DREAMIN: Channel-Aware Inter-Slices Radio Resource Scheduling for Efficient SLA Assurance

Daniel Campos[1], Gabriel M. Almeida[1], Mohammad J. Abdel-Rahman[2], Kleber V. Cardoso[1]

[1]Institute of Informatics (INF), Universidade Federal de Goiás (UFG), Goiânia, Brazil,

[2]School of Computing Sciences (SCC), Princess Sumaya University for Technology (PSUT), Amman, Jordan.

E-mail: {danielcampossilva, gabrielmatheus, kleber}@inf.ufg.br[1] E-mail: m.AbdelRahman@psut.edu.Jo[2]

Agenda

1. Introduction and related work
2. System model and problem formulation
3. DREAMIN scheduler
4. Evaluation
5. Conclusion and future work

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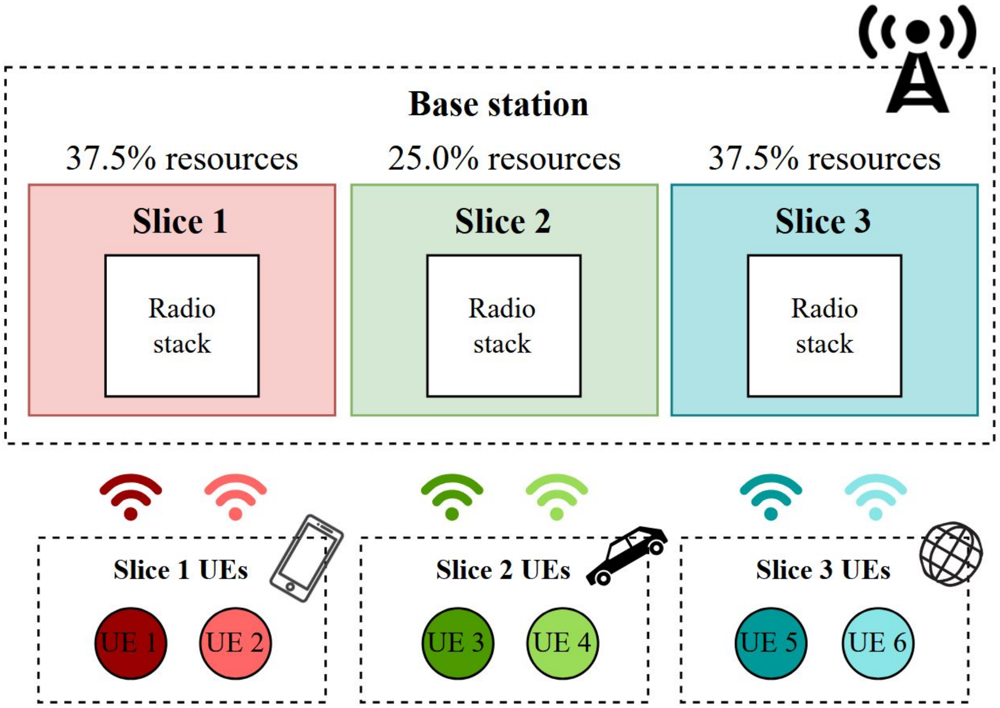
Network slicing

Network slicing isolates resources among groups of User Equipments (UEs) who have similar service requirements

Radio resource scheduling determines the UE data transmission directly

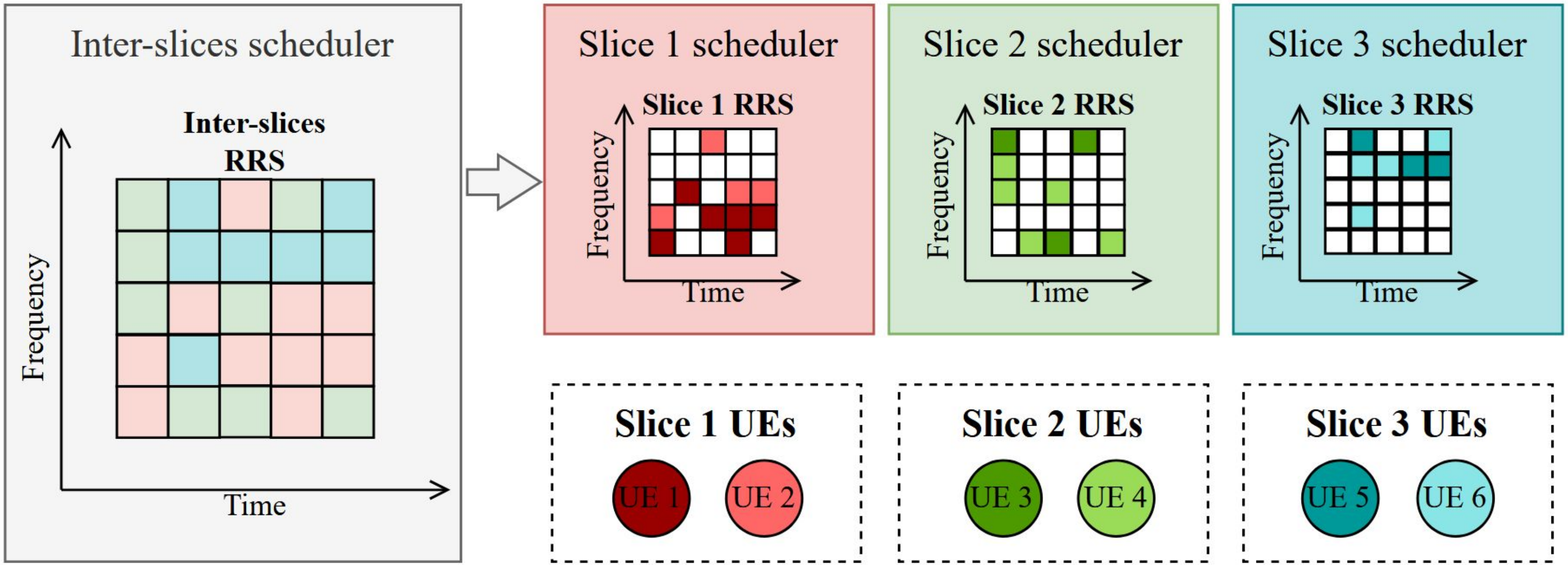
We schedule **resource block groups** (RBGs) at every **transfer time interval** (TTI)



Radio Resource Scheduling (RRS) with network slicing

Each slice has a **intra-slice scheduler** to distribute resources among its UEs

The inter-slice scheduler can only **schedule resources among slices**, not UEs



Service Level Agreement (SLA)

The scheduler main goal is to **ensure SLA**

Each slice specifies its own SLA: a set of required values for network metrics

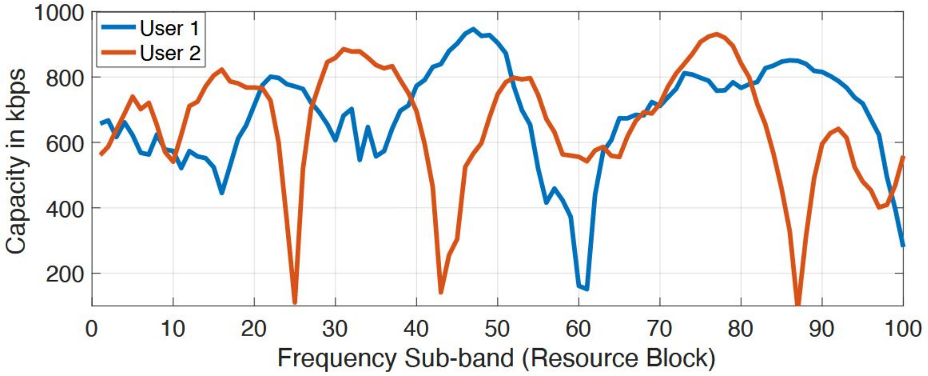
- **Latency**: 15 ms at maximum
- **Instantaneous capacity**: 1 Mbps at minimum
- **Long-term capacity**: 8 Mbps at minimum

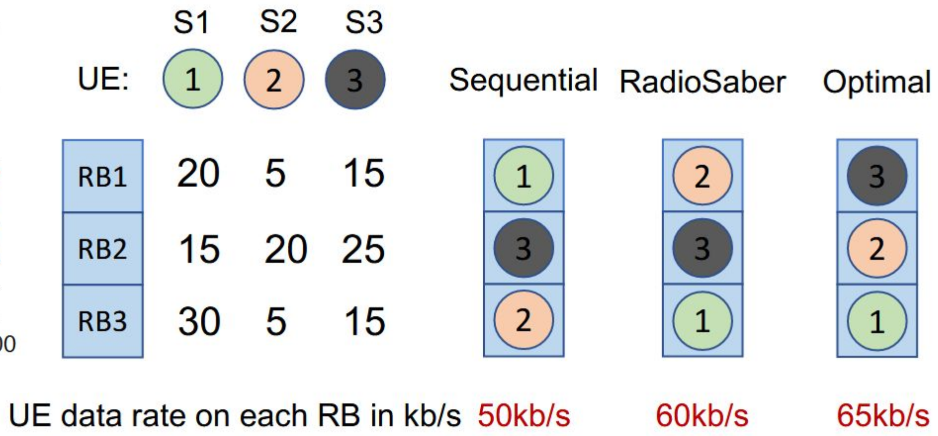
Channel-awareness

The capacity reached by a user may vary depending on **which RBG** it receives

The scheduler **chooses** not only how many RBGs, but **which RBGs** are allocated

An inter-slice scheduler must **predict the intra-slice scheduler** to be channel-aware





Source: [1] Y. Chen, R. Yao, H. Hassanieh, e R. Mittal, “Channel-Aware 5G RAN Slicing with Customizable Schedulers”.

Related work

[1] RadioSaber scheduler

- Has a **static quota of RBGs** for each slice
- Always allocates the RBG-Slice with higher capacity - as **maximum-throughput**
- Evaluates the scheduler in a **trace-driven simulation**
  - Leverages a Channel Quality Indicator **(CQI) dataset**

[2] Intent-aware Deep Reinforcement Learning (DRL) scheduler

- Based on **intent-drift**: normalized distance between network metric and SLA requirement
  - **Zero if meets** the requirement
  - We call it **SLA-drift (SLAd)** to broaden the term
- Develops a DRL agent whose **action is the ratio of resources** for each slice
  - **Non-channel-aware**
  - If changed the number of slices, needs to be **retrained**

Related work

- Most related work **allocate 100% resources** and **maximize/minimize network metrics**
  - This leads to **overprovisioning UEs**
  - **Minimizing allocated RBGs** in low-demand scenarios can reduce power consumption and **improve energy efficiency**

The problem we are solving

Inter-slice Radio Resource Scheduling

- Channel-aware
- Minimize SLAd
- Minimize resource usage

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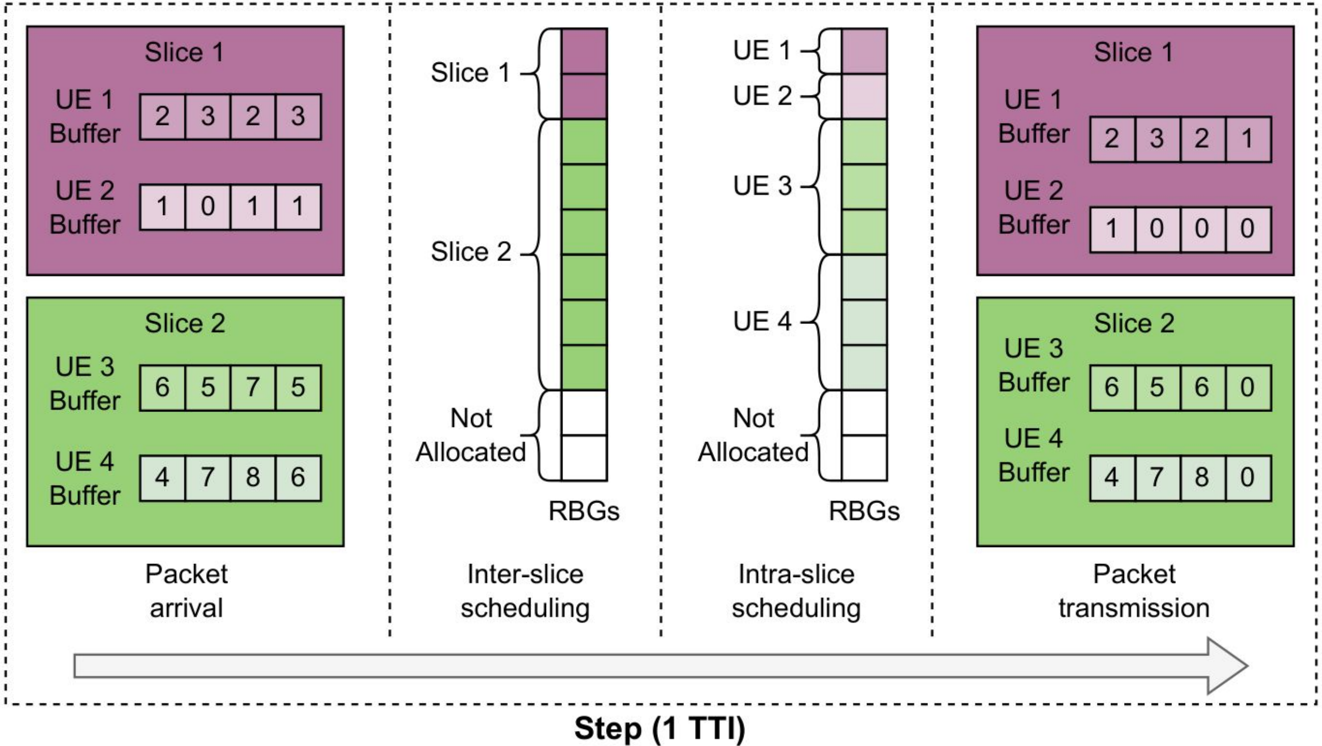
System model

The system is represented as a **sequence of TTIs**



Sets, decision variables, and capacity

Sets

TTIs $\mathcal{T} = \{0, \ldots, |\mathcal{T}| - 1\}$

RBGs $\mathcal{R} = \{r_1, \ldots, r_{|\mathcal{R}|}\}$

Slices $\mathcal{S} = \{s_1, \ldots, s_{|\mathcal{S}|}\}$

Users (per-slice) $\mathcal{U}_s = \{u_j, \ldots, u_{j+|\mathcal{S}|-1}\}$

Users $\mathcal{U} = \bigcup_{s \in \mathcal{S}} \mathcal{U}_s$

SLA metrics (per-slice) $\mathcal{M}_s \subseteq \{CAP, LTC, LAT\}$

Decision variables

$$\rho^u_{r,t} \in \{0, 1\}$$

Capacity

$$c^u_t = \sum_{r \in \mathcal{R}} \rho^u_{r,t} \cdot C^u_{r,t}$$

Inputs

Arrived packets A_t^u

Buffer size (packets) Z_s

TTI length (seconds) I

Packet size (bits) P_s

Maximum latency (TTIs) L_s

Achievable capacity (bits/s) $C_{r,t}^u$

Time window (TTIs) for historical metrics TW

Adjusted time window (TTIs) for the first TTIs in the model

$$AW_t = \begin{cases} t+1, & \text{if } t < TW \\ TW, & \text{if } t \geq TW \end{cases}$$

Inputs

Initial historical capacity (bits/s)	y_u
SLA-required instantaneous capacity (bits/s)	Q_s^{CAP}
SLA-required long-term capacity (bits/s)	Q_s^{LTC}
SLA-required latency (TTIs)	Q_s^{LAT}
Weight of metric m in the slice's SLA	W_s^m
Weight of the slice	W_s

Buffer modeling

Packets in the buffer at the beginning of the TTI

$$b_t^u = \begin{cases} 0, & \text{if } t = 0 \\ b_{t-1}^u + A_{t-1}^u - k_{t-1}^u - df_{t-1}^u - dl_{t-1}^u, & \text{if } t > 0 \end{cases}$$

Packets dropped due to buffer full

$$df_t^u = \max(0, b_t^u + A_t^u - Z_u)$$

Fully sent packets

$$k_t^u = \min\left(\left\lfloor \frac{c_t^u \cdot I}{P_u} + \bar{k}_{t-1}^u \right\rfloor, b_t^u + A_t^u - df_t^u\right)$$

Partially sent packets

$$\bar{k}_t^u = \begin{cases} 0, & \text{if } b_{t+1}^u = 0 \text{ or } dl_t^u > 0 \\ \frac{c_t^u \cdot I}{P_u} - k_t^u, & \text{otherwise} \end{cases}$$

Buffer modeling

Packets with latency l in buffer at the end of TTI t

$$p_{t,l}^{u} = \max\left(0, b_{t-l}^{u} + A_{t-l}^{u} - df_{t-l}^{u} - \sum_{t'=t-l}^{t} k_{t'}^{u} - \sum_{t'=t-l}^{t-1} dl_{t'}^{u}\right)$$

Packets dropped due to maximum latency achieved

$$dl_{t}^{u} = p_{t,L_s}^{u}$$

SLA metrics

Instantaneous capacity (CAP)

$$CAP_t^u = c_t^u$$

Long-term capacity (LTC)

$$LTC_t^u = \frac{\sum_{t'=t-AW_t+1}^{t} c_{t'}^u}{AW_t}$$

Latency (LAT)

$$LAT_{t,s}^u = \max_{l \in 0,\ldots,L_s} (l \cdot (p_{t,l}^u > 0))$$

Metric SLAd

CAP SLAd

$$f_{t,s}^{CAP,u} = \begin{cases} \frac{Q_s^{CAP} - CAP_t^u}{Q_s^{CAP}}, & \text{if } CAP_t^u < Q_s^{CAP} \\ 0, & \text{if } CAP_t^u \geq Q_s^{CAP} \end{cases}$$

LTC SLAd

$$f_{t,s}^{LTC,u} = \begin{cases} \frac{Q_s^{LTC} - LTC_t^u}{Q_s^{LTC}}, & \text{if } LTC_t^u < Q_s^{LTC} \\ 0, & \text{if } LTC_t^u \geq Q_s^{LTC} \end{cases}$$

LAT SLAd

$$f_{t,s}^{LAT,u} = \begin{cases} \frac{LAT_{t,s}^u - Q_s^{LAT}}{L_s - Q_s^{LAT}}, & \text{if } LAT_t^u > Q_s^{LAT} \\ 0, & \text{if } LAT_t^u \leq Q_s^{LAT} \end{cases}$$

Aggregated SLAd

User SLAd

$$f^u_{t,s} = \sum_{m \in \mathcal{M}_s} f^{m,u}_{t,s} \cdot W^m_s$$

Slice SLAd

$$f_{t,s} = \frac{1}{|\mathcal{U}_s|} \sum_{u \in \mathcal{U}_s} f^u_{t,s}$$

Overall SLAd at base station

$$f_t = \sum_{s \in \mathcal{S}} f_{t,s} \cdot W_s$$

Objective function

Scenario indicator - scarce or plentiful

$$a_t = \begin{cases} 0, & \text{if } f_t = 0 \\ 1, & \text{if } f_t > 0 \end{cases}$$

Primary objective: minimize SLAd

Secondary : minimize resource usage

$$\underset{\rho^u_{r,t}}{\text{minimize}} \quad \sum_{t \in \mathcal{T}} \left(a_t(1 + f_t) + (1 - a_t)\frac{1}{|\mathcal{R}|} \sum_{u \in \mathcal{U}} \sum_{r \in \mathcal{R}} \rho^u_{r,t} \right)$$

Constraints

Allocate each RBG to at most 1 UE at the same TTI

$$\sum_{u \in \mathcal{U}} \rho^{u}_{r,t} \leq 1, \qquad \forall r \in \mathcal{R}, t \in \mathcal{T}$$

Historical capacity (calculated as an EWMA)

$$h^{u}_{t} = \begin{cases} y_u, & \text{if } t = 0 \\ (1 - \frac{1}{TW})h^{u}_{t-1} + \frac{1}{TW} c^{u}_{t-1}, & \text{if } t > 0 \end{cases}$$

Proportional Fairness model: always choose the UE with highest coefficient

$$\sum_{u' \in \mathcal{U}_s} \frac{C^{u'}_{r,t}}{h^{u'}_{t}} \cdot \rho^{u'}_{t,r} \geq \frac{C^{u}_{r,t}}{h^{u}_{t}} \cdot \sum_{u' \in \mathcal{U}_s} \rho^{u'}_{t,r},$$

$$\forall s \in \mathcal{S}, u \in \mathcal{U}_s, r \in \mathcal{R}, t \in \mathcal{T}$$

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Proposed heuristic

Drift and REsource Allocation MINimization (DREAMIN) scheduler

- Fast **greedy** algorithm **approximating the optimal** solution in polynomial time
- As RadioSaber [1], checks through **every possible RBG-slice** allocation
- Chooses the one **most reducing the overall SLAd**
- **Stops** when
  - The overall SLAd is zero - **plentiful scenario**
  - All RBGs are allocated - **scarce cenario**
- Has the same complexity of RadioSaber [1]: $O(|\mathcal{R}|^2 \cdot |\mathcal{S}|)$
  - Assuming SLAd calculation in constant time - with the use of data structures

DREAMIN scheduler

Algorithm 1: DREAMIN allocation process.

Data: $\mathcal{R}$, $\mathcal{S}$, $\mathcal{U}$, $C^{u}_{r,t}$, t
Result: RBGs allocated for each slice $s \in \mathcal{S}$

for $s \in \mathcal{S}$, **do**
  allocation[s] $\leftarrow \emptyset$
for $u \in \mathcal{U}$ **do**
  cap[u] $\leftarrow 0$
  slad[u] $\leftarrow$ slad_for_cap(u, 0)
available_rbgs $\leftarrow R$
while |available_rbgs| > 0 **do**
  if $\sum_{u \in \mathcal{U}}$ slad[u] = 0 **then**
    return allocation
  best_reduction $\leftarrow 0$
  for $r \in$ available_rbgs **do**
    for $s \in \mathcal{S}$ **do**
      $u \leftarrow$ intra_sched(s, r)
      reduction $\leftarrow$ slad[u] - slad_for_cap(u, cap[u] + $C^{u}_{r,t}$)
      if best_reduction $<$ reduction / $|\mathcal{U}_s|$ * W_s **then**
        best_reduction $\leftarrow$ reduction / $|\mathcal{U}_s|$ * W_s
        $u^* \leftarrow u$
        $r^* \leftarrow r$
        $s^* \leftarrow s$
  cap[u^*] $\leftarrow$ cap[u^*] + $C^{u^*}_{r^*,t}$
  slad[u^*] $\leftarrow$ slad_for_cap(u^*, cap[u^*])
  available_rbgs $\leftarrow$ available_rbgs $\setminus \{r^*\}$
  allocation[s^*] $\leftarrow$ allocation[s^*] $\bigcup \{r^*\}$
return allocation

Initializing data structures

Plentiful scenario

Selecting the allocation that most reduces SLAd

Updating data structures

Scarce scenario

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Simulation and parameters

Channel data: RadioSaber traces dataset [1]

- 475 TTIs
- 512 PRBs (100 MHz)

3GPP TS 38.214 Table 5.2.2.1-2 maps CQI to spectral efficiency

Slice	GBR	Non-GBR	DC-GBR
5QI	2	80	86
Service	Conversational video	Augmented reality	V2X messages
Demand/UE	12 Mbps[5]	50 Mbps[6]	10 Mbps[7]
Packet size P_u	256 bytes	1024 bytes	128 bytes
Max. latency L_u	200 ms	100 ms	3 ms
Weight W_s	0.333	0.333	0.333
Q_s^{CAP} (W_s^{CAP})	12 Mbps (0.5)	-	10 Mbps (1.0)
Q_s^{LTC} (W_s^{LTC})	-	50 Mbps (0.5)	-
Q_s^{LAT} (W_s^{LAT})	130 ms (0.5)	8 ms (0.5)	-

$Z_s = 256$ Kbits $\quad TW = 10$ TTIs

Each experiment is executed 20 times (with different randomness seeds)

Baselines

- **RadioSaber (RS)** [1] - channel-aware, maximizing throughput, fixed slice quotas

- **Weighted Round-Robin (RS)** - non-channel-aware, “random”, fixed slice quotas

- **Approximated solution (APPR)**: solved with IBM’s Constraint Programming Optimizer
  - Only evaluated in very small scenarios
  - Even in small scenarios, we can not obtain the optimality certificate for the solution
  - Limited to 1 hour running the solver

Scenarios

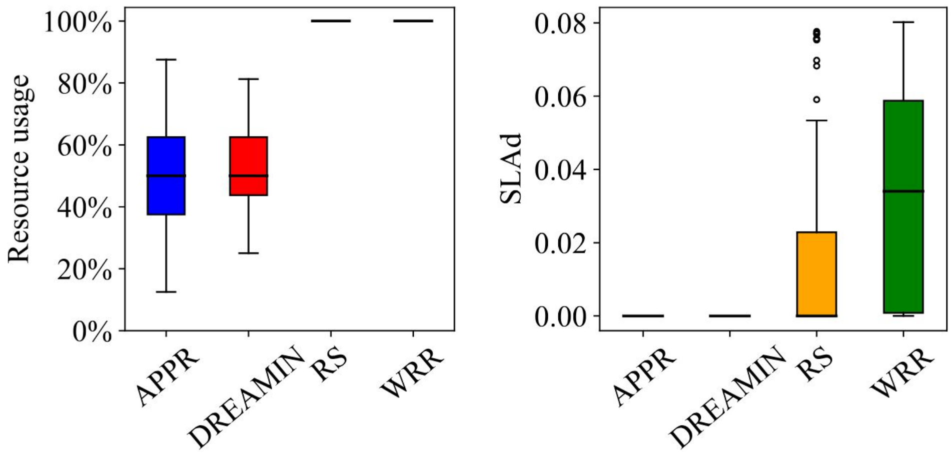
- **Small–scale**
  - **10 TTIs**
  - **8 RBGs with 32 PRBs/RBG** (same bandwidth, large granulosity on allocation)
  - **1 UE/slice**
  - **Plentiful x Scarce scenarios: requirements 3x more restrict**

- **Large–scale**
  - **475 TTIs**
  - **128 RBGs with 4 PRBs/RBG** (same bandwidth, large granulosity on allocation)
  - **Plentiful x Scarce scenarios:** 1 UE/slice for plentiful, 3 UEs/slice for scarce

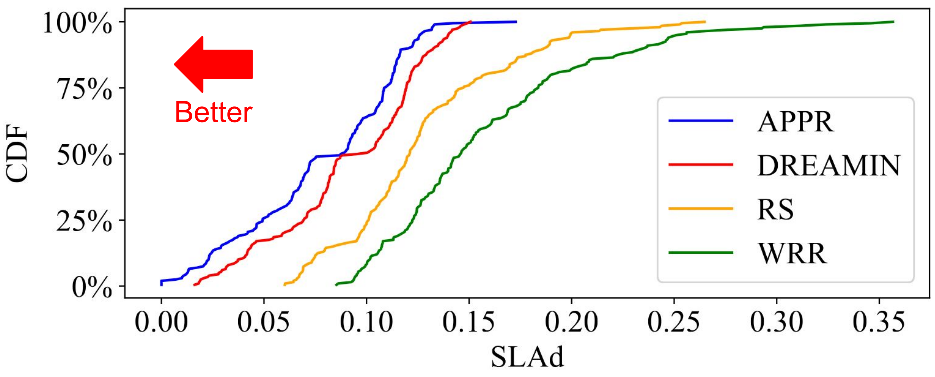
Small-scale scenario

DREAMIN approximates well the optimization model's solution

RS and WRR have similar performances - **fixed slice resource proportions**



Plentiful scenario

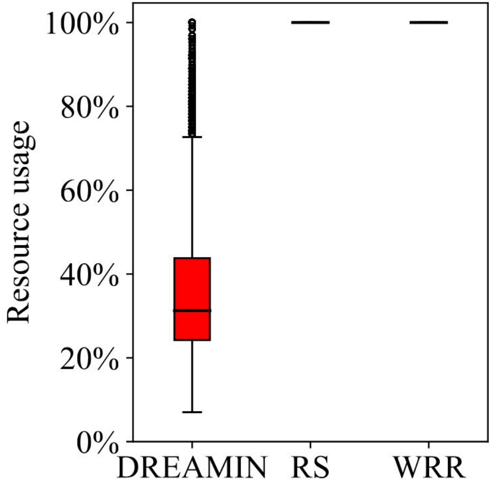


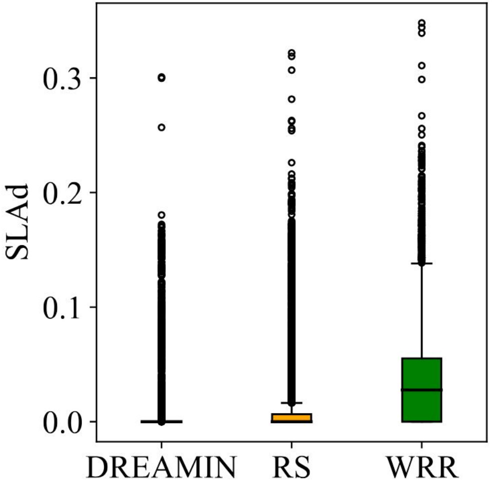
Scarce scenario

Large-scale plentiful scenario

The lower granularity (more RBGs) leads to **more efficient allocations** (DREAMIN's average resource usage drops **from 52% to 38%**)

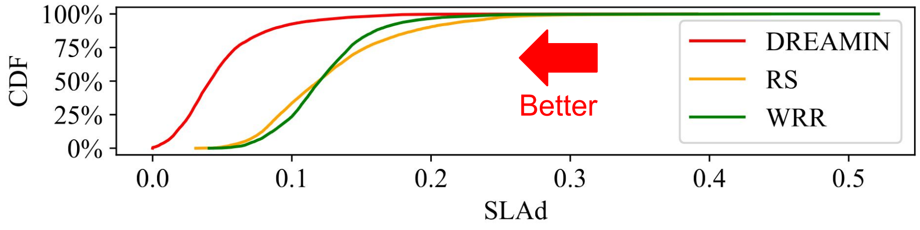
With more TTIs, there are **outlier** moments where **channel quality is broadly poor** and the **SLAd is greater than 0**

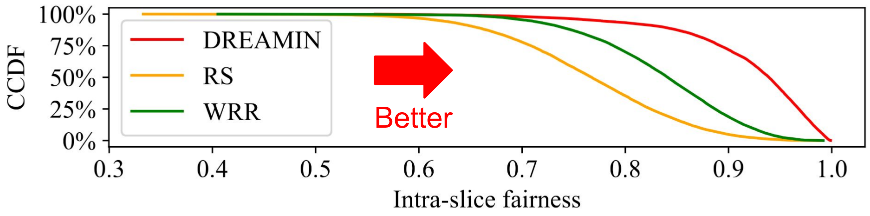




Large-scale scarce scenario

- DREAMIN's average **SLAd is 62% lower than RS's** despite also using 100%
- **Intra-slice fairness**: high values (>0.9) occur for DREAMIN in 72% of the TTIs, **14 times greater** than RS's 5%
    - **RS manipulates the proportional fair scheduler** (by predicting its allocations) to **impose unfair allocations** that maximize throughput, overprovisioning UEs with good channel qualities and starving UEs in worse conditions, which generates SLAd worse than WRR
    - The **SLAd is a metric correlated to fairness** since the slice SLAd is the average SLAd of its UEs
    - Such behaviour could only appear in a **scenario with more UEs/slice**





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Conclusion

This work approached the **channel-aware inter-slice radio resource scheduling problem oriented to minimizing SLA-drift and resource allocation**

- **Formulation** - **constraint programming** problem
- **Heuristic** - **DREAMIN approximates** well the **optimal** solution
- **RadioSaber** - **overperformed by DREAMIN**, which reduces allocation in 62% (plentiful scenario) and average SLAd in 62% (scarce scenario)
- **Fairness** - **SLAd-oriented** schedulers have **higher intra-slice fairness** indexes (DREAMIN has 14 times more occurrences of high values than RadioSaber)

Future work

- **Integrate DREAMIN with an xApp** (Open-RAN architecture) defining RRMPolicies to evaluate a **joint data-driven + channel-aware scheduling**

- **Increase problem scalability** by using other optimization techniques

- Evaluate more **complex 3GPP-compliant scenarios**
  - Multi-slice user association
  - MIMO channel simulation
  - Mixed numerology
  - Stochastic traffic models

References used in the presentation

- **[1] CHEN, Yongzhou et al. Channel-Aware 5G RAN slicing with customizable schedulers. In: 20th USENIX Symposium on Networked Systems Design and Implementation (NSDI 23). 2023. p. 1767-1782.**

- **[2] NAHUM, Cleverson Veloso et al. Intent-aware radio resource scheduling in a ran slicing scenario using reinforcement learning. IEEE Transactions on Wireless Communications, v. 23, n. 3, p. 2253-2267, 2023.**

Thank you!

https://github.com/LABORA-INF-UFG/paper-DGMK-2024/

dcamposfsa@vt.edu

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