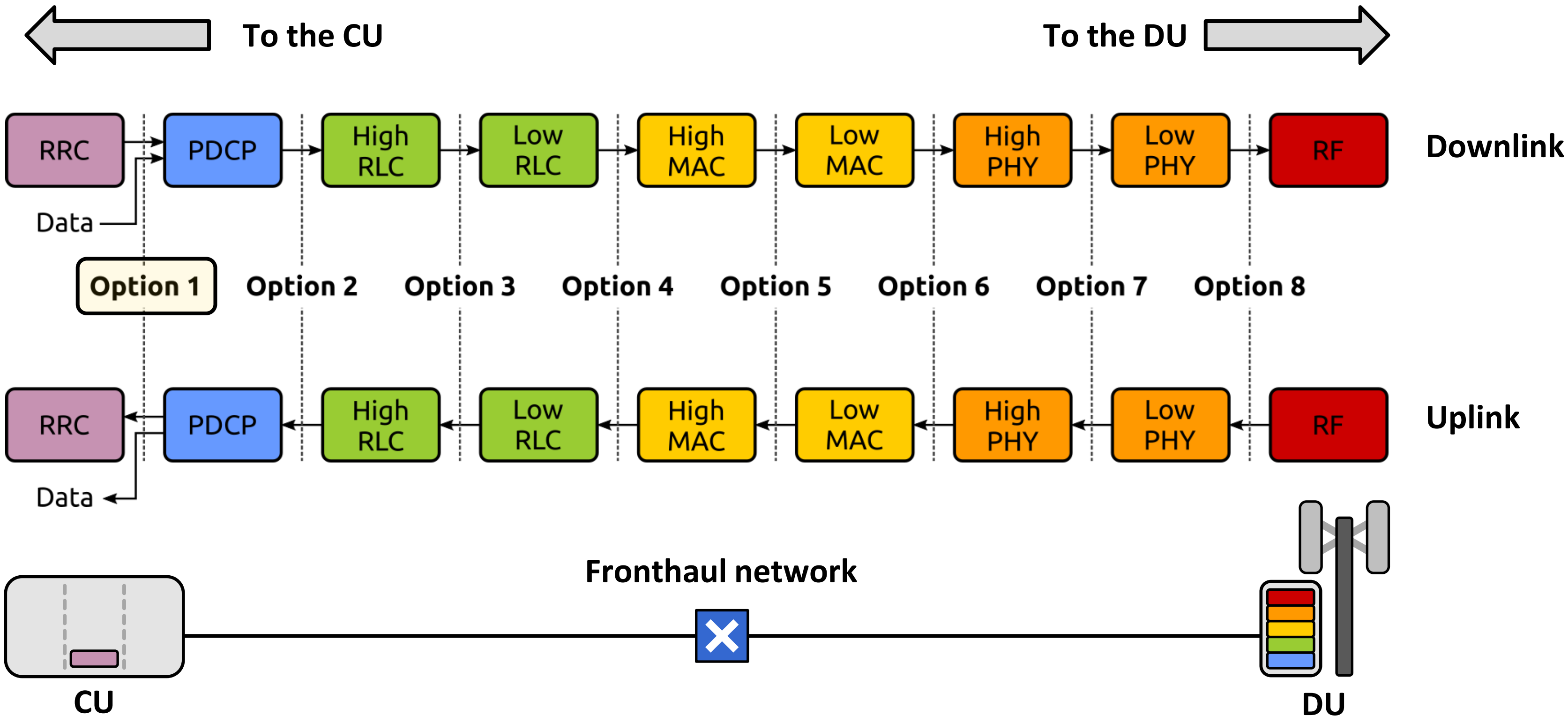

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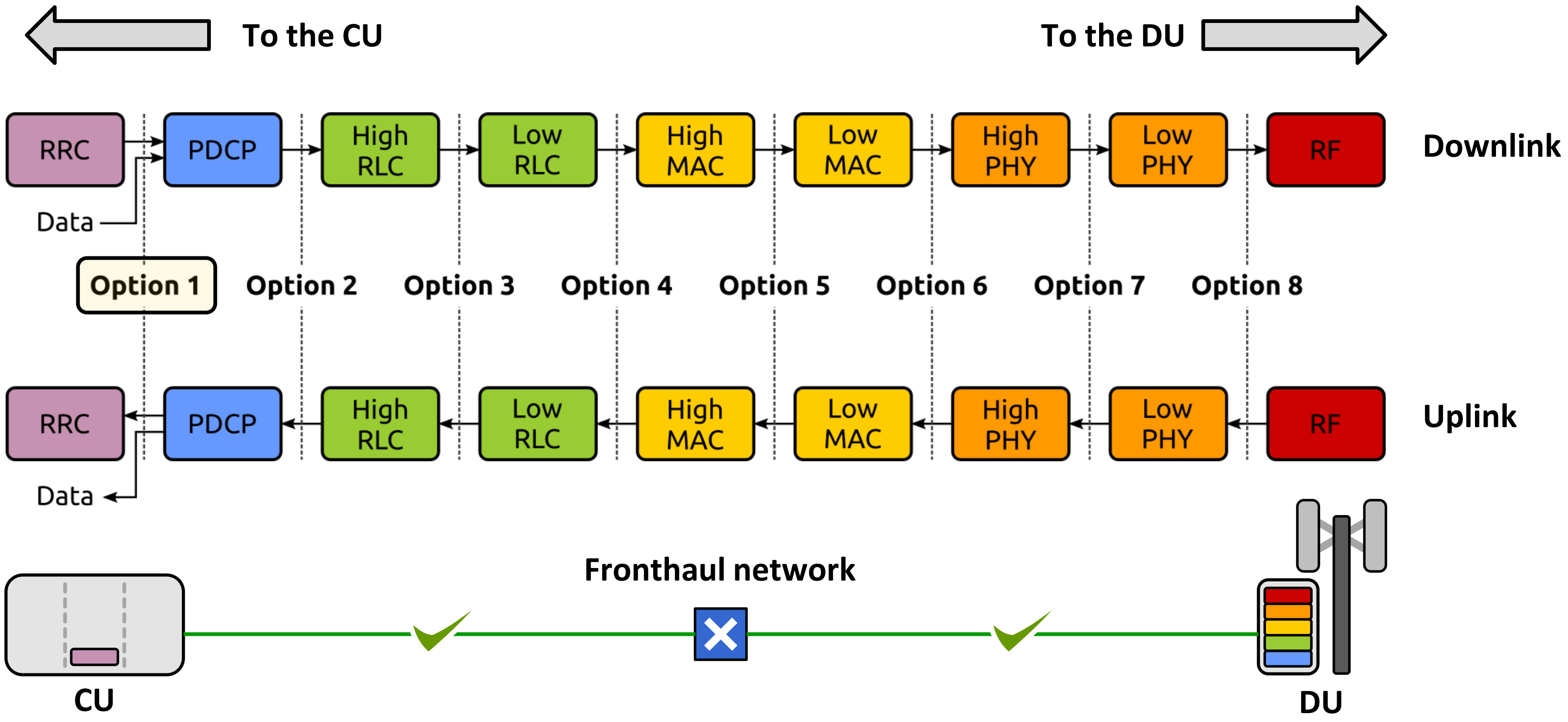

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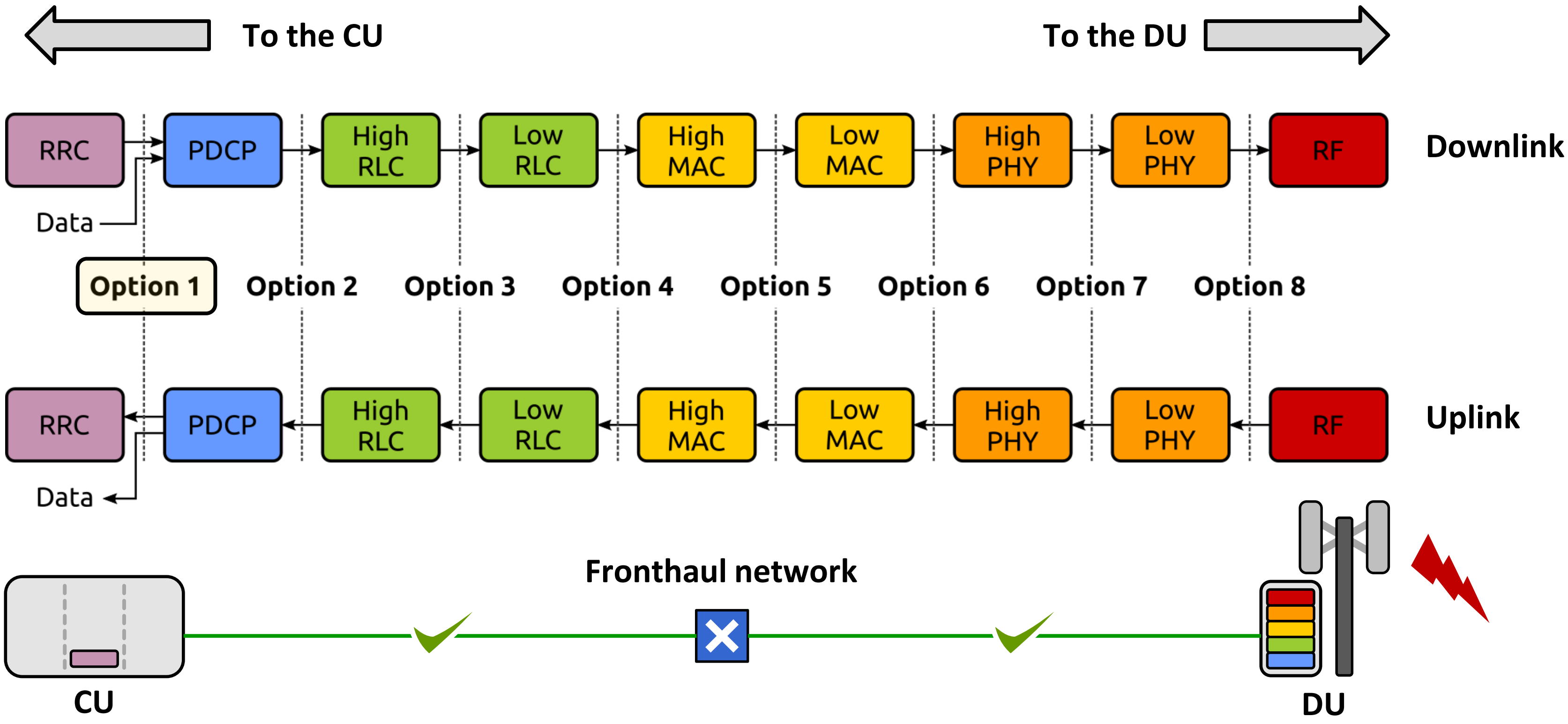

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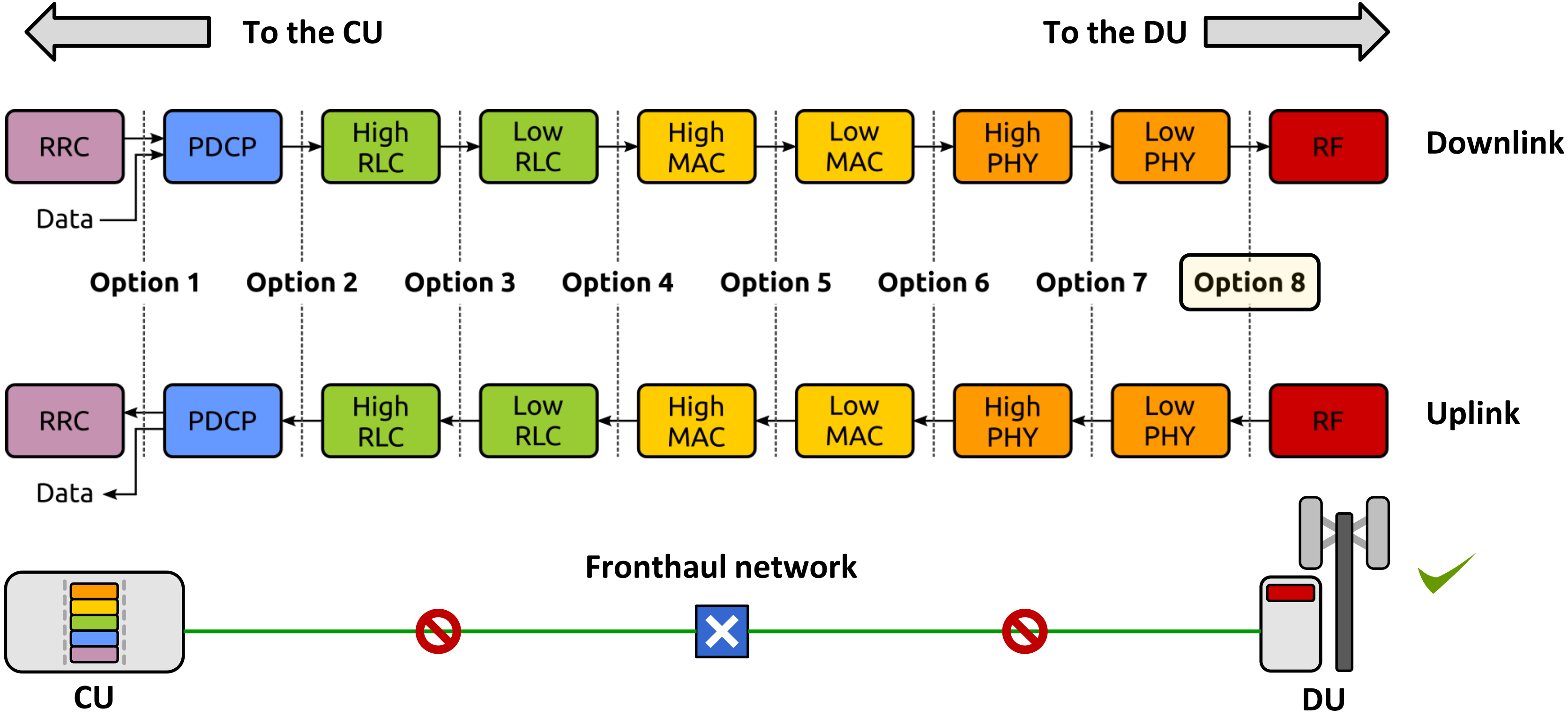

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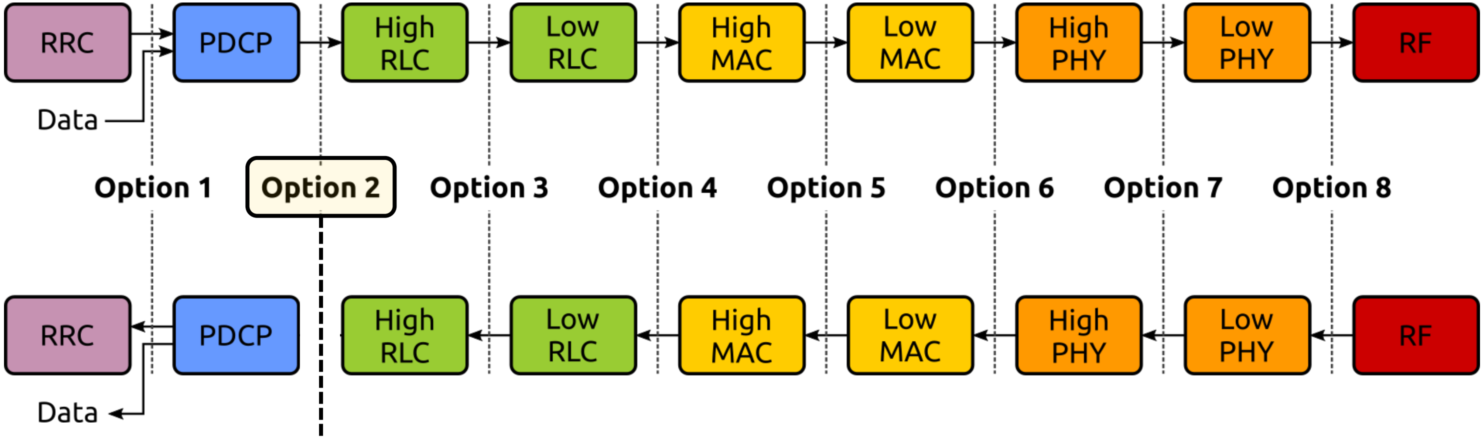

PDCP-RLC split

- Traffic aggregation and easy to implement
- No advanced interference management

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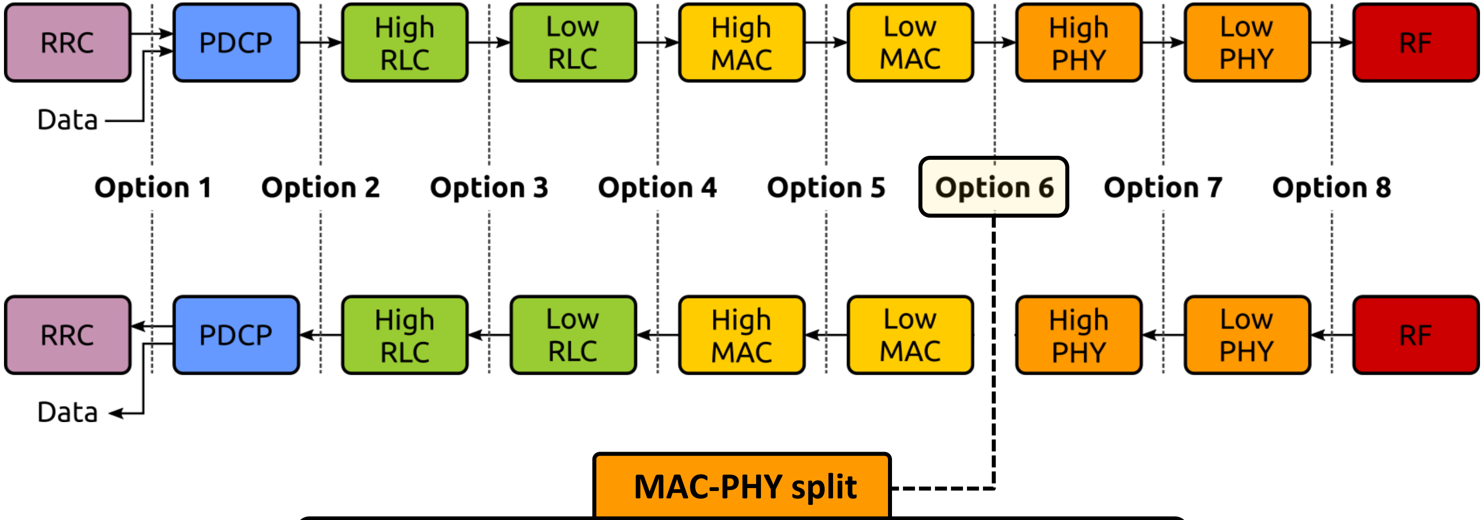

- Coordinated scheduling and beamforming
- Increased fronthaul traffic (50–100% overhead)

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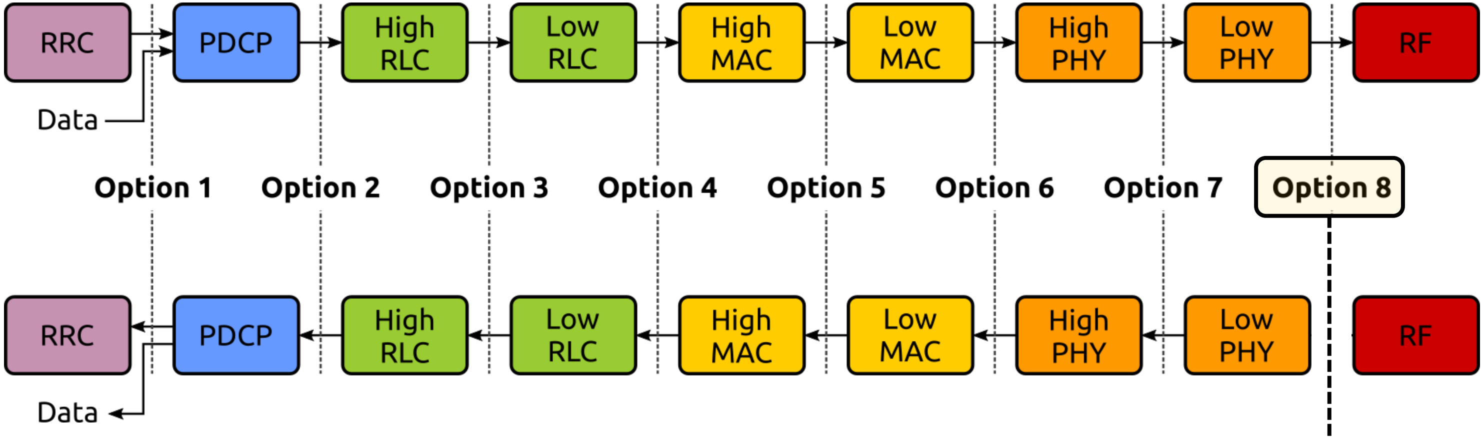

C-RAN split

- Joint transmission and reception
- Very high fronthaul traffic (3800% overhead)

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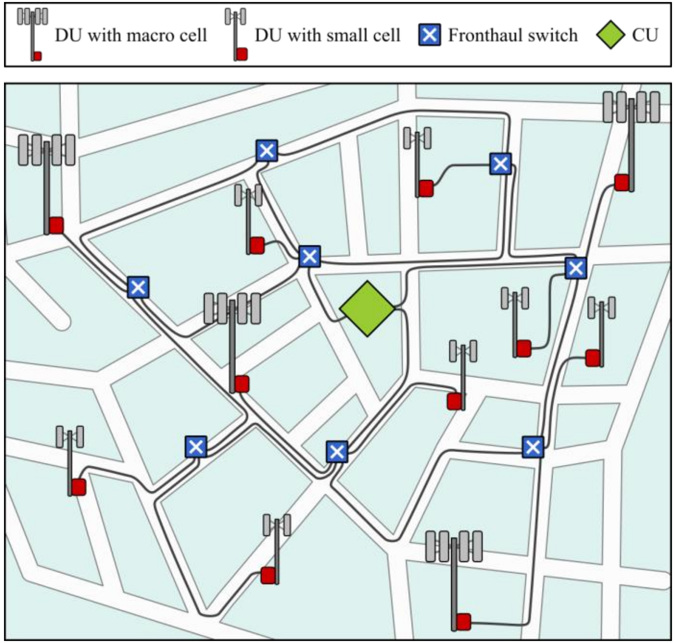
Selecting the right functional split

- **For each base station**, we select its **functional split** so that...
  - ...overall user **data rates** are **maximized**
  - ...overall **operating costs** are **minimized**
  - ...the **capacities** of CU-DU links are **not exceeded**

- **For the whole network**, we select its state $\boldsymbol{s}$:

$$\boldsymbol{s} = \langle \mathbf{a}, \mathbf{f} \rangle$$

  - $\mathbf{a}$: functional splits of all base stations
  - $\mathbf{f}$: flows in the fronthaul network



The static Functional Split Selection Problem (FSSP)

- For **an instantaneous snapshot**, the optimal state is… [MAJK21]

$$\boldsymbol{s}^* = \arg\max_{\boldsymbol{s}} \Gamma(\mathbf{a}, \boldsymbol{I}(\mathbf{a}), \mathbf{f})$$

Subject to…

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Flow conservation

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Flow conservation

$$\sum_{g \in \mathbb{G}} f_e^g \le \vartheta_e \quad \forall e \in \mathbb{E}$$

Link capacity

[MAJK21] A. Martínez Alba, S. Janardhanan, and W. Kellerer. "Enabling dynamically centralized RAN architectures in 5G and beyond". *IEEE Transactions on Network and Service Management* (2021).

The static Functional Split Selection Problem (FSSP)

- For **an instantaneous snapshot**, the optimal state is... [MAJK21]

Performance function
(spectral efficiency, cost, etc.)

$$\boldsymbol{s}^* = \arg\max_{\boldsymbol{s}} \Gamma(\mathbf{a}, \boldsymbol{I}(\mathbf{a}), \mathbf{f})$$

Interference mitigation function

Subject to...

$$\sum_{e \in \mathbb{E}^+(n)} f_e^g - \sum_{e \in \mathbb{E}^-(n)} f_e^g = \begin{cases} 0 & \forall n \in \mathbb{N} \setminus \{n_0, n_g\} \\ \nu(a_g) & for\ n = n_0 \\ -\nu(a_g) & for\ n = n_g \end{cases} \quad \forall g \in \mathbb{G}$$

Flow conservation

$$\sum_{g \in \mathbb{G}} f_e^g \leq \vartheta_e \quad \forall e \in \mathbb{E}$$

Link capacity

- But interference and user activity **change over time!**

[MAJK21] A. Martínez Alba, S. Janardhanan, and W. Kellerer. "Enabling dynamically centralized RAN architectures in 5G and beyond". *IEEE Transactions on Network and Service Management* (2021).

The dynamic Functional Split Selection Problem (FSSP)

- At every instant τ, we care about…
  - The instantaneous **cost of each state**: $\Gamma(\boldsymbol{a}, \boldsymbol{I}(\boldsymbol{a}), \boldsymbol{f}) \Rightarrow K(\mathbf{s}(\tau))$
  - The **cost of changing the state** (if required): $C(\tau)$

- For a sequence of monitoring intervals $\tau \in \{0, \tau^{max}\}$, the optimal state sequence is [MAK21]:

$$\boldsymbol{s}(\tau)^* = \arg\min_{\boldsymbol{s}(\tau)} \sum_{\tau=0}^{\tau^{max}} K\big(\boldsymbol{s}(\tau)\big) + C(\tau)$$

Subject to: **Flow conservation** **Link capacity**

- **How to calculate these costs?**

[MAK21] A. Martínez Alba and W. Kellerer. "Dynamic Functional Split Adaptation in Next-Generation Radio Access Networks". *IEEE Transactions on Network and Service Management* (2021). [Under review].

Outline

Outline

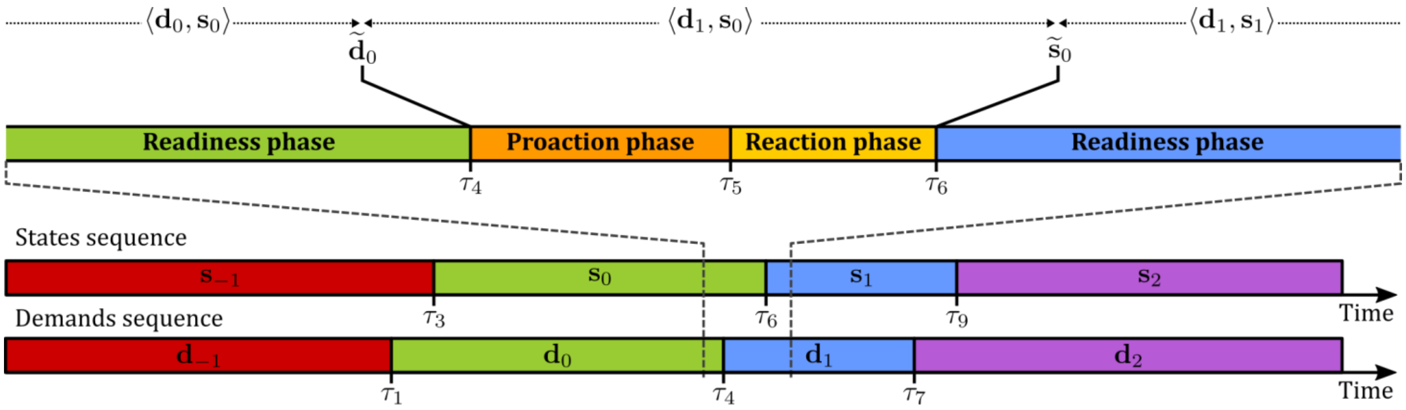
Modeling the cost of flexible communication networks

- Conventional cost models are **inadequate** for dynamic communication networks
  - Operating states may **be difficult to estimate**
  - **Cost of changing states** have to be considered
- We propose **a dedicated cost model** that takes into account:
  - State of the network: $\mathbf{s}(\tau)$
  - Instantaneous demand: $\mathbf{d}(\tau)$
  - Maximum network flexibility [Bab+20]: φ

[Bab+20] P. Babarczi, M. Klügel, A. Martínez Alba, M. He, J. Zerwas, P. Kalmbach, A. Blenk, and W. Kellerer. "A mathematical framework for measuring network flexibility". *Computer Communications 164* (2020), pp. 13–24.

The adaptation process

- Three **adaptation phases** [MA+21]**:**
  - If the network is operating in a **valid state** (satisfied demand) $\Longrightarrow$ **Readiness phase**
  - If the network is **deciding** on the next state $\Longrightarrow$ **Proaction phase**
  - If the network is **transitioning** to the next state $\Longrightarrow$ **Reaction phase**



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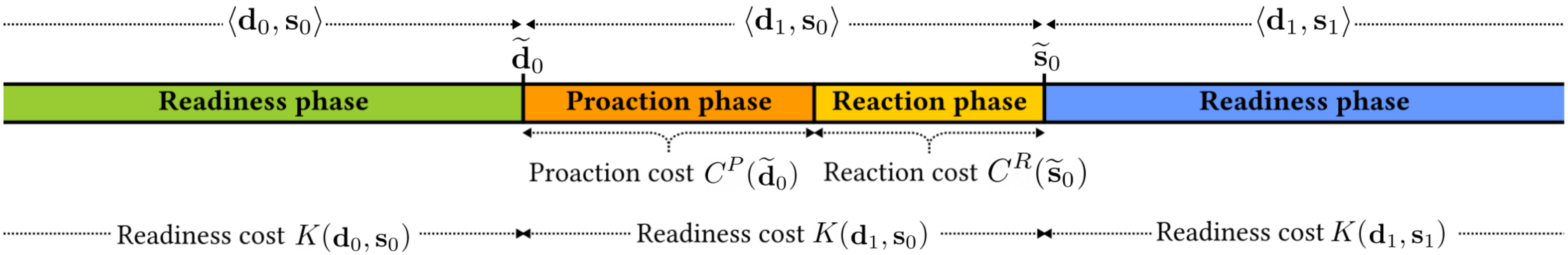
Cost of the adaptation process

- The **total operating cost** $Q = K + C^P + C^R$ of a flexible network is the sum of [MA+21]:
  - **Readiness cost** K: cost of operating the network at the current state given an active demand
  - **Proaction cost** C^P: cost of finding a new state during the proaction phase
  - **Reaction cost** C^R: cost of implementing a new state during the reaction phase



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The resulting toolkit

- Probability-theory framework to model the **dynamic network operation** [MA+21]

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Theorem III.6. *The mean readiness cost K of an action-interrupting network is*

$$K = \alpha\varphi K_{\mathcal{X}}(0) + (1 - \alpha\varphi)\beta\varphi\widehat{K}_{\beta}, \tag{19}$$

where

$$\widehat{K}_{\beta} \triangleq \sum_{x=1}^{\infty} K_{\mathcal{X}}(x)(1 - \beta\varphi)^{x-1}. \tag{20}$$

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$$C^P = \frac{C_0^P}{T} + \left(\frac{\beta^P Z^P}{T} + 1 - \beta^P\right) C_z^P, \tag{25}$$

where

$$\beta^P \triangleq \int_0^{\infty} F_{\mathcal{Z}^P}(t) f_{\mathcal{T}}(t) dt, \tag{26}$$

and $Z^P \triangleq E\{\mathcal{Z}^P\}$.

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$$\frac{\alpha}{(\alpha\varphi-1)\beta} < \frac{\widehat{K}_\beta}{K_{\mathcal{X}}(0)}. \tag{21}$$

given that $K_{\mathcal{X}}(0) < 0$.

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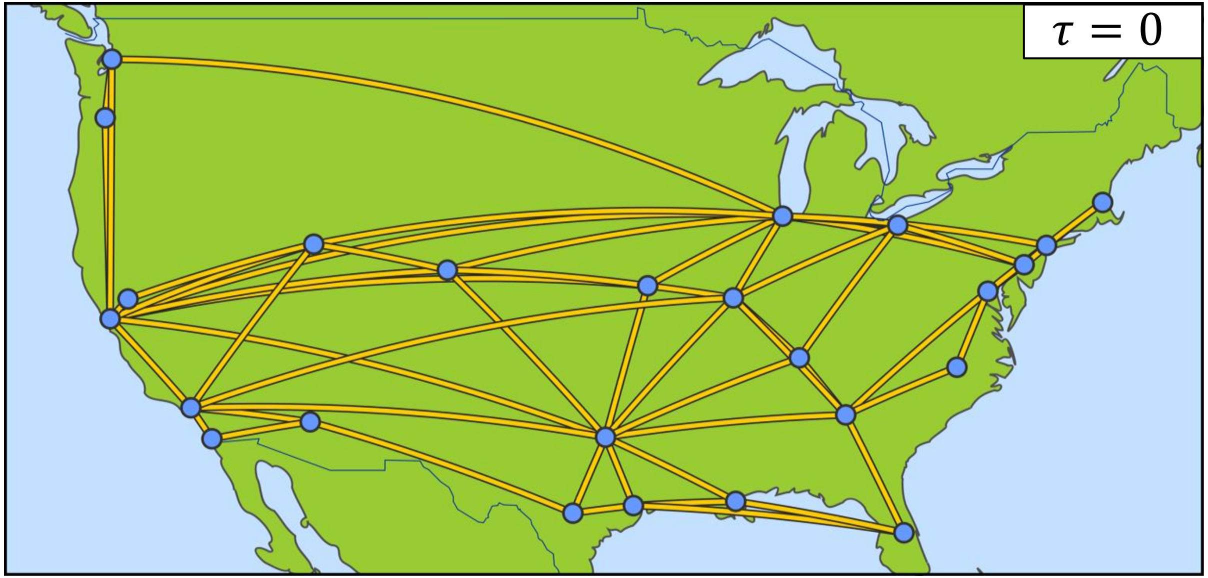
Example: dynamic flow allocation in SDN network

- **Service:** provide a connection between two nodes when demanded
- **Objective:** minimize number of used links



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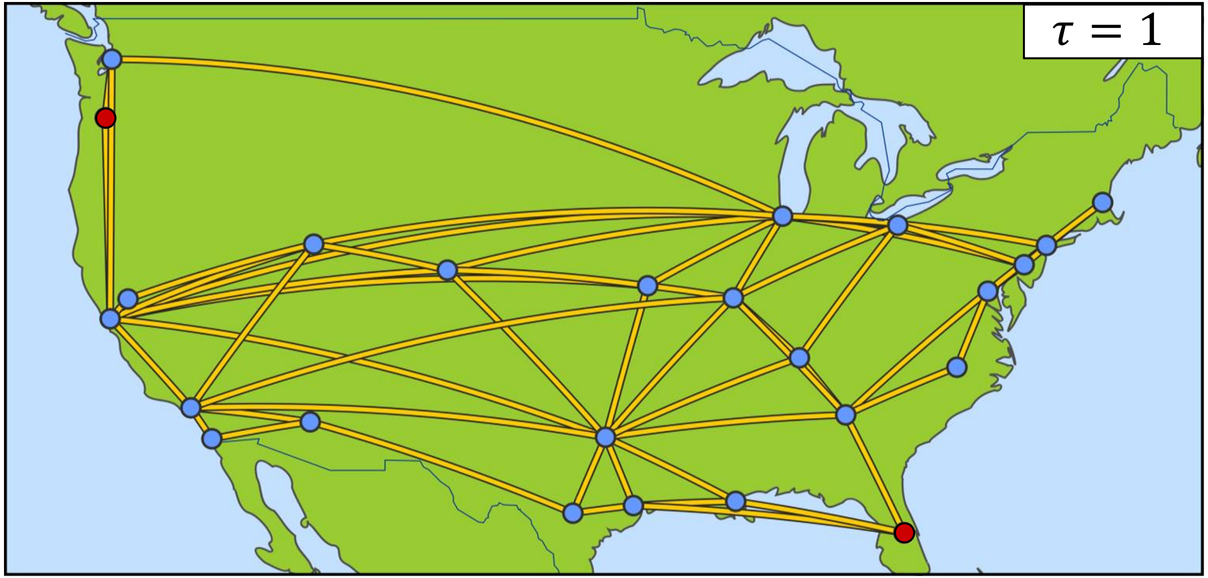

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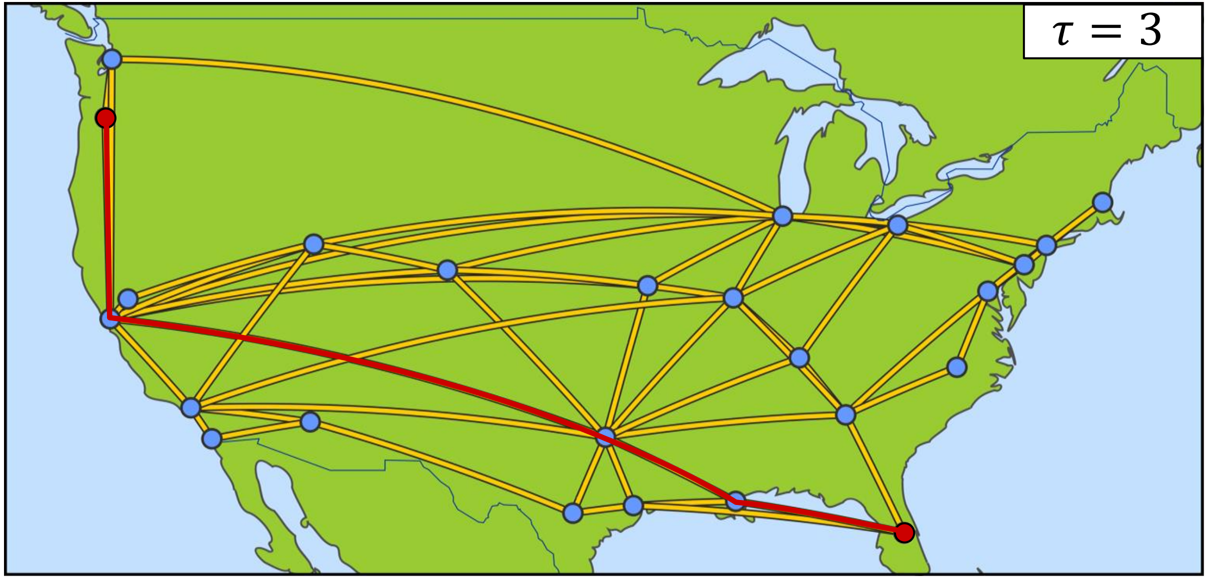

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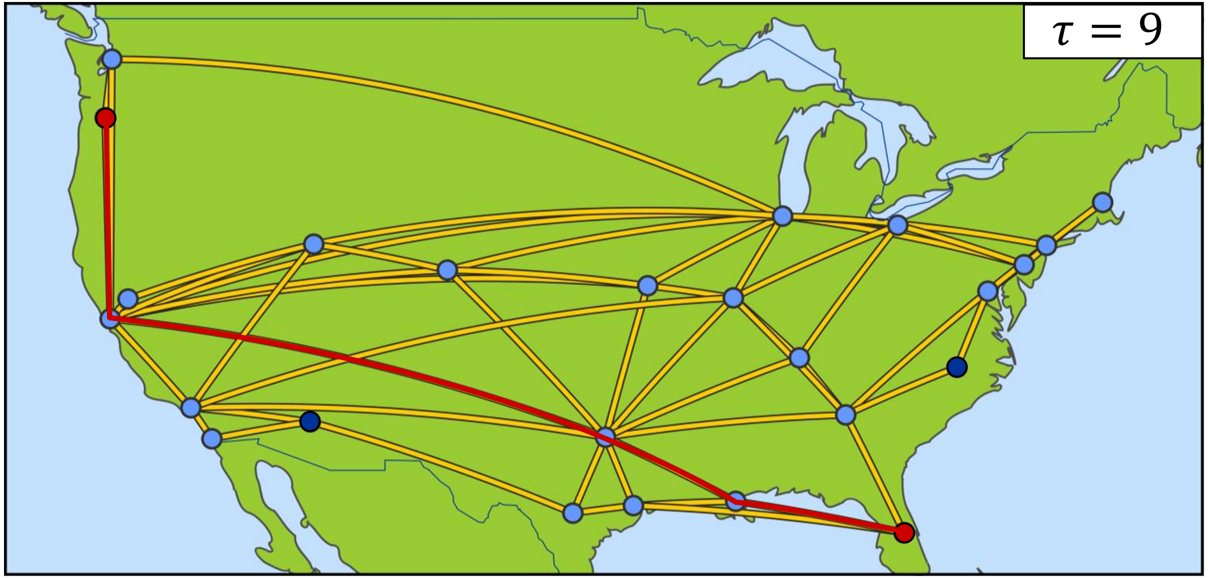

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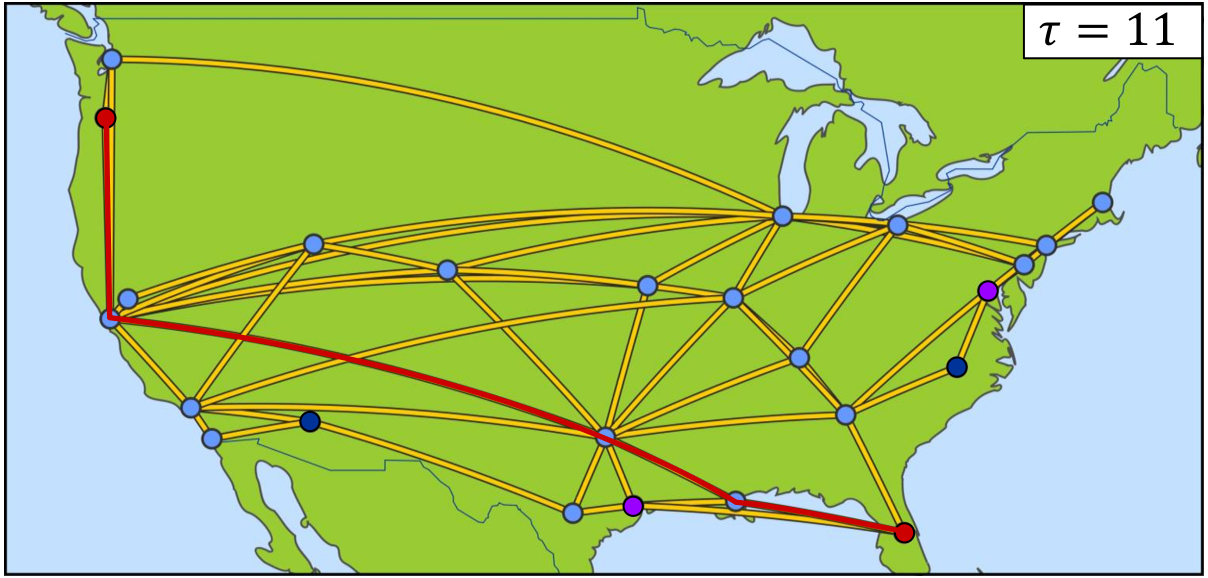

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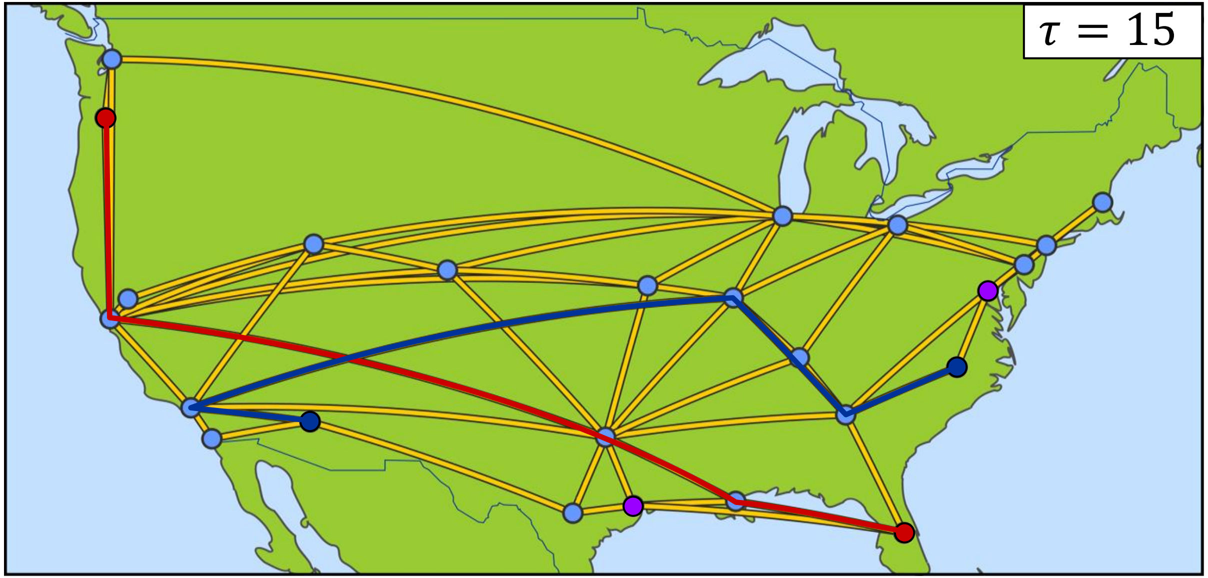

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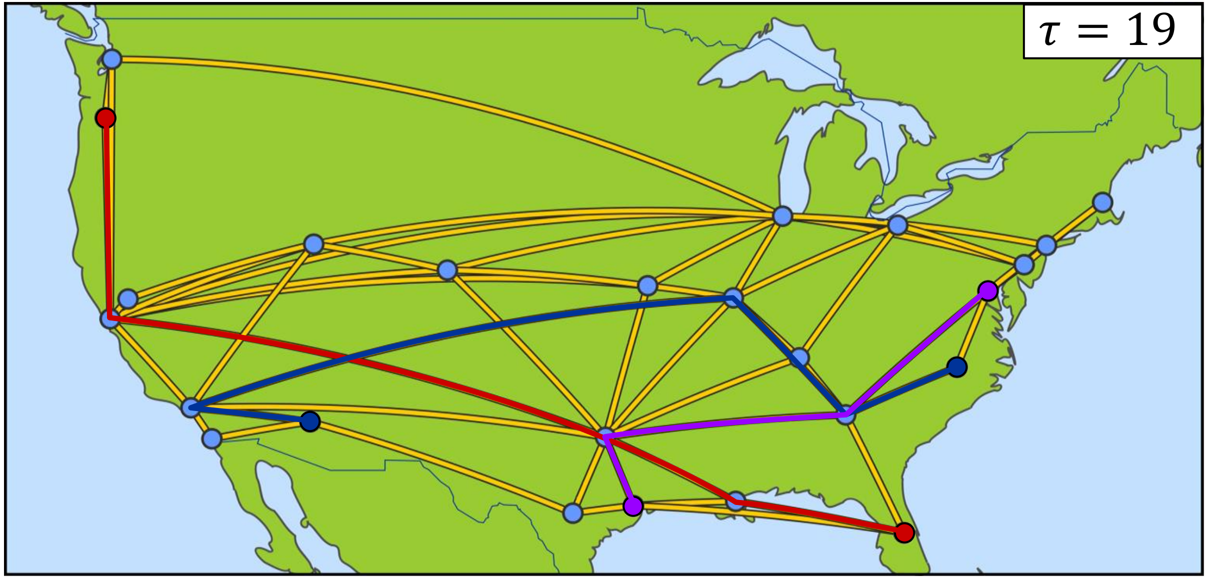
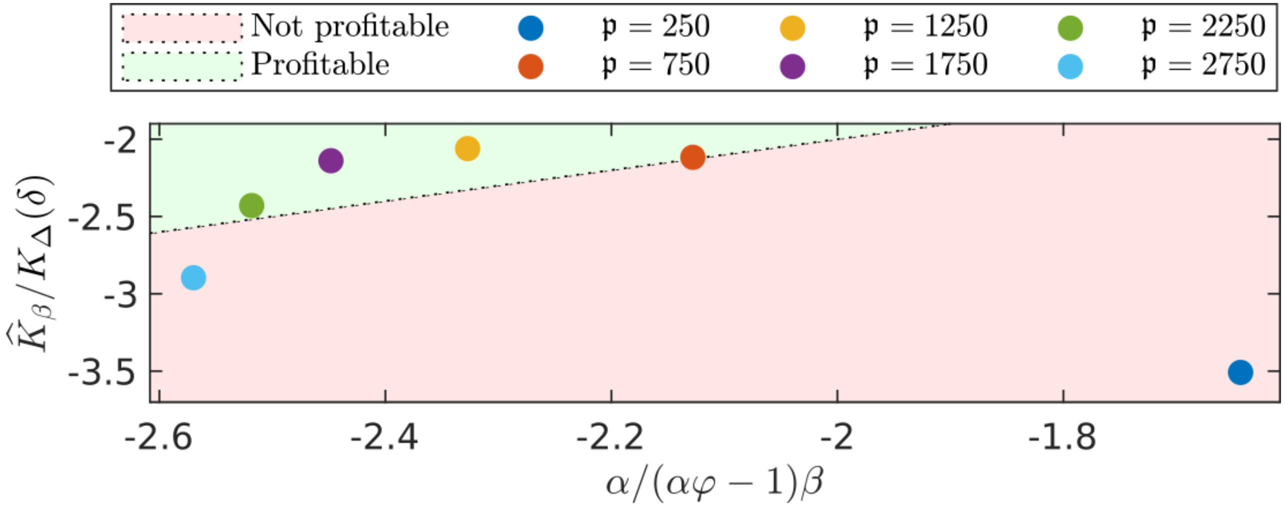


Example: evaluating adaptation algorithms

- Operator uses a **genetic algorithm** to find a near-optimal integer path
- Possible **initial populations**: $\mathfrak{p} = \{250, 750, 1250, 1750, 2250, 2750\}$
- Which initial population values lead to **profitable** networks? [MA+21]



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Outline

- Chapter I — *Motivation, Objective, and Challenges*
- Chapter II — *The Dynamic Functional Split Selection Problem*
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The static Functional Split Selection Problem (FSSP)

- The optimal instantaneous state minimizes the instantaneous **readiness cost**:

$$\mathbf{s}^* = \arg\max_{\boldsymbol{s}} \Gamma(\mathbf{a}, \boldsymbol{I}(\mathbf{a}), \mathbf{f}) = \arg\min_{\mathbf{s}} K(\mathbf{s}) = \arg\min_{\mathbf{s}} \overbrace{K_{\text{oper}}(\mathbf{s})}^{\text{Operating cost}} + \underbrace{K_{\text{rev}}(\mathbf{s})}_{\text{Revenue}}$$

- **Three-way approach:**

$\min_{\mathbf{s}} K_{\text{rev}}(\mathbf{s})$ $\Rightarrow$ **Performance-maximizing FSSP**

$\min_{\mathbf{s}} K_{\text{oper}}(\mathbf{s})$ $\Rightarrow$ **Operating-cost-minimizing FSSP**

$\min_{\mathbf{s}} K_{\text{oper}}(\mathbf{s}) + K_{\text{rev}}(\mathbf{s})$ $\Rightarrow$ **Readiness-cost-minimizing FSSP**

Performance-maximizing FSSP

- Proportionally-fair performance-maximizing FSSP formulation [MAJK21]:

$$\arg\min_{\mathbf{s}} K_{\mathrm{rev}}(\mathbf{s}) \; = \arg\max_{\mathbf{s}} \sum_{u=1}^{U} \log\left(\log_2\left(1 + \frac{p_u}{\varsigma + \boldsymbol{I}_u(\mathbf{a})}\right)\right)$$

Subject to: **Flow conservation** **Link capacity**

- **Mixed-integer non-linear problem** (MINLP) in non-standard form

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Over all UEs

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Proportional fairness

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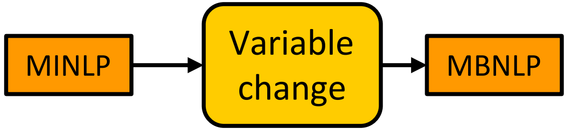
Solving the performance-maximizing FSSP

MINLP

Solving the performance-maximizing FSSP



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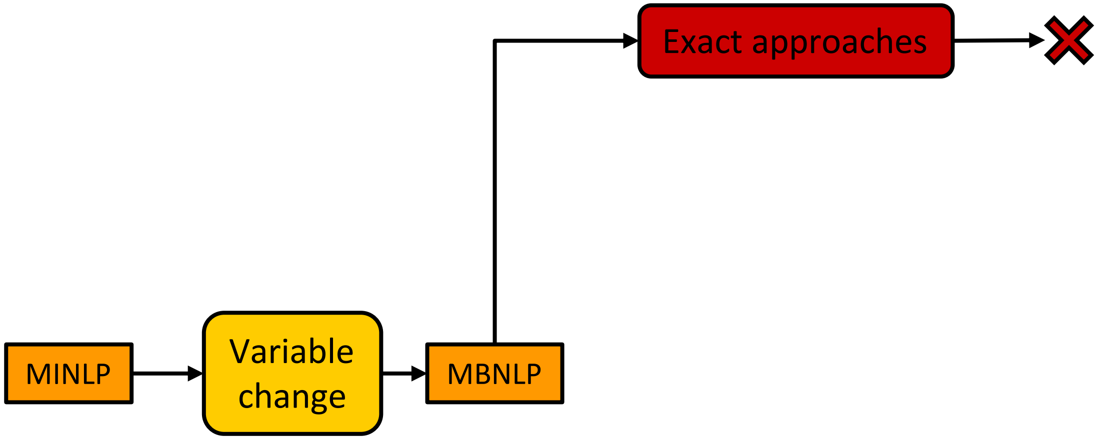

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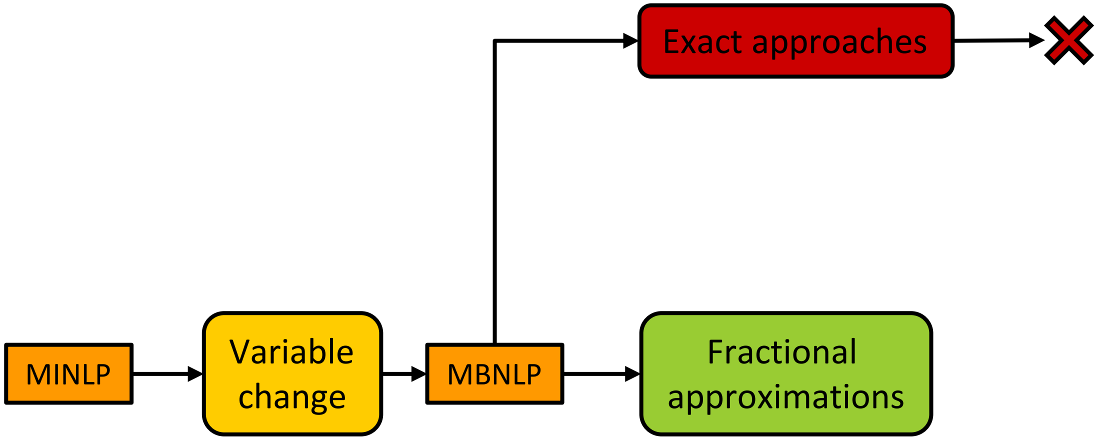

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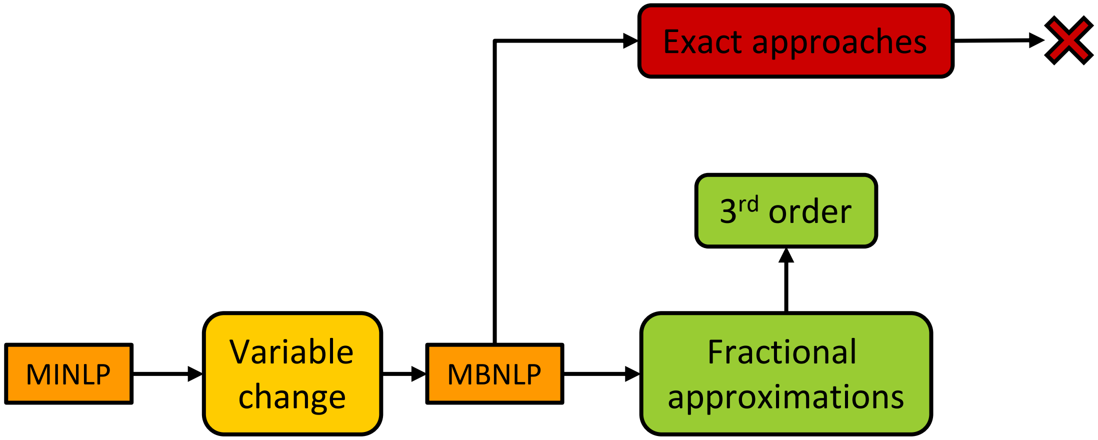

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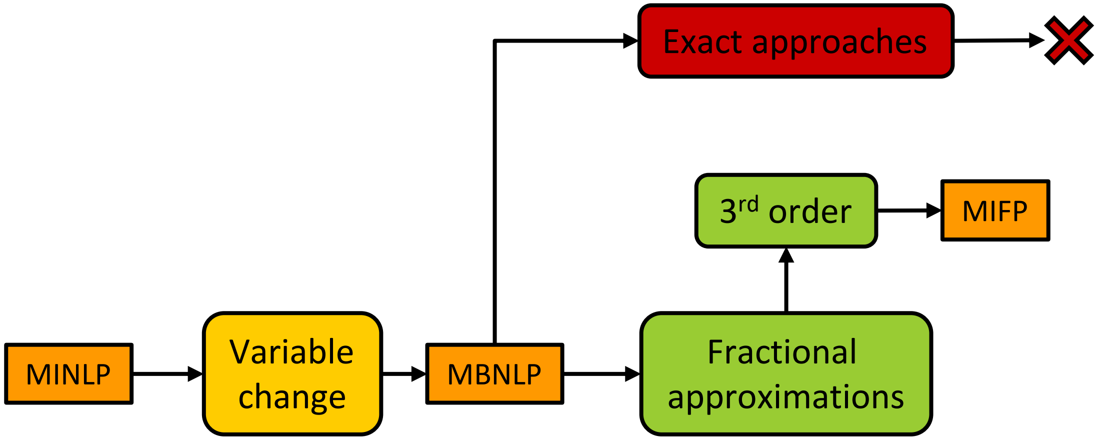

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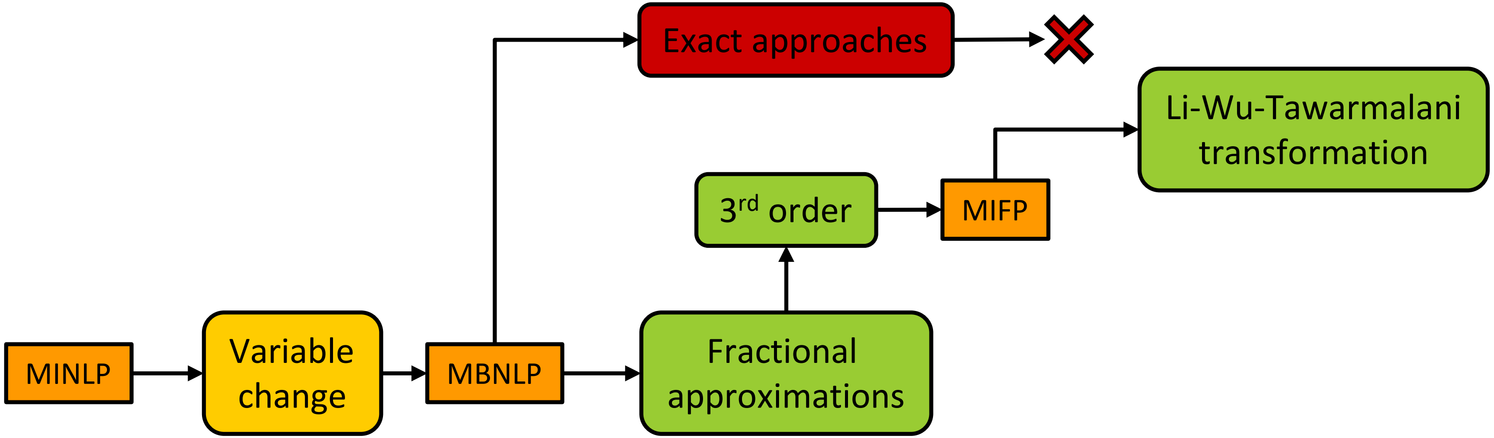

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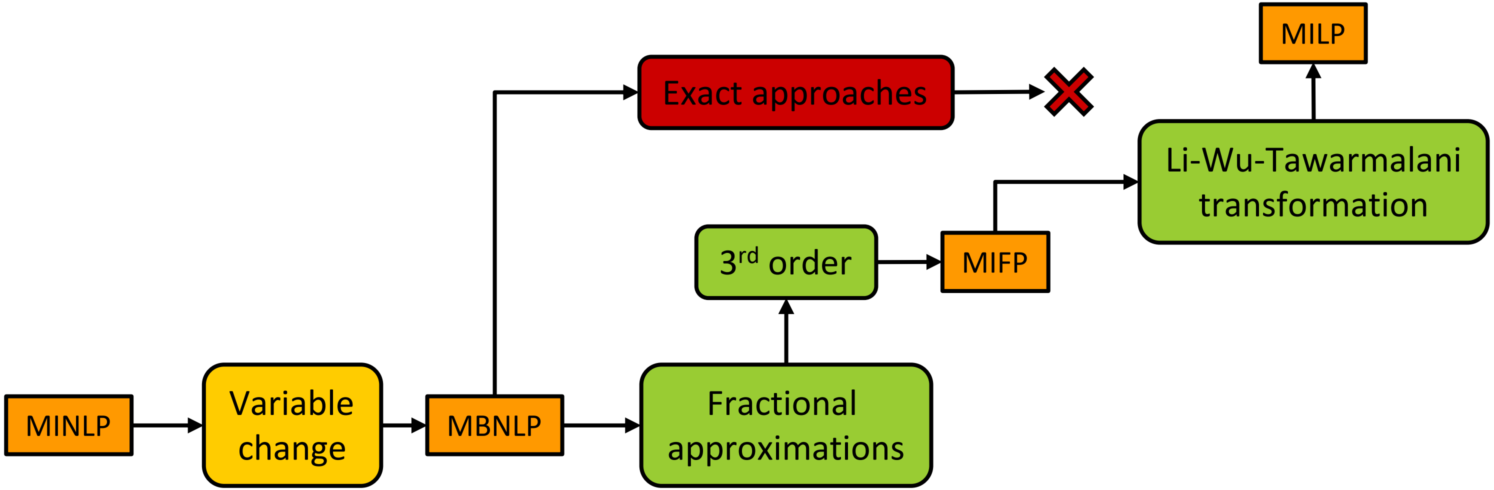

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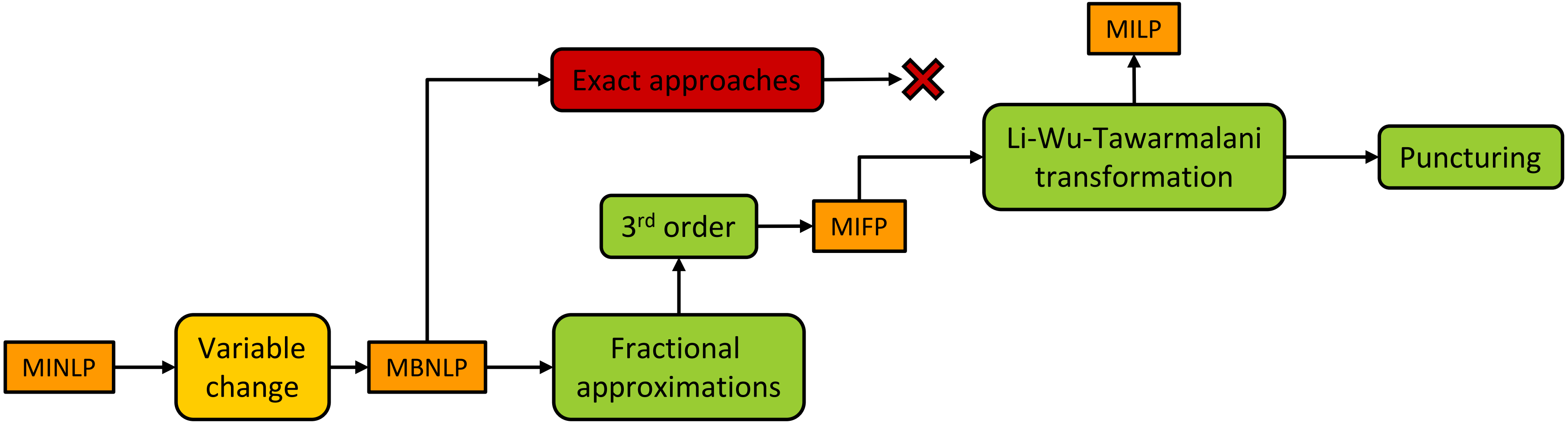

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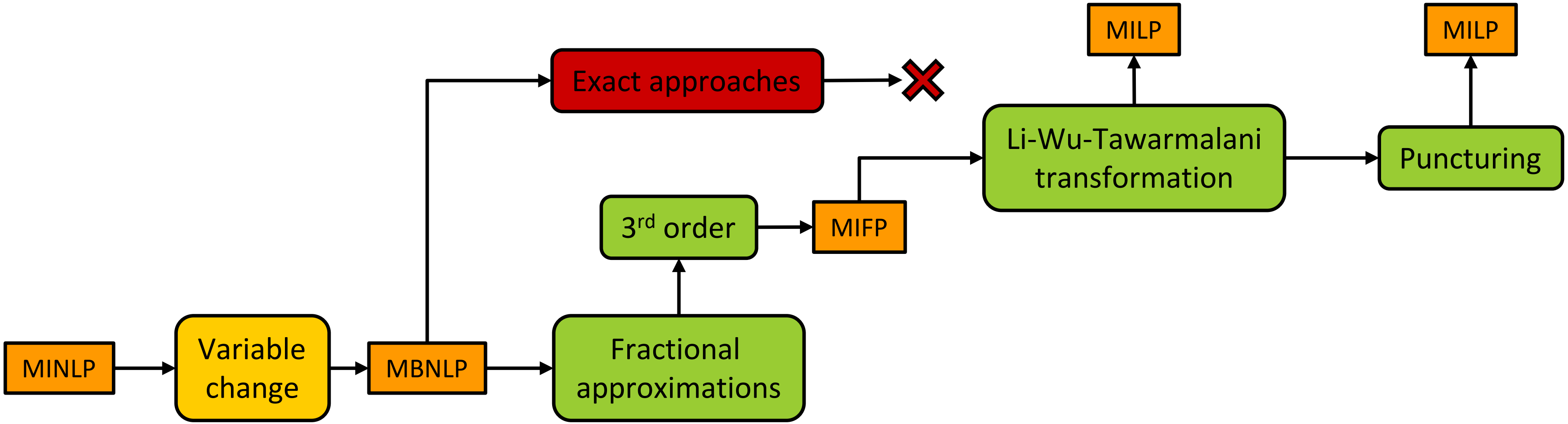

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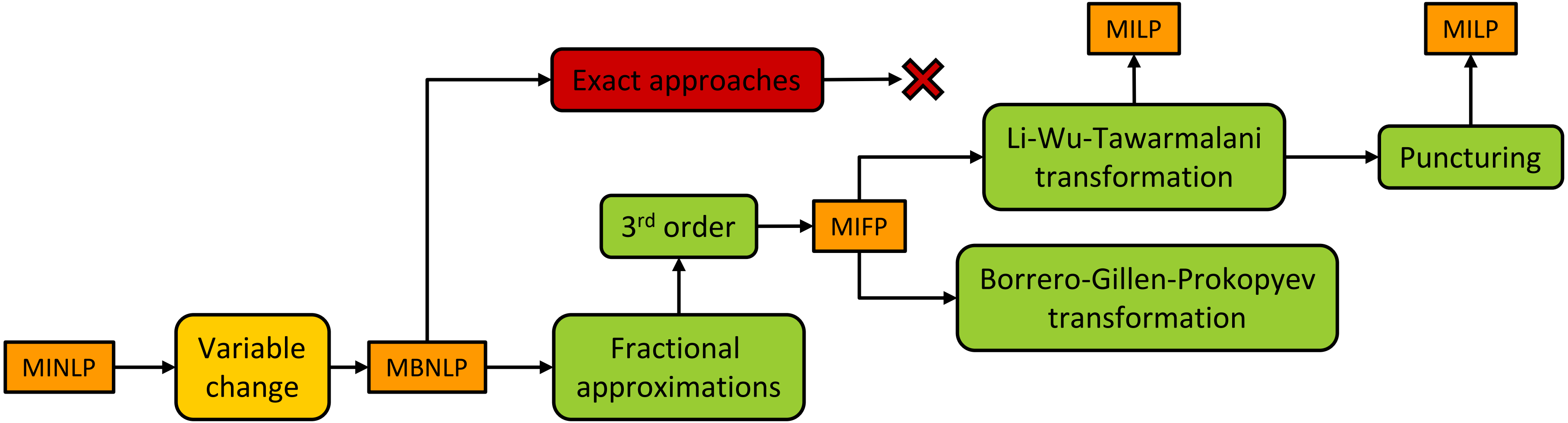

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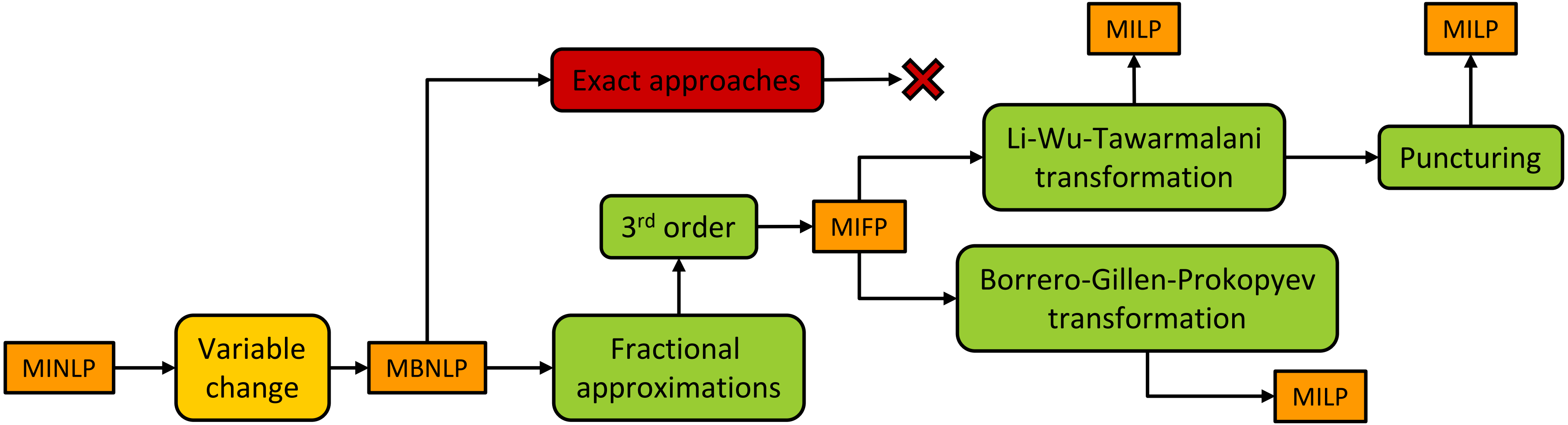

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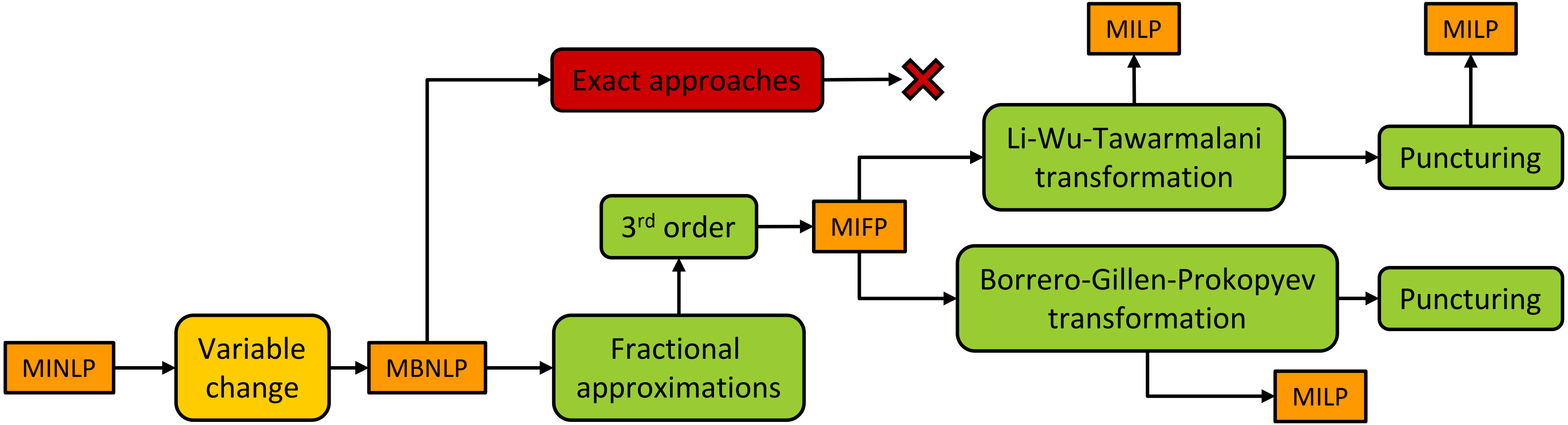

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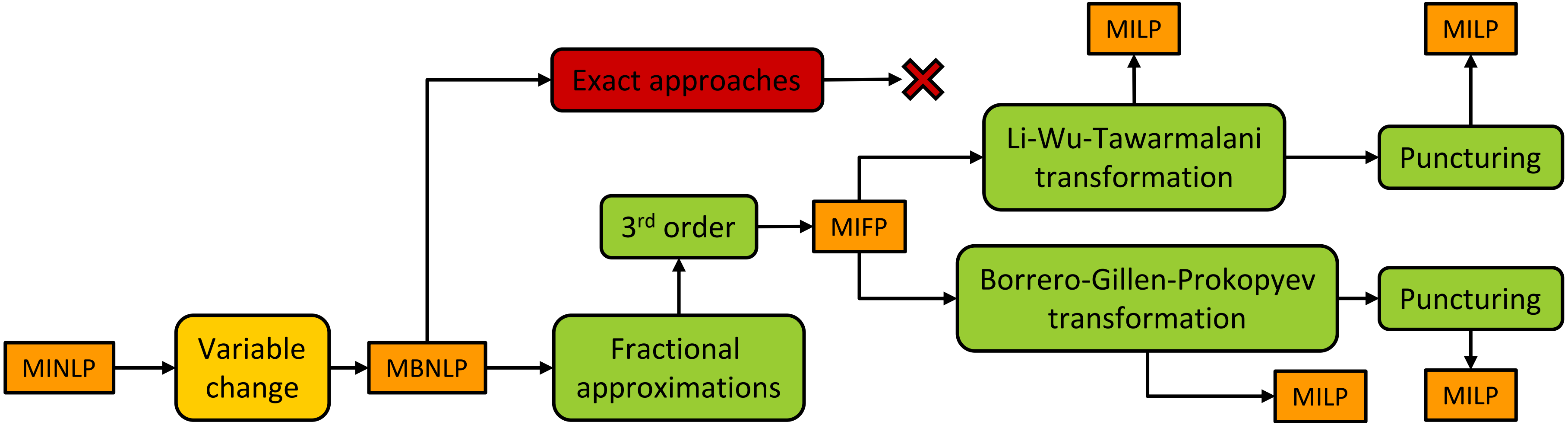

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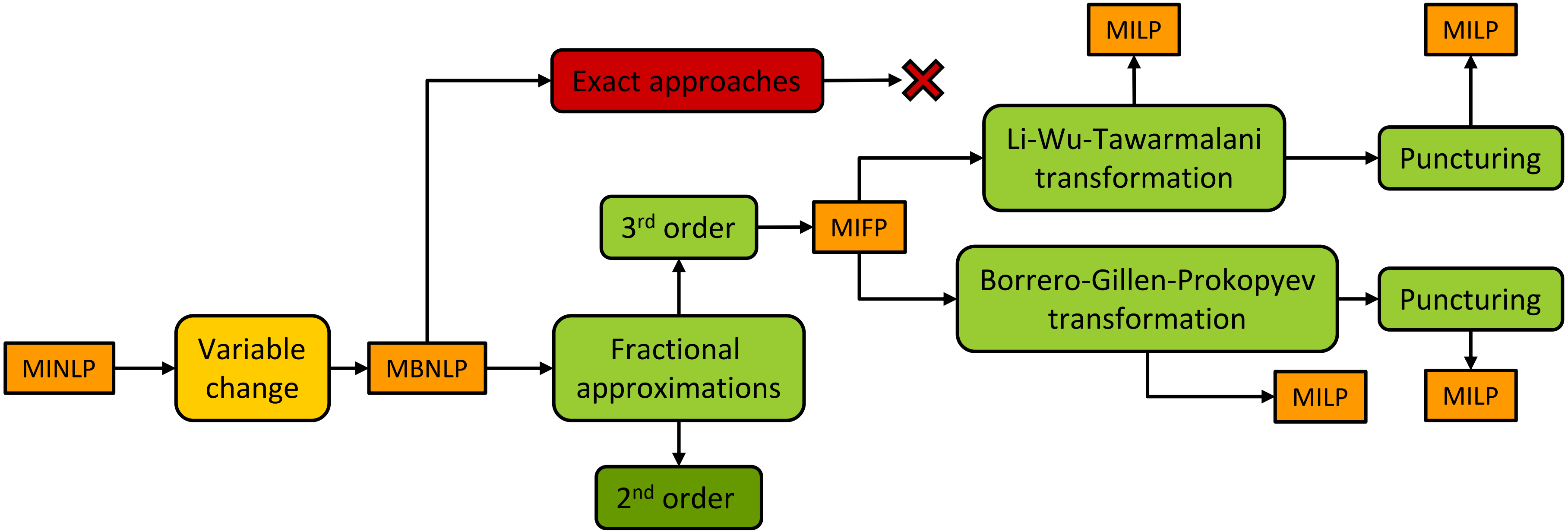

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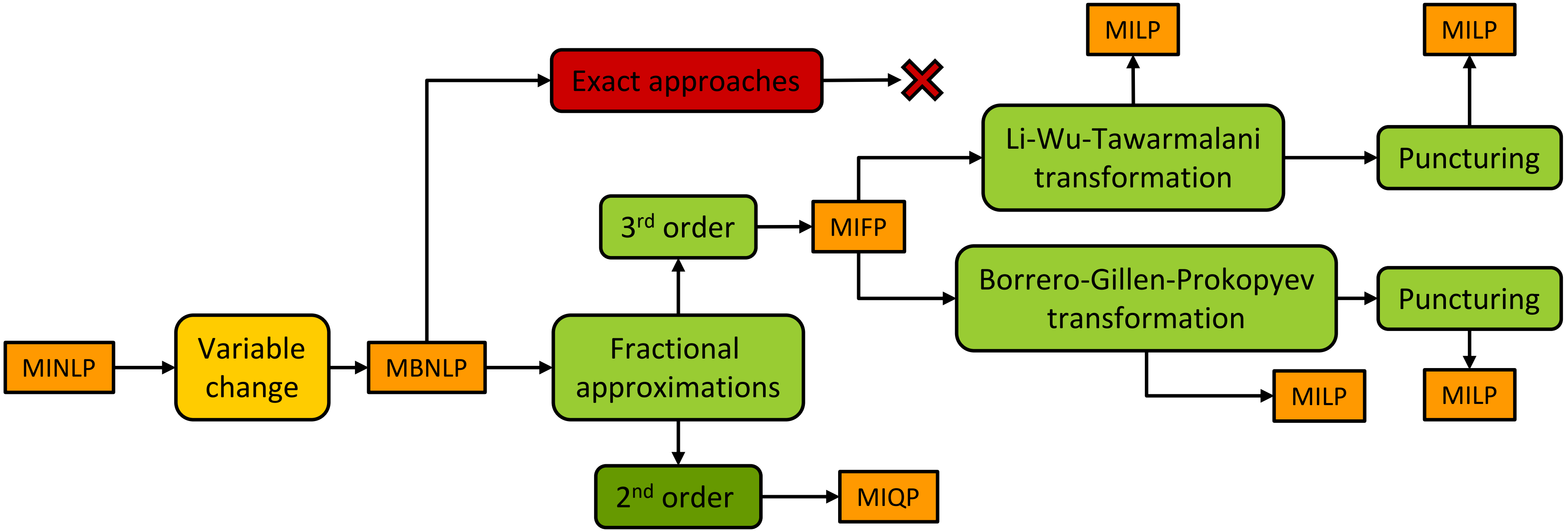
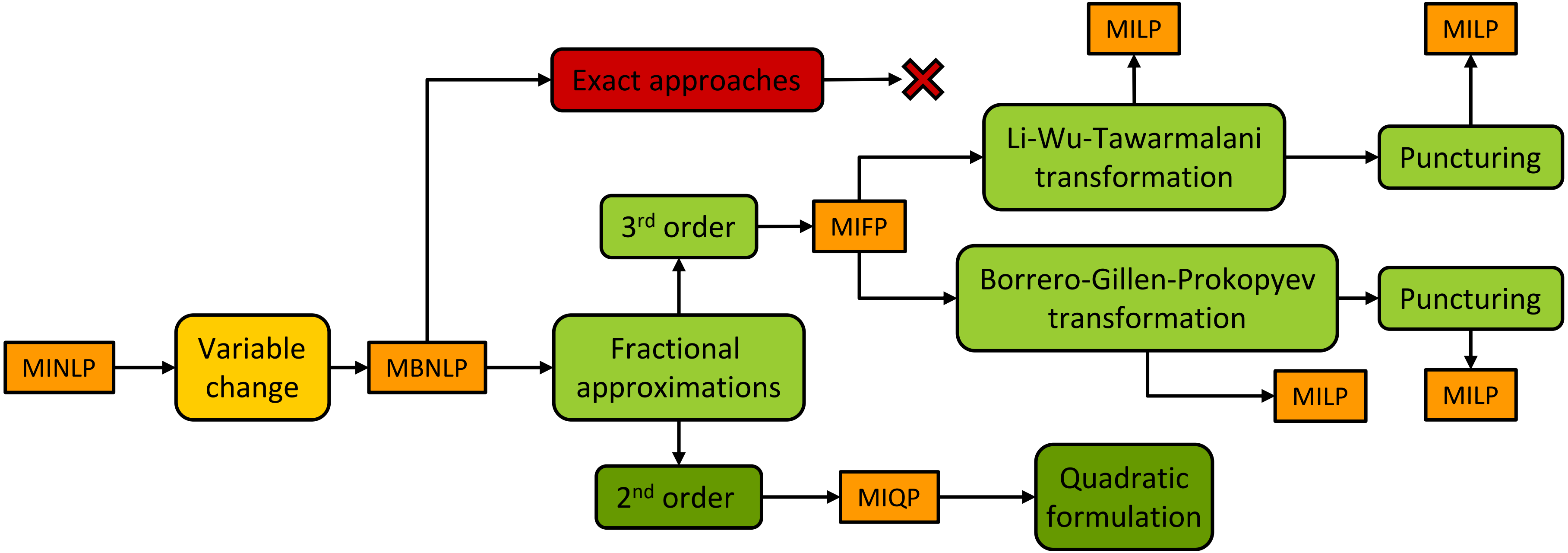


Solving the performance-maximizing FSSP



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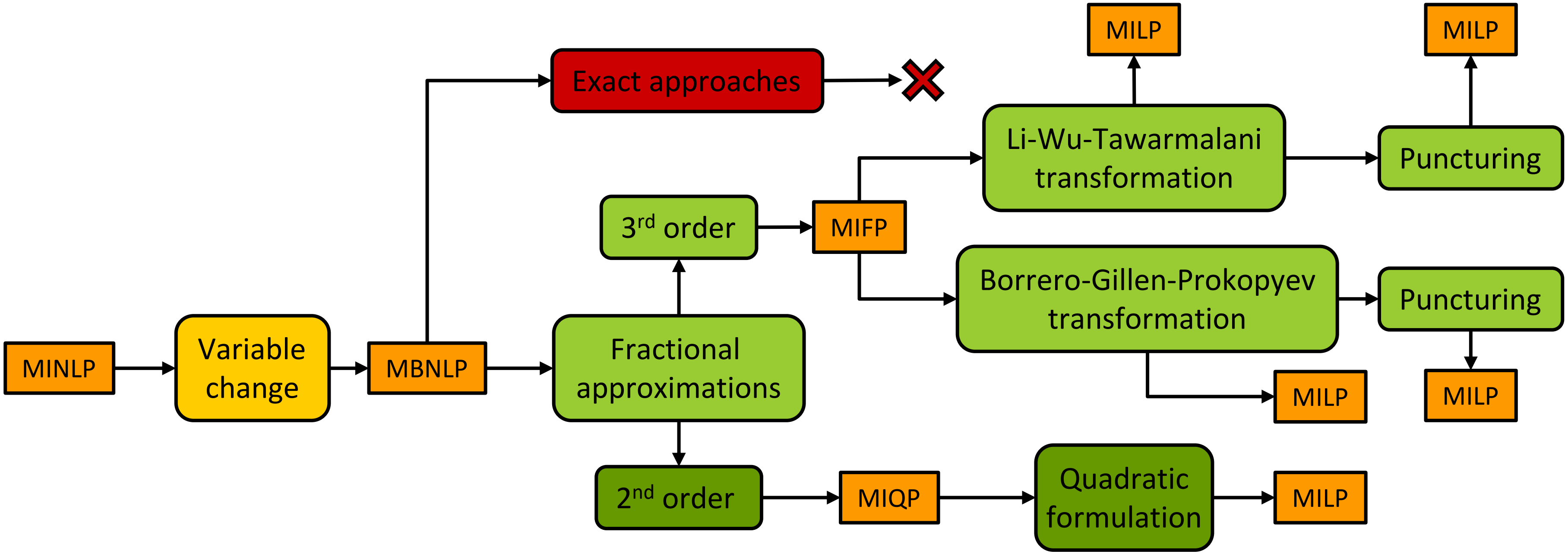

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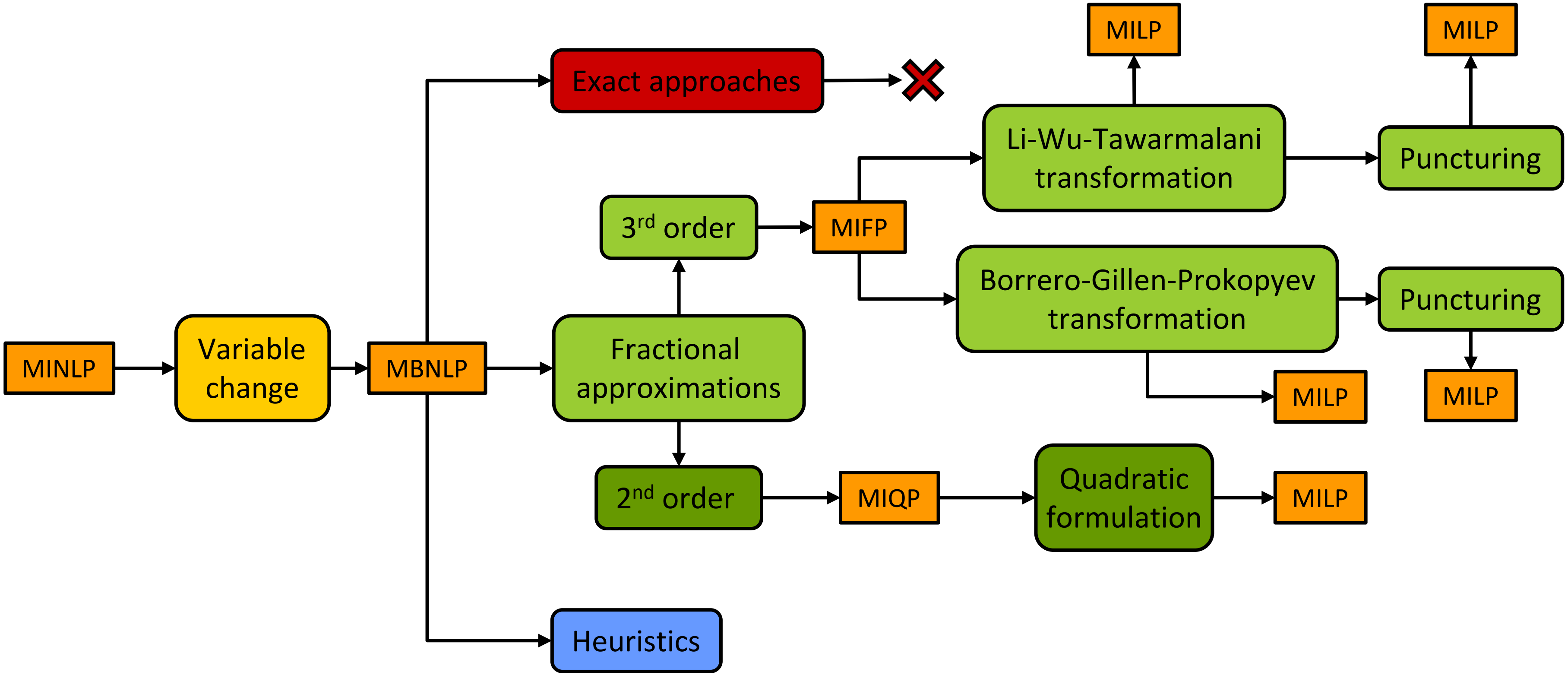

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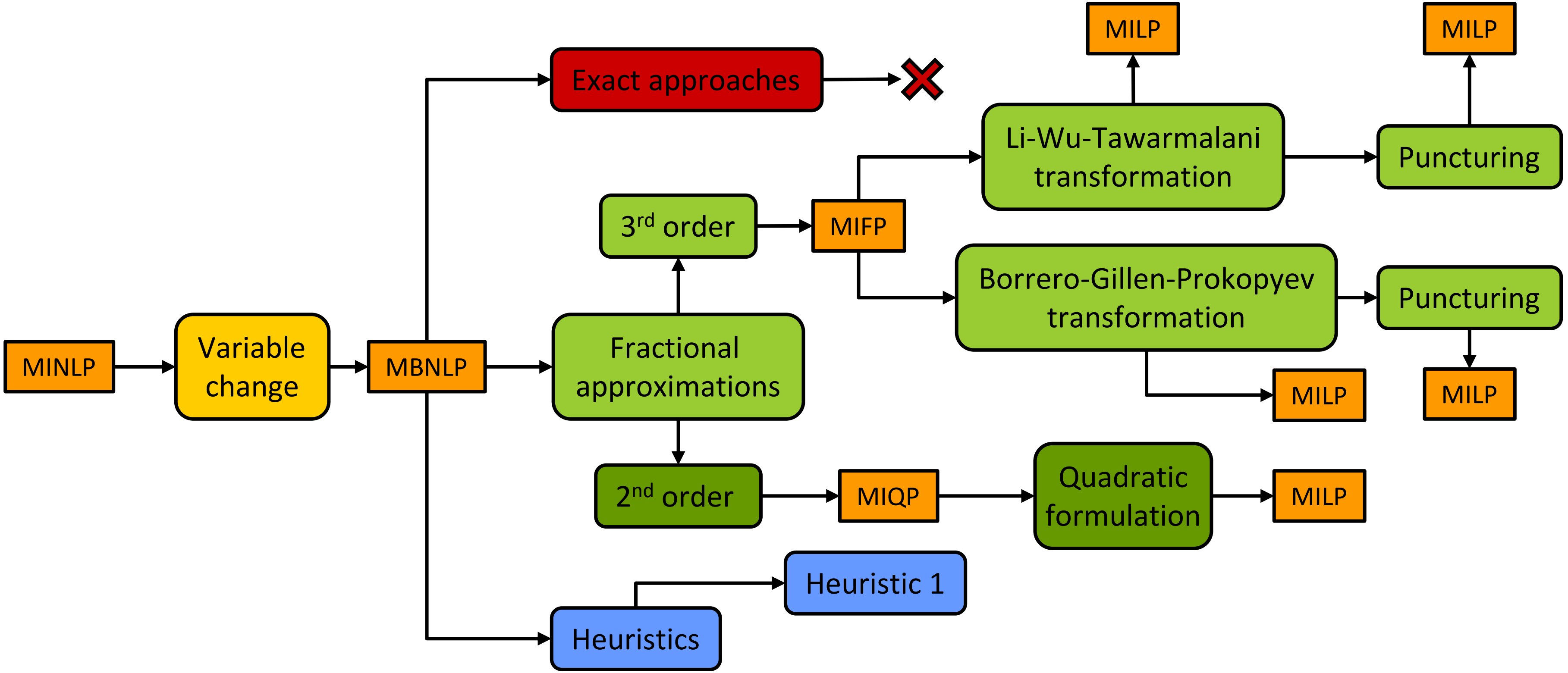

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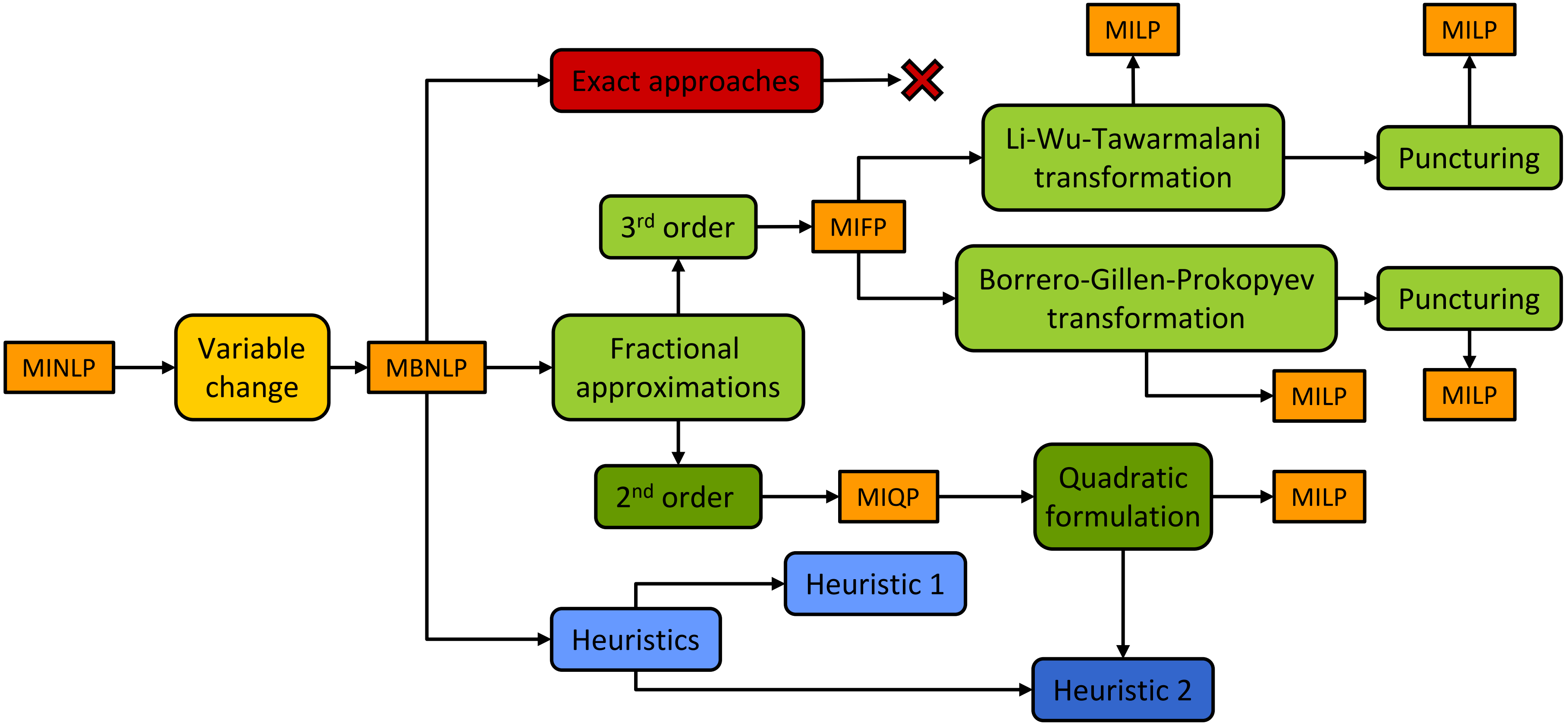
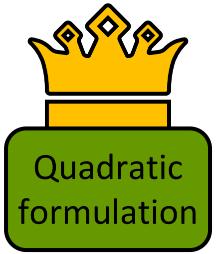


Evaluation of performance-maximizing FSSP approaches

- **LWT, BGP, and Punctured** formulations exhibit **long convergence times**
  - Over **15 minutes** for a network with $G = 80$ base stations
- **Quadratic** formulation can be solved **quickly**
  - Around **10 seconds** for $G = 450$
- **Solution qualities** of LWT, BGP, Punctured, Quadratic, and Heuristic 2 **are very similar**
- **Heuristic 1** is very fast but **inaccurate**
- **Conclusion:**
  - **Quadratic formulation** is the best option!



[MAJK21] A. Martínez Alba, S. Janardhanan, and W. Kellerer. “Enabling dynamically centralized RAN architectures in 5G and beyond”. *IEEE Transactions on Network and Service Management* (2021).

Operating-cost-minimizing FSSP

- Resulting operating-cost-minimizing FSSP formulation [MAJK21, GS+18b]:

$$\arg\min_{\mathbf{s}} K_{\mathrm{oper}}(\mathbf{s}) = \arg\min_{\mathbf{s}} K_{\mathrm{inst}} + K_{\mathrm{comp}}(\mathbf{a}) + K_{\mathrm{rout}}(\mathbf{f})$$

Subject to: **Flow conservation** **Link capacity**

- **Mixed-integer non-linear problem** → Can be straightforwardly converted to MILP

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Instantiating cost

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Instantiating cost

Computational cost

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Subject to: **Flow conservation** **Link capacity**

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Readiness-cost-minimizing FSSP

- Resulting readiness-cost-minimizing FSSP formulation [MAJK21]:

$$\arg\min_{\mathbf{s}} K_{\text{oper}}(\mathbf{s}) + K_{\text{rev}}(\mathbf{s}) = \arg\min_{\mathbf{s}} K_{\text{inst}} + K_{\text{comp}}(\mathbf{a}) + K_{\text{rout}}(\mathbf{f}) + \widehat{K}_{\text{rev}}\left(\sum_{u=1}^{U} \log\left(\log_2\left(1 + \frac{p_u}{\varsigma + \boldsymbol{I}_u(\mathbf{a})}\right)\right)\right)$$

Subject to: **Flow conservation** **Link capacity**

- The **performance-to-revenue function** can be modeled as a family of **linear functions**
- When using the **quadratic formulation** for performance optimization → MILP

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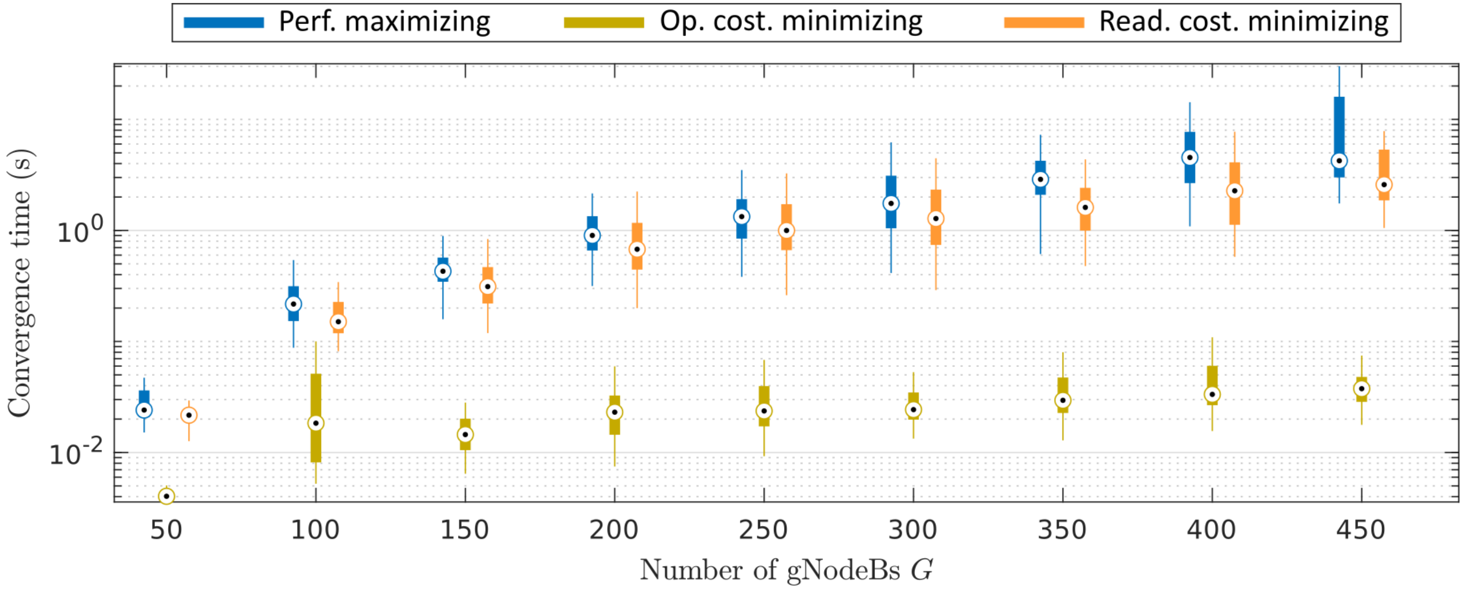
Evaluation of FSSP approaches: convergence time

- Operator-grade **computing platform**: 48x Intel Xeon E5 CPU cores
- The readiness-cost-minimizing approach converges in **less than 10 seconds** for $G \leq 450$ base stations



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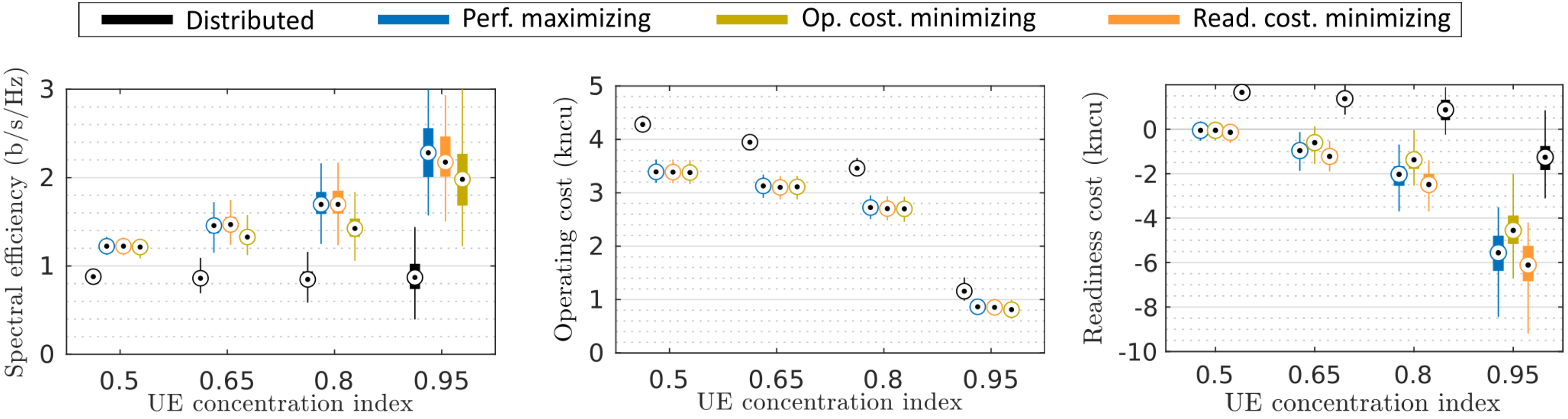
Evaluation of FSSP approaches: performance and cost

- W. r. t. a distributed deployment, the **readiness-cost-minimizing** approach achieves [MAJK21, MAPK21]:
  - 35%–145% higher **spectral efficiency**
  - 20%–30% lower **operating cost**
  - Being **profitable** for more uniformly-populated scenarios



[MAJK21] A. Martínez Alba, S. Janardhanan, and W. Kellerer. “Enabling dynamically centralized RAN architectures in 5G and beyond”. *IEEE Transactions on Network and Service Management* (2021).

[MAPK21] A. Martínez Alba, S. Pundt, and W. Kellerer. “Comparison of performance and cost-optimal functional splits in 5G and beyond”. *IEEE Global Communications Conference (GLOBECOM)*. 2021.

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Can we actually change the functional split?

- We want to be able to change the functional split **in real time**

- Considered 4G/5G **software platforms:**
  - OpenAirInterface [Nik+14]
  - srsLTE/srsRAN [SRSa]

- Considered **functional splits:**
  - **Centralized split:** MAC-PHY
    - Coordinated scheduling possible, high fronthaul traffic
  - **Distributed split:** PDCP-RLC
    - No interference mitigation, low fronthaul traffic

[Nik+14] N. Nikaein, et al. "OpenAirInterface: A flexible platform for 5G research". *ACM SIGCOMM Computer Communication Review 44.5* (2014), pp. 33–38.

[SRSa] SRS. *srsRAN - Your own mobile network*. URL: https://srsran.com/

Implementing an adaptive functional split

- **Challenges:**
  - Minimize signaling overhead
  - Minimize function downtime

[MAGVK19a] A. Martínez Alba, J. H. Gómez Velásquez, and W. Kellerer. "An adaptive functional split in 5G networks". *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE. 2019, pp. 410–416.

Implementing an adaptive functional split

- **Challenges:**
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- **Strategies for function migration:**
  - **Virtualization-based:** high overhead signaling and downtime
  - **Replication-based:** low overhead signaling and downtime

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  - **Virtualization-based:** high overhead signaling and downtime
  - **Replication-based:** low overhead signaling and downtime

- **State transfer:**
  - Identifiers, timers, [sub]frame numbers, etc. → **Small and easy to transfer**
  - Content of the buffers → **Drop or soft transfer**

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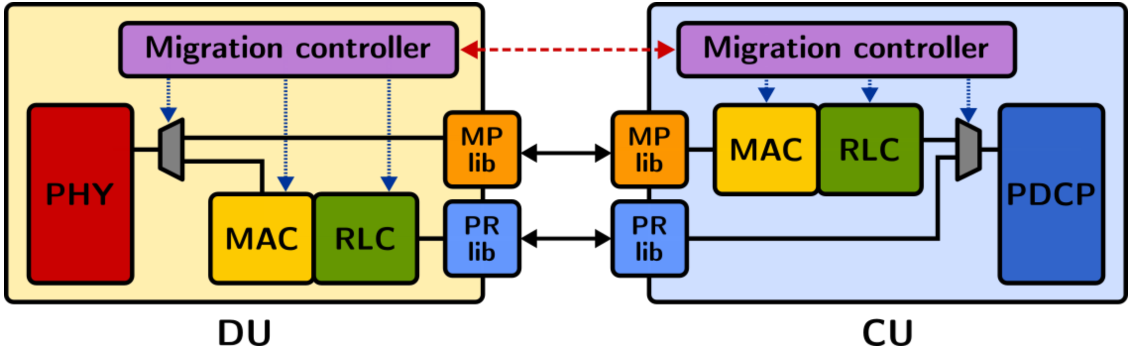
Replication-based dynamic functional split

- A **migration controller** switches functions on or off when requested
- **Migration types:**
  - **Soft migration:** buffers drain normally → No packet losses
  - **Hard migration:** packets dropped → No delay
  - **Custom migration:** soft migration with hard deadline



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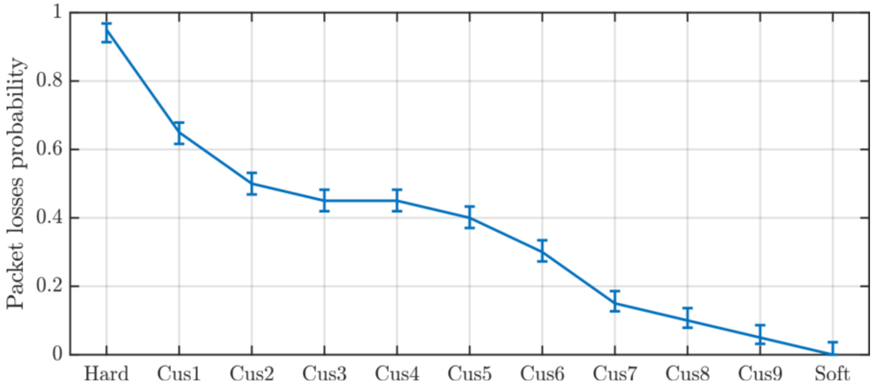
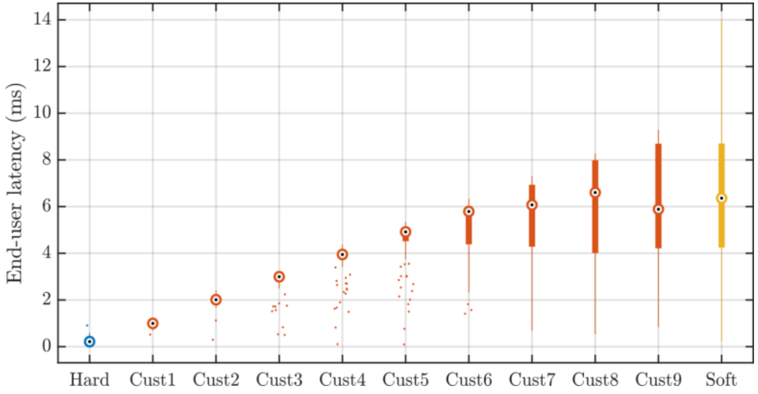
Performance of dynamic functional split adaptation

- **Soft migrations:**
  - **0% packet losses**
  - Up to **15 ms** additional end-to-end latency
- **Hard migrations:**
  - **95% packet losses**
  - No additional end-to-end latency





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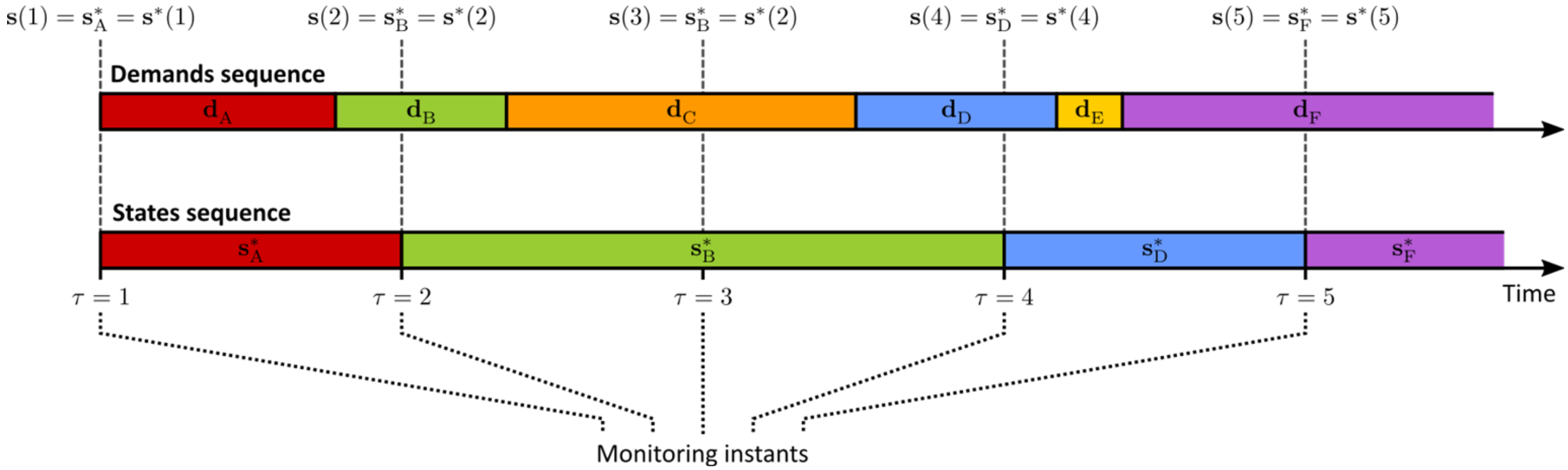
When should we change the functional split?

- We can **periodically monitor** the optimality of our current state [MAK21]
- If the state is not optimal, **should we change?**
- We need **adaptation rules (strategies)** to achieve near-optimal performance



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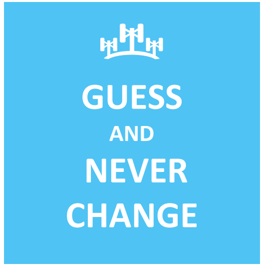
Adaptation strategies (I)

- **Uniform-static strategy:**
  - Static functional split
  - Minimizes readiness cost assuming uniform UE distribution



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- **Mean-static strategy:**
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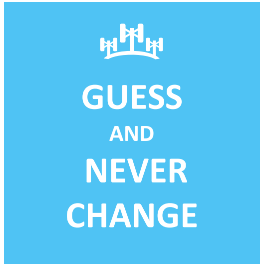

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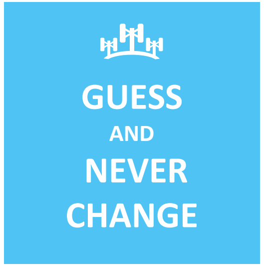

- **Mean-static strategy:**
  - Static functional split
  - Minimizes readiness cost for actual UE distribution

- **Impatient strategy:**
  - The state changes whenever a new optimal state is detected
  - Minimal readiness cost, maximal action cost

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Adaptation strategies (II)

- **Random deferral strategy:**
  - Decision to change to the optimal state is randomly chosen (with probability φ)
  - Probability φ can be chosen to be optimal → **Optimal random deferral strategy**

GAMBLE
AND
CHANGE

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Adaptation strategies (II)

- **Random deferral strategy:**
  - Decision to change to the optimal state is randomly chosen (with probability φ)
  - Probability φ can be chosen to be optimal → **Optimal random deferral strategy**

- **Dynamic programming strategy:**
  - Future demands are assumed to be known
  - Dynamic programming is used to get optimal sequence of states
  - Unfeasible, but it serves as a lower bound

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Adaptation strategies (III)

- **Greedy strategy:**
  - The accumulated cost gap between current and optimal state is monitored
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Adaptation strategies (III)

- **Greedy strategy:**
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- **Adaptive threshold strategy:**
  - Generalized greedy strategy with iterative threshold for state change

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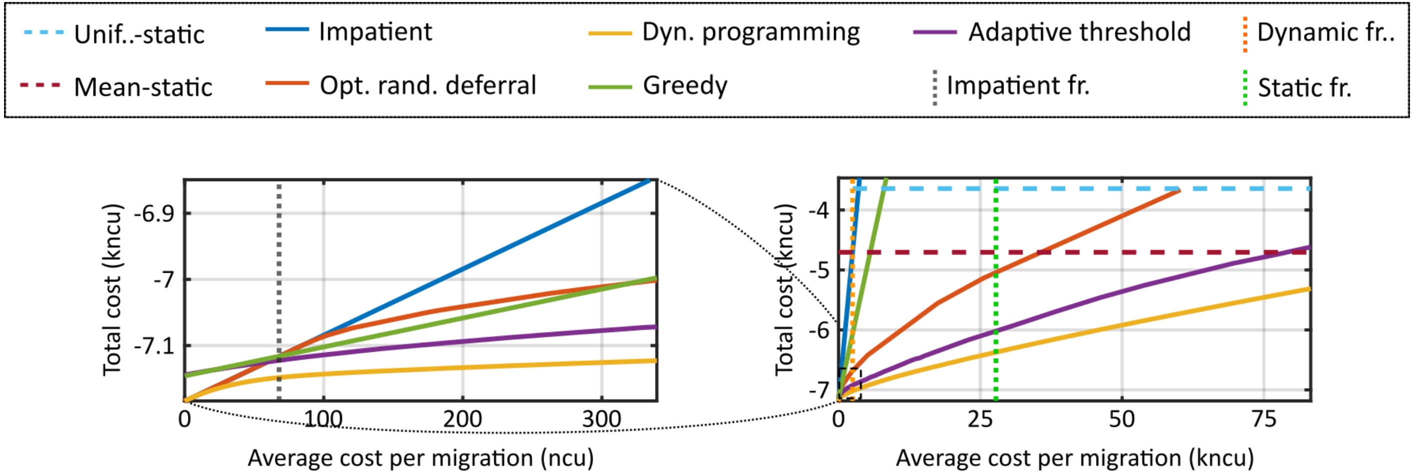
Performance of adaptation strategies

- Best adaptation strategy depends on **how costly migrations are**
- For **low migration costs, impatient** is optimal!
- For **higher migration costs**, **adaptive threshold** yields low readiness cost



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Is it worthwhile to change dynamically?

- Assuming a **conservative performance-to-revenue function** and the **adaptive threshold strategy**

- **Uniformly distributed users:**
  - **Average cost per migration** to beat static strategies: up to **5%–8% of static readiness cost**

- **Mixed distribution of users:**
  - **Average cost per migration** to beat static strategies: up to **110%–270% of static readiness cost**

- **Highly concentrated users:**
  - **Average cost per migration** to beat static strategies: up to **230%–500% of static readiness cost**

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Conclusions and Outlook

- We study the possibility of **dynamically changing the functional split** of a 5G radio access network with the intention **of improving user performance**, **reducing operating cost**, and **enhancing network revenue**

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- We formulate the **functional split selection problem** and propose a fast and effective approach to solve it

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- We present a dedicated **cost model for flexible softwarized networks** that can be to any dynamically adapting communication network

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- We demonstrate a **proof-of-concept implementation** of a dynamically adaptive RAN that can change its functional split in less than 15 ms
- We evaluate multiple **adaptation strategies** and select one of them that leads to profitable dynamically adapting radio access networks

References

[3GP17] 3GPP. Study on new radio access technology: Radio access architecture and interfaces. Technical Report (TR) 38.801. Version 14.0.0. 3rd Generation Partnership Project (3GPP), Mar. 2017.

[3GP21a] 3GPP. 5G; NG-RAN; Architecture description. Technical Specification (TS) 38.401. Version 16.6.0. 3rd Generation Partnership Project (3GPP), July 2021.

[Bab+20] P. Babarczi, M. Klügel, A. Martínez Alba, M. He, J. Zerwas, P. Kalmbach, A. Blenk, and W. Kellerer. "A mathematical framework for measuring network flexibility". *Computer Communications 164* (2020), pp. 13–24.

[Che+14a] A. Checko, et al. "Cloud RAN for mobile networks–A technology overview". *IEEE Communications surveys & tutorials 17.1* (2014), pp. 405–426.

[Che+16a] A. Checko, et al. "Evaluating C-RAN fronthaul functional splits in terms of network level energy and cost savings". *Journal of Communications and Networks 18.2* (2016), pp. 162–172.

[Cis20] Cisco public. Cisco annual internet report (2018–2023). *White Paper* (2020).

[GAO17] R. A. Gustav A. Oertzen. On the Technical Future of the Telecommunications Industry. *White Paper*. Oliver Wyman, (2017).

[GS+18b] A. Garcia-Saavedra, et al. "Joint optimization of edge computing architectures and radio access networks". *IEEE Journal on Selected Areas in Communications 36.11* (2018), pp. 2433–2443.

[KS17] G. P. Koudouridis and P. Soldati. "Spectrum and network density management in 5G ultra-dense networks". *IEEE Wireless Communications 24.5* (2017), pp. 30–37

References

[MA+21] A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer. "Modeling the Cost of Flexibility in Communication Networks". *IEEE Conference on Computer Communications (INFOCOM).* IEEE. 2021.

[MAGVK19a] A. Martínez Alba, J. H. Gómez Velásquez, and W. Kellerer. "An adaptive functional split in 5G networks". *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS).* IEEE. 2019, pp. 410–416.

[MAJK21] A. Martínez Alba, S. Janardhanan, and W. Kellerer. "Enabling dynamically centralized RAN architectures in 5G and beyond". *IEEE Transactions on Network and Service Management* (2021).

[MAK19a] A. Martínez Alba and W. Kellerer. "A Dynamic Functional Split in 5G Radio Access Networks". *IEEE Global Communications Conference (GLOBECOM).* IEEE. 2019, pp. 1–6.

[MAK21] A. Martínez Alba and W. Kellerer. "Dynamic Functional Split Adaptation in Next-Generation Radio Access Networks*". IEEE Transactions on Network and Service Management* (2021). [Under review].

[MAPK21] A. Martínez Alba, S. Pundt, and W. Kellerer. "Comparison of performance and cost-optimal functional splits in 5G and beyond". *IEEE Global Communications Conference (GLOBECOM)*. 2021.

[Nik+14] N. Nikaein, et al. "OpenAirInterface: A flexible platform for 5G research". *ACM SIGCOMM Computer Communication Review 44.5* (2014), pp. 33–38.

[SRSa] SRS. *srsRAN - Your own mobile network*. URL: https://srsran.com/

Thank you!