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Orbit Slot Allocation in Earth Observation Constellations

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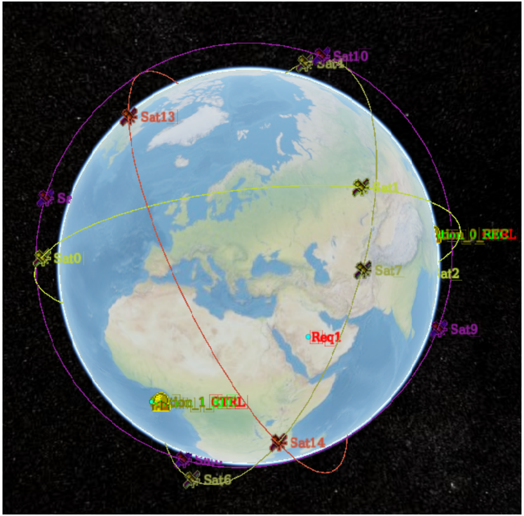
Introduction
Applicative Context and Motivation

LiChIE projet for a new constellation for observing Earth (ADS, INRIA, ONERA, IXBLUE, EREMS)

- **Huge number of image requests** to (a single) mission center
- More and more **complex requests** (periodic, systematic, etc.)
- **Overloading** and **over-constraining**
- **No guarantee** for end-users

⇒ New paradigm: **orbit slot ownership**



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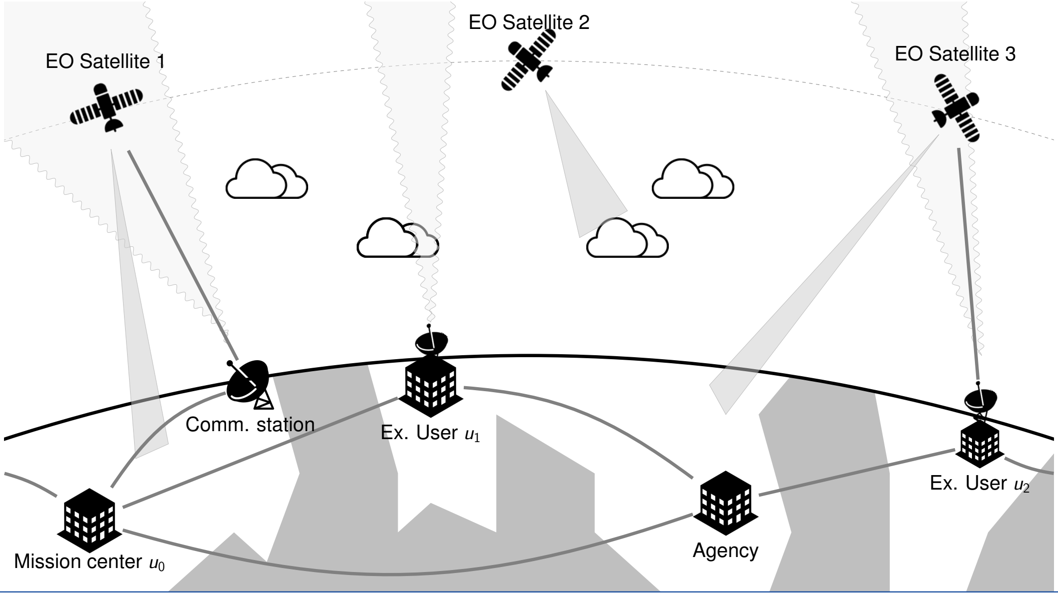
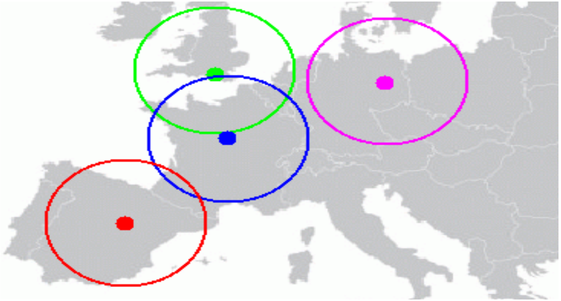


Introduction
Illustrative Example

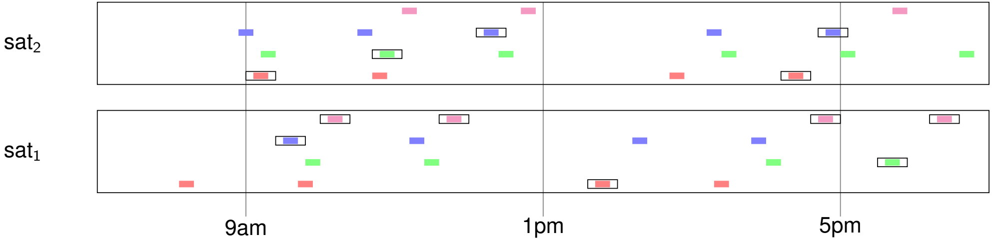


r_4 (global-30min)

r_3 (periodic-4h)

r_2 (periodic-4h)

r_1 (periodic-4h)



Introduction
Objective

- **Problem :** exploitation of the same constellation by several stakeholders

Offline reservation orbit slots —— Exclusivity periods → **Online planning** Image acquisition

- **Current allocation scheme:** first come, first served

- **Objective**

Requests (POI, dates tolerance, ...) → **Candidate slots** (Objects to allocate) → **Utilitarian** or **fair allocation**

Today's Menu

Today's Menu

General Definitions

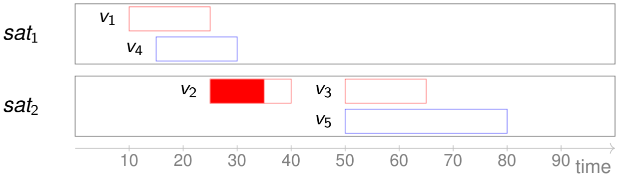
Satellite reservation window

A *satellite reservation window* w is defined by

- a satellite sat_w
- a time window $[start_w, end_w]$
- an individual score ω_w

Allocated orbit slot

An *allocated orbit slot* o within satellite reservation window w corresponds to a time window $[start_o, end_o]$ included in $[start_w, end_w]$

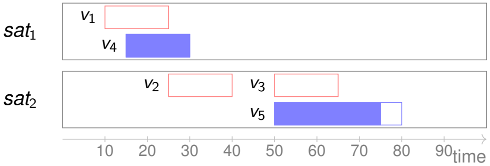


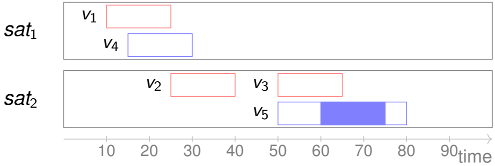
Global Allocation Request

Global allocation request

A (multi-mode) *global allocation request* r is defined by

- a set of satellite reservation windows $\mathcal{V}_r$
- a minimum duration $minSlotDur_r$ for each slot
- a list of allocation modes $\mathcal{M}_r = [\mathcal{M}_{r,1}, \ldots, \mathcal{M}_{r,K}]$, where for all $m \in \mathcal{M}_r$
  - m is an alternative to fulfill r
  - $globalDur_m$ is a global duration required over all orbit slots reserved in $\mathcal{V}_r$



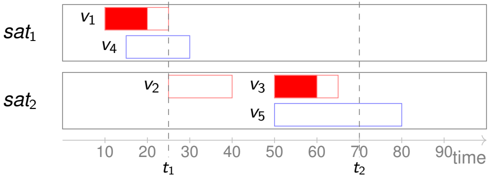


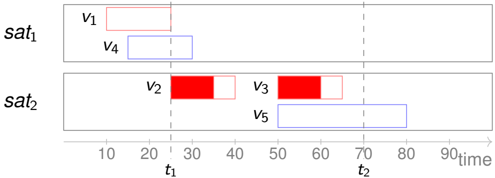
Time-tagged Allocation Request

Time-tagged allocation request

A *time-tagged allocation request* r is defined by

- a set of satellite reservation windows $\mathcal{V}_r$
- a minimum duration $minSlotDur_r$ for each slot
- a set of time references $\mathcal{T}_r$, with for each time reference $t \in \mathcal{T}_r$ a subset $\mathcal{V}^r_t \subseteq \mathcal{V}_r$ that defines the reservation windows associated with t
- a list of allocation modes $\mathcal{M}_r = [\mathcal{M}_{r,1}, \ldots, \mathcal{M}_{r,K}]$, where each allocation mode $m \in \mathcal{M}_r$ is defined by a subset $\mathcal{T}_m \subseteq \mathcal{T}_r$ of time references around which an orbit slot must actually be reserved





Orbit Slot Allocation Problem

Orbit Slot Allocation Problem

An *Orbit Slot Allocation Problem* (OSAP) is defined by

- a set of satellites $\mathcal{S}$
- a set of requests $\mathcal{R} = \mathcal{R}_G \cup \mathcal{R}_T$
  - $\mathcal{R}_G$ a set of global allocation requests
  - $\mathcal{R}_T$ a set of tagged-time allocation requests

Solution for an OSAP

A *solution* $\mathcal{A}$ for an OSAP is defined by one allocation $\mathcal{A}_r$ for each $r \in \mathcal{R}$

A solution is said to be feasible if and only if

- for every request r, allocation $\mathcal{A}_r$ satisfies request r
- for each satellite $s \in \mathcal{S}$, there is no overlapping between the orbit slots booked over s for all allocations in $\{\mathcal{A}_r \mid r \in \mathcal{R}\}$

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OSAP is NP-hard

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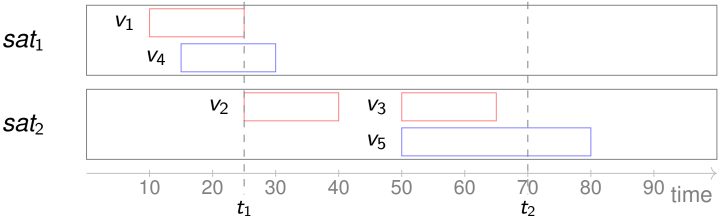
Example



- a time-tagged allocation request A (in red)
  - $minSlotDur_A = 10$
  - $\mathcal{V}_A = \{v_1, v_2, v_3\}$ with $v_1 = [10, 25]$, $v_2 = [25, 40]$, $v_3 = [50, 65]$
  - $\mathcal{V}_{r_1}^{t_1} = \{v_1, v_2\}$ and $\mathcal{V}_{r_1}^{t_2} = \{v_3\}$
  - 3 modes a_1, a_2 and a_3, with $\mathcal{T}_{a_1} = \emptyset$, $\mathcal{T}_{a_2} = \{t_1\}$ and $\mathcal{T}_{a_3} = \{t_1, t_2\}$
- a global allocation request B (in blue)
  - $minSlotDur_B = 15$
  - $\mathcal{V}_B = \{v_4, v_5\}$ with $v_4 = [15, 30]$, $v_5 = [50, 80]$
  - 3 modes b_1, b_2 and b_3, with global duration of 0, 15 and 40

How to Assess Allocation Quality?

Mode reward for global allocation request

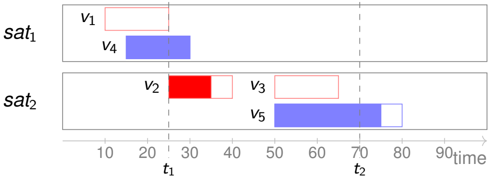
For a global allocation request r and a possible mode $m \in \mathcal{M}_r$, the reward Ω_m associated with m corresponds to quantity $globalDur_m$

Mode reward for time-tagged allocation request

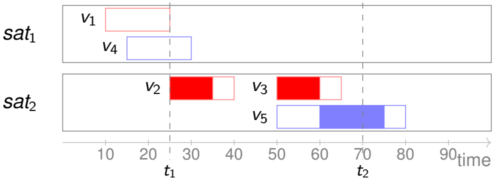
For a time-tagged allocation request r and a possible mode $m \in \mathcal{M}_r$, the reward Ω_m associated with mode m corresponds to quantity $|\mathcal{T}_m| \cdot minSlotDur_r$, that is to the total satellite time required by m over all its relevant time references

- Mode utility
  - *utilitarian allocation*: maximizing $u(\mathcal{A}) = \sum_{r \in \mathcal{R}} \Omega_{m(\mathcal{A}_r)}$
  - *fair (leximin) allocation*: maximizing $\vec{u}(\mathcal{A}) = [\Omega_{m(\mathcal{A}_{r_1})}, \ldots, \Omega_{m(\mathcal{A}_{r_n})}]$
- Window utility : $u^{slot}(\mathcal{A}) = \sum_{r \in \mathcal{R}} \sum_{v \in \mathcal{A}_r} \omega_v$

Example



(a) Utilitarian-optimal allocation $\mathcal{A}_{util}$



(b) Leximin-optimal allocation $\mathcal{A}_{fair}$

- modes a_2 for A and b_3 for B
- $u(\mathcal{A}_{util}) = 10 + 40 = 50$
- $\vec{u}(\mathcal{A}_{util}) = [10, 40]$

- modes a_3 for A and b_2 for B
- $u(\mathcal{A}_{util}) = 20 + 15 = 35$
- $\vec{u}(\mathcal{A}_{util}) = [15, 20]$

Today's Menu

Utilitarian CP Encoding

$$\text{maximize} \quad \sum_{r \in \mathcal{R}} \sum_{m \in \mathcal{M}_r} \Omega_m \cdot \mathrm{x}_m \tag{1}$$

$$\text{s.t.} \quad (2), (3), (4), (5), (6)$$

- itv_v: interval variables with minimun size of $minSlotDur_r$
- x_m: boolean variable for choosing mode m

$$\forall r \in \mathcal{R}, \quad \sum_{m \in \mathcal{M}_r} \mathrm{x}_m = 1 \tag{2}$$

$$\forall s \in S, \quad noOverlap(\{\mathrm{itv}_v | v \in \bigcup_{r \in \mathcal{R}} \mathcal{V}_r \wedge sat_v = s\}) \tag{3}$$

$$\forall r \in \mathcal{R}_T, \forall m \in \mathcal{M}_r, \forall t \in \mathcal{T}_m, \quad \sum_{v \in \mathcal{V}_r^t} presenceOf(\mathrm{itv}_v) \geq \mathrm{x}_m, \tag{4}$$

$$\forall r \in \mathcal{R}_T, \forall t \in \mathcal{T}_r, \quad \sum_{v \in \mathcal{V}_t} presenceOf(\mathrm{itv}_v) \leq 1 \tag{5}$$

$$\forall r \in \mathcal{R}_G, \forall m \in \mathcal{M}_r, \quad \sum_{v \in \mathcal{V}_r} lengthOf(\mathrm{itv}_v) \geq \mathrm{x}_m \cdot globalDur_r \tag{6}$$

Leximin CP Encoding

Intuition

- Solve as many CP optimization problems as requests
- The k-th CP problem allows to compute the k-th component of the sorted leximin vector $\vec{u} = [u_1, \ldots, u_n]$
- The objective is to lexicographically maximize vector $\Lambda = [\Lambda_1, \ldots, \Lambda_n]$ obtained after ordering $[u_1, \ldots, u_n]$ following an increasing order

- Variables
  - $\lambda \in [\Lambda_{K-1}, \max_{r \in \mathcal{R}} Z_r]$ is a real variable representing the utility obtained at level K in Λ
  - y_{rk} is a binary variable equal to 1 if request $r \in \mathcal{R}$ plays the role of the request associated with level $k \in [1..K-1]$ in $[\Lambda_1, \ldots, \Lambda_{K-1}]$, 0 otherwise
  - u_r is a real variable in $[0, Z_r]$ representing the utility of request r

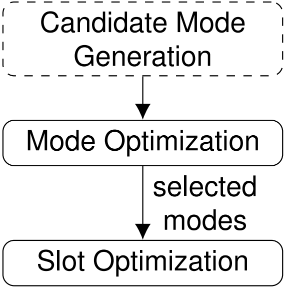
Leximin CP Encoding (cont.)

- Determining the Kth level

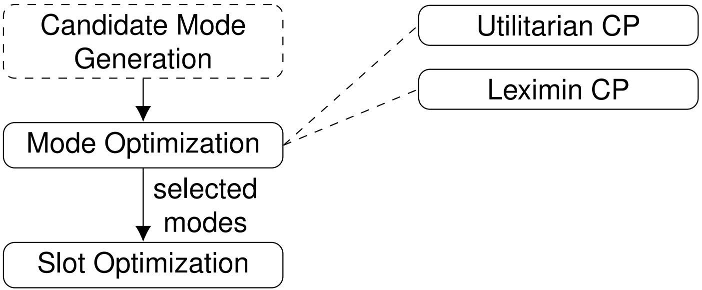
$$
\begin{aligned}
\text{maximize} \quad & \lambda && (7)\\
\text{s.t.} \quad & (2), (3), (4), (5), (6) && \\
\forall r \in \mathcal{R}, \quad & \mathrm{u}_r = \sum_{m \in \mathcal{M}_r} \Omega_m \cdot \mathrm{x}_m && (8)\\
\forall k \in [1..K-1], \quad & \sum_{r \in \mathcal{R}} \mathrm{y}_{rk} = 1 && (9)\\
\forall r \in \mathcal{R}, \quad & \sum_{k \in [1..K-1]} \mathrm{y}_{rk} \leq 1 && (10)\\
\forall r \in \mathcal{R}, \quad & \lambda \leq \mathrm{u}_r + M \sum_{k \in [1..K-1]} \mathrm{y}_{rk} && (11)\\
\forall r \in \mathcal{R}, \quad & \mathrm{u}_r \geq \sum_{k \in [1..K-1]} \Lambda_k \cdot \mathrm{y}_{rk} && (12)
\end{aligned}
$$

Today’s Menu

Optimization Architecture



Optimization Architecture



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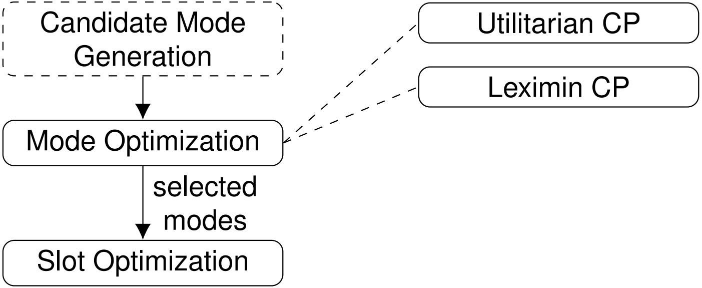
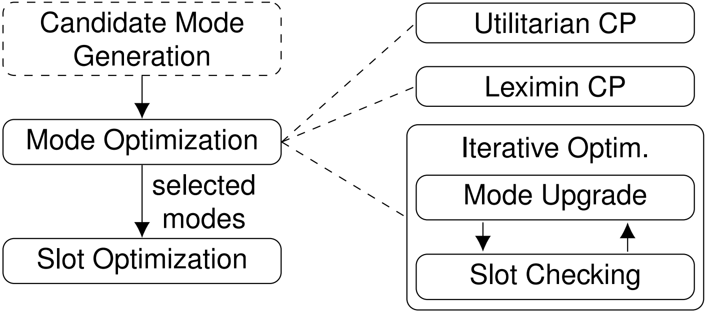


- Major issue: optimal CP approaches won't scale up!

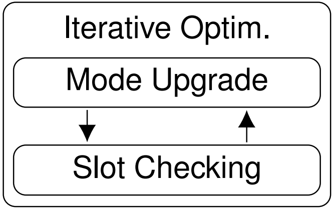
Optimization Architecture



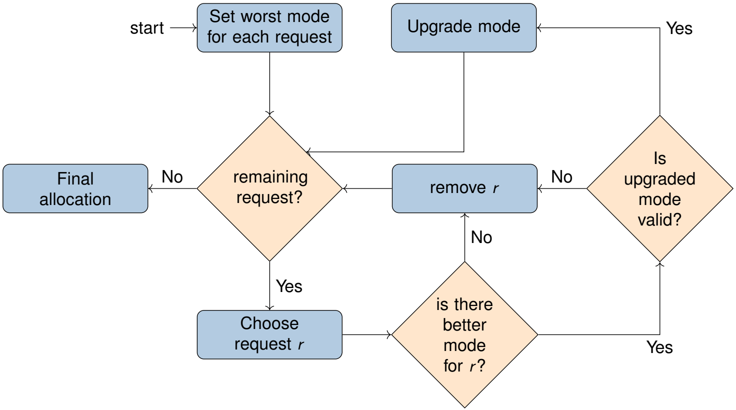
- Major issue: optimal CP approaches won't scale up!
- Proposal: iterative heuristic approach based on mode quality upgrade

Iterative Optimization

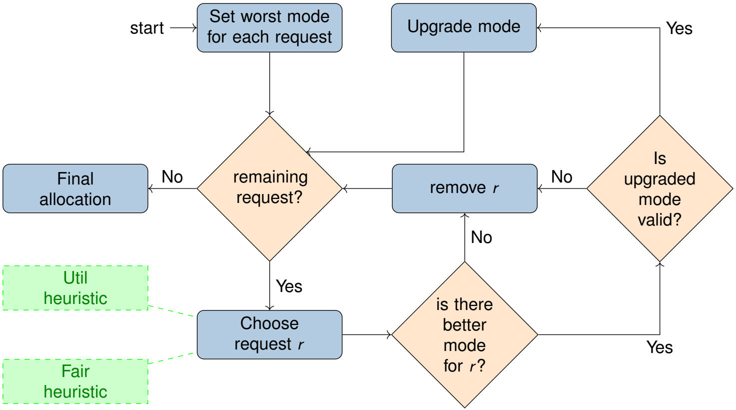
- **Purposes**: balance between utilitarianism and fairness, and scale up
- **Mode Upgrade** produces allocations so that
  - Constraint (2) is satisfied
  - Criteria (1) and (7) are optimized
- **Slot Checking** layer checks Constraints (2)– (6)



Iterative Optimization (cont.)



Iterative Optimization (cont.)



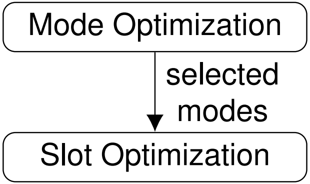
- h^{util} selects the request whose next mode increases the most the global utility of the allocation
- h^{fair} selects the request with the smallest utility

Slot Optimization

- **Purpose:** Optimizing the **slots** for the modes that have been selected at the Mode Optimization step
- **Maximizing the window utility**

$$\begin{aligned} \text{maximize} \quad & \sum_{r \in \mathcal{R}} \sum_{v \in \mathcal{V}_r} \omega_v \cdot \textit{presenceOf}(\mathrm{itv}_v) \quad (13) \\ \text{s.t.} \quad & (2), (3), (4), (5), (6) \end{aligned}$$

with $x_m = 1$ iff m is selected by the Mode Optimization module



Today's Menu

Experimental Setup

Constellation

- Low-Earth Orbit (500km altitude)
- 8 mono-satellite orbital planes with a 60 degrees inclination

Requests

1. randomly selecting a subset of national capitals $\mathcal{C}$
2. randomly parameterize requests
   - Global requests
     - most preferred global duration in $[2h, 4h]$
     - less preferred modes remove 30min down to 0 ($\mathcal{M}_{r,1}$)
     - minimum slot duration in [2min, 4min]
   - Time-tagged requests
     - 2 time references patterns: [8am, 12pm, 4pm, 8pm] and [9am, 1pm, 5pm]
     - 1-hour tolerance: $[t - 1\text{hour}, t + 1\text{hour}]$
     - less preferred mode $\mathcal{M}_{r,1}$ has an empty set of time references
     - more preferred modes add one random time reference
3. randomly picking a national capital in $\mathcal{C}$ as a ground station for each request

Experimental Setup (cont.)

Orderbooks

- 5 different order book instances per configuration (defined by $|\mathcal{R}_G|$ and $|\mathcal{R}_T|$)
- For slot optimization, the reward is linear in [0,1]
- The number of requests we consider is larger than current realistic data

Computing Environment

- Solvers are coded in Java 1.8
- Executon on 20-core Intel(R) Xeon(R) CPU E5-2660 v3 @ 2.60GHz, 62GB RAM, Ubuntu 18.04.5 LTS
- CP Optimizer included in IBM ILOG CPLEX Studio 20.1 is used by the solvers through the Java API, with timeouts

Method	**Mode opt.**	**Slot opt.**	**Slot check**
upgrade – util	n/a	300s	120s
upgrade – fair	n/a	300s	300s
cp – util / cp – fair	300s$\times|\mathcal{R}|$	300s	300s

Utility

configurations				cp — fair		cp — util		upgrade — fair		upgrade — util	
$\|\mathcal{R}_G\|$	$\|\mathcal{R}_T\|$	$\|\mathcal{M}\|$	$\|\mathcal{V}\|$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
0	5	22.0	107.0	**1980.20**†	**4.43**	**1980.20**∗	**4.43**	**1980.20**	**4.43**	**1980.20**	**4.43**
0	10	44.6	218.2	3925.00†	**8.85**	**3953.40**∗	8.66	3925.00	**8.85**	**3953.40**	8.66
0	15	67.2	326.2	6260.40†	13.15	**6288.80**∗	12.96	6260.40	**13.16**	**6288.80**	12.96
0	20	90.0	439.6	8294.00†	**17.27**	**8322.40**	17.06	8294.00	17.25	**8322.40**	17.03
0	25	112.0	549.8	10313.20	21.09	**10341.60**	20.94	10313.20	**21.16**	10276.60	20.78
5	0	31.4	198.6	39874.00	**4.64**	39911.20	4.50	**42394.00**	4.31	42034.00	4.31
10	0	63.8	405.0	**44646.60**	9.20	42953.60	8.20	44286.60	**9.32**	44286.60	9.27
15	0	96.4	606.2	42109.20	13.29	42730.20	10.76	44291.60	13.51	**44420.00**	**13.90**
20	0	129.6	814.6	27927.20	9.80	40992.60	9.32	43131.20	**14.14**	**43409.00**	13.86
25	0	161.4	1018.2	28864.80	9.80	40489.20	9.30	39645.40	**13.87**	**43117.40**	13.23
5	5	53.8	311.0	39515.60	**8.97**	40998.60	8.43	42395.60	8.30	**44388.00**	7.23
10	10	109.6	627.0	43594.40	15.93	42664.40	15.52	44674.40	**15.98**	**47071.60**	13.98
15	15	165.2	944.0	34171.40	**23.29**	39015.00	20.00	46368.80	21.74	**47244.60**	19.10
20	20	219.4	1258.2	31823.00	**26.31**	41759.80	24.18	45223.60	25.16	**47728.40**	19.45
25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

Utility

configurations				cp − fair		cp − util		upgrade − fair		upgrade − util	
$\|\mathcal{R}_G\|$	$\|\mathcal{R}_T\|$	$\|\mathcal{M}\|$	$\|\mathcal{V}\|$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
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25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

Time-tagged-only allocation requests:

cp − util and upgrade − util provide the best mode utilitarian allocation

Utility

configurations				cp − fair		cp − util		upgrade − fair		upgrade − util	
$\|\mathcal{R}_G\|$	$\|\mathcal{R}_T\|$	$\|\mathcal{M}\|$	$\|\mathcal{V}\|$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
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0	10	44.6	218.2	3925.00†	**8.85**	**3953.40**∗	8.66	3925.00	**8.85**	**3953.40**	8.66
0	15	67.2	326.2	6260.40†	13.15	**6288.80**∗	12.96	6260.40	**13.16**	**6288.80**	12.96
0	20	90.0	439.6	8294.00†	**17.27**	**8322.40**	17.06	8294.00	17.25	**8322.40**	17.03
0	25	112.0	549.8	10313.20	21.09	**10341.60**	20.94	10313.20	**21.16**	10276.60	20.78
5	0	31.4	198.6	39874.00	**4.64**	39911.20	4.50	**42394.00**	4.31	42034.00	4.31
10	0	63.8	405.0	**44646.60**	9.20	42953.60	8.20	44286.60	**9.32**	44286.60	9.27
15	0	96.4	606.2	42109.20	13.29	42730.20	10.76	44291.60	13.51	**44420.00**	**13.90**
20	0	129.6	814.6	27927.20	9.80	40992.60	9.32	43131.20	**14.14**	**43409.00**	13.86
25	0	161.4	1018.2	28864.80	9.80	40489.20	9.30	39645.40	**13.87**	**43117.40**	13.23
5	5	53.8	311.0	39515.60	**8.97**	40998.60	8.43	42395.60	8.30	**44388.00**	7.23
10	10	109.6	627.0	43594.40	15.93	42664.40	15.52	44674.40	**15.98**	**47071.60**	13.98
15	15	165.2	944.0	34171.40	**23.29**	39015.00	20.00	46368.80	21.74	**47244.60**	19.10
20	20	219.4	1258.2	31823.00	**26.31**	41759.80	24.18	45223.60	25.16	**47728.40**	19.45
25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

For small instances:
Utility-optimal and fairness-optimal allocations returned by cp − util and cp − fair

Utility

configurations				cp − fair		cp − util		upgrade − fair		upgrade − util	
$\|\mathcal{R}_G\|$	$\|\mathcal{R}_T\|$	$\|\mathcal{M}\|$	$\|\mathcal{V}\|$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
0	5	22.0	107.0	**1980.20**†	**4.43**	**1980.20**∗	**4.43**	**1980.20**	**4.43**	**1980.20**	**4.43**
0	10	44.6	218.2	3925.00†	**8.85**	**3953.40**∗	8.66	3925.00	**8.85**	**3953.40**	8.66
0	15	67.2	326.2	6260.40†	13.15	**6288.80**∗	12.96	6260.40	**13.16**	**6288.80**	12.96
0	20	90.0	439.6	8294.00†	**17.27**	**8322.40**	17.06	8294.00	17.25	**8322.40**	17.03
0	25	112.0	549.8	10313.20	21.09	**10341.60**	20.94	10313.20	**21.16**	10276.60	20.78
5	0	31.4	198.6	39874.00	**4.64**	39911.20	4.50	**42394.00**	4.31	42034.00	4.31
10	0	63.8	405.0	**44646.60**	9.20	42953.60	8.20	44286.60	**9.32**	44286.60	9.27
15	0	96.4	606.2	42109.20	13.29	42730.20	10.76	44291.60	13.51	**44420.00**	**13.90**
20	0	129.6	814.6	27927.20	9.80	40992.60	9.32	43131.20	**14.14**	**43409.00**	13.86
25	0	161.4	1018.2	28864.80	9.80	40489.20	9.30	39645.40	**13.87**	**43117.40**	13.23
5	5	53.8	311.0	39515.60	**8.97**	40998.60	8.43	42395.60	8.30	**44388.00**	7.23
10	10	109.6	627.0	43594.40	15.93	42664.40	15.52	44674.40	**15.98**	**47071.60**	13.98
15	15	165.2	944.0	34171.40	**23.29**	39015.00	20.00	46368.80	21.74	**47244.60**	19.10
20	20	219.4	1258.2	31823.00	**26.31**	41759.80	24.18	45223.60	25.16	**47728.40**	19.45
25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

With more than 5 time-tagged requests:
utilitarian and fair approaches converge to different optima

Utility

configurations				cp − fair		cp − util		upgrade − fair		upgrade − util	
$\|\mathcal{R}_G\|$	$\|\mathcal{R}_T\|$	$\|\mathcal{M}\|$	$\|\mathcal{V}\|$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
0	5	22.0	107.0	**1980.20**†	**4.43**	**1980.20**∗	**4.43**	**1980.20**	**4.43**	**1980.20**	**4.43**
0	10	44.6	218.2	3925.00†	**8.85**	**3953.40**∗	8.66	3925.00	**8.85**	**3953.40**	8.66
0	15	67.2	326.2	6260.40†	13.15	**6288.80**∗	12.96	6260.40	**13.16**	**6288.80**	12.96
0	20	90.0	439.6	8294.00†	**17.27**	**8322.40**	17.06	8294.00	17.25	**8322.40**	17.03
0	25	112.0	549.8	10313.20	21.09	**10341.60**	20.94	10313.20	**21.16**	10276.60	20.78
5	0	31.4	198.6	39874.00	**4.64**	39911.20	4.50	**42394.00**	4.31	42034.00	4.31
10	0	63.8	405.0	**44646.60**	9.20	42953.60	8.20	44286.60	**9.32**	44286.60	9.27
15	0	96.4	606.2	42109.20	13.29	42730.20	10.76	44291.60	13.51	**44420.00**	**13.90**
20	0	129.6	814.6	27927.20	9.80	40992.60	9.32	43131.20	**14.14**	**43409.00**	13.86
25	0	161.4	1018.2	28864.80	9.80	40489.20	9.30	39645.40	**13.87**	**43117.40**	13.23
5	5	53.8	311.0	39515.60	**8.97**	40998.60	8.43	42395.60	8.30	**44388.00**	7.23
10	10	109.6	627.0	43594.40	15.93	42664.40	15.52	44674.40	**15.98**	**47071.60**	13.98
15	15	165.2	944.0	34171.40	**23.29**	39015.00	20.00	46368.80	21.74	**47244.60**	19.10
20	20	219.4	1258.2	31823.00	**26.31**	41759.80	24.18	45223.60	25.16	**47728.40**	19.45
25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

With global allocation requests:
Higher reward but difficult to solve by cp − fair and cp − util

Utility

configurations				cp — fair		cp — util		upgrade — fair		upgrade — util	
$\lvert\mathcal{R}_G\rvert$	$\lvert\mathcal{R}_T\rvert$	$\lvert\mathcal{M}\rvert$	$\lvert\mathcal{V}\rvert$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
0	5	22.0	107.0	**1980.20**†	**4.43**	**1980.20**∗	**4.43**	**1980.20**	**4.43**	**1980.20**	**4.43**
0	10	44.6	218.2	3925.00†	**8.85**	**3953.40**∗	8.66	3925.00	**8.85**	**3953.40**	8.66
0	15	67.2	326.2	6260.40†	13.15	**6288.80**∗	12.96	6260.40	**13.16**	**6288.80**	12.96
0	20	90.0	439.6	8294.00†	**17.27**	**8322.40**	17.06	8294.00	17.25	**8322.40**	17.03
0	25	112.0	549.8	10313.20	21.09	**10341.60**	20.94	10313.20	**21.16**	10276.60	20.78
5	0	31.4	198.6	39874.00	**4.64**	39911.20	4.50	**42394.00**	4.31	42034.00	4.31
10	0	63.8	405.0	**44646.60**	9.20	42953.60	8.20	44286.60	**9.32**	44286.60	9.27
15	0	96.4	606.2	42109.20	13.29	42730.20	10.76	44291.60	13.51	**44420.00**	**13.90**
20	0	129.6	814.6	27927.20	9.80	40992.60	9.32	43131.20	**14.14**	**43409.00**	13.86
25	0	161.4	1018.2	28864.80	9.80	40489.20	9.30	39645.40	**13.87**	**43117.40**	13.23
5	5	53.8	311.0	39515.60	**8.97**	40998.60	8.43	42395.60	8.30	**44388.00**	7.23
10	10	109.6	627.0	43594.40	15.93	42664.40	15.52	44674.40	**15.98**	**47071.60**	13.98
15	15	165.2	944.0	34171.40	**23.29**	39015.00	20.00	46368.80	21.74	**47244.60**	19.10
20	20	219.4	1258.2	31823.00	**26.31**	41759.80	24.18	45223.60	25.16	**47728.40**	19.45
25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

upgrade — util **performs better in terms of utility** in most of the settings

Utility

configurations				cp — fair		cp — util		upgrade — fair		upgrade — util	
$\|\mathcal{R}_G\|$	$\|\mathcal{R}_T\|$	$\|\mathcal{M}\|$	$\|\mathcal{V}\|$	u	u^{slot}	u	u^{slot}	u	u^{slot}	u	u^{slot}
0	5	22.0	107.0	**1980.20†**	**4.43**	**1980.20∗**	**4.43**	**1980.20**	**4.43**	**1980.20**	**4.43**
0	10	44.6	218.2	3925.00†	**8.85**	**3953.40∗**	8.66	3925.00	**8.85**	**3953.40**	8.66
0	15	67.2	326.2	6260.40†	13.15	**6288.80∗**	12.96	6260.40	**13.16**	**6288.80**	12.96
0	20	90.0	439.6	8294.00†	**17.27**	**8322.40**	17.06	8294.00	17.25	**8322.40**	17.03
0	25	112.0	549.8	10313.20	21.09	**10341.60**	20.94	10313.20	**21.16**	10276.60	20.78
5	0	31.4	198.6	39874.00	**4.64**	39911.20	4.50	**42394.00**	4.31	42034.00	4.31
10	0	63.8	405.0	**44646.60**	9.20	42953.60	8.20	44286.60	**9.32**	44286.60	9.27
15	0	96.4	606.2	42109.20	13.29	42730.20	10.76	44291.60	13.51	**44420.00**	**13.90**
20	0	129.6	814.6	27927.20	9.80	40992.60	9.32	43131.20	**14.14**	**43409.00**	13.86
25	0	161.4	1018.2	28864.80	9.80	40489.20	9.30	39645.40	**13.87**	**43117.40**	13.23
5	5	53.8	311.0	39515.60	**8.97**	40998.60	8.43	42395.60	8.30	**44388.00**	7.23
10	10	109.6	627.0	43594.40	15.93	42664.40	15.52	44674.40	**15.98**	**47071.60**	13.98
15	15	165.2	944.0	34171.40	**23.29**	39015.00	20.00	46368.80	21.74	**47244.60**	19.10
20	20	219.4	1258.2	31823.00	**26.31**	41759.80	24.18	45223.60	25.16	**47728.40**	19.45
25	25	274.6	1572.8	29788.40	**28.87**	41641.00	26.05	46824.60	27.16	**47474.80**	21.24

upgrade — fair **outputs quite good utilitarian allocations**

Computation Time (ms)

configurations				cp — fair		cp — util		upgrade — fair		upgrade — util	
$\lvert\mathcal{R}_G\rvert$	$\lvert\mathcal{R}_T\rvert$	$\lvert\mathcal{M}\rvert$	$\lvert\mathcal{V}\rvert$	mode	slot	mode	slot	mode	slot	mode	slot
0	5	22.0	107.0	6.34	2.09	12.96	**1.63**	**4.24**	1.96	4.89	2.32
0	10	44.6	218.2	77.79	3.93	45.96	3.94	**9.73**	4.00	10.45	**3.79**
0	15	67.2	326.2	164.48	242.04	439.87	242.63	**9.41**	243.74	9.63	**241.06**
0	20	90.0	439.6	195.42	300.38	6000.21	300.09	**9.50**	300.13	10.19	300.36
0	25	112.0	549.8	759.76	300.16	7500.19	300.09	**237.50**	300.25	294.00	300.25
5	0	31.4	198.6	1500.57	300.04	1500.14	300.06	390.88	300.03	**339.86**	300.04
10	0	63.8	405.0	3002.12	300.08	3700.13	300.13	**1249.88**	300.06	1279.68	300.06
15	0	96.4	606.2	4502.34	300.06	4500.43	300.12	1849.59	300.11	**1834.56**	300.05
20	0	129.6	814.6	6003.48	300.07	6000.23	300.07	**2496.88**	300.08	2526.24	300.08
25	0	161.4	1018.2	7504.20	300.07	7500.22	300.07	3137.79	300.10	**3074.31**	300.09
5	5	53.8	311.0	1504.79	300.05	3000.13	300.04	**420.16**	300.09	433.25	300.06
10	10	109.6	627.0	3029.96	300.08	6000.21	300.09	**1206.61**	300.08	2026.38	300.06
15	15	165.2	944.0	8926.65	300.09	9000.24	300.14	**2410.81**	300.10	3530.65	300.08
20	20	219.4	1258.2	12011.00	300.15	12000.43	300.12	**3438.31**	300.16	4494.19	300.10
25	25	274.6	1572.8	15014.64	300.19	15000.44	300.14	**5187.83**	300.17	6019.73	300.11

Computation Time (ms)

configurations				cp − fair		cp − util		upgrade − fair		upgrade − util	
$\lvert\mathcal{R}_G\rvert$	$\lvert\mathcal{R}_T\rvert$	$\lvert\mathcal{M}\rvert$	$\lvert\mathcal{V}\rvert$	mode	slot	mode	slot	mode	slot	mode	slot
0	5	22.0	107.0	6.34	2.09	12.96	**1.63**	**4.24**	1.96	4.89	2.32
0	10	44.6	218.2	77.79	3.93	45.96	3.94	**9.73**	4.00	10.45	**3.79**
0	15	67.2	326.2	164.48	242.04	439.87	242.63	**9.41**	243.74	9.63	**241.06**
0	20	90.0	439.6	195.42	300.38	6000.21	300.09	**9.50**	300.13	10.19	300.36
0	25	112.0	549.8	759.76	300.16	7500.19	300.09	**237.50**	300.25	294.00	300.25
5	0	31.4	198.6	1500.57	300.04	1500.14	300.06	390.88	300.03	**339.86**	300.04
10	0	63.8	405.0	3002.12	300.08	3700.13	300.13	**1249.88**	300.06	1279.68	300.06
15	0	96.4	606.2	4502.34	300.06	4500.43	300.12	1849.59	300.11	**1834.56**	300.05
20	0	129.6	814.6	6003.48	300.07	6000.23	300.07	**2496.88**	300.08	2526.24	300.08
25	0	161.4	1018.2	7504.20	300.07	7500.22	300.07	3137.79	300.10	**3074.31**	300.09
5	5	53.8	311.0	1504.79	300.05	3000.13	300.04	**420.16**	300.09	433.25	300.06
10	10	109.6	627.0	3029.96	300.08	6000.21	300.09	**1206.61**	300.08	2026.38	300.06
15	15	165.2	944.0	8926.65	300.09	9000.24	300.14	**2410.81**	300.10	3530.65	300.08
20	20	219.4	1258.2	12011.00	300.15	12000.43	300.12	**3438.31**	300.16	4494.19	300.10
25	25	274.6	1572.8	15014.64	300.19	15000.44	300.14	**5187.83**	300.17	6019.73	300.11

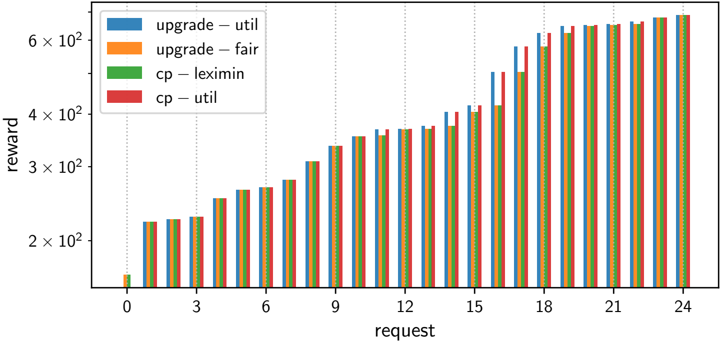
Upgrade-based heuristic methods clearly outperform optimal ones

Computation Time (ms)

configurations				cp − fair		cp − util		upgrade − fair		upgrade − util	
$\lvert\mathcal{R}_G\rvert$	$\lvert\mathcal{R}_T\rvert$	$\lvert\mathcal{M}\rvert$	$\lvert\mathcal{V}\rvert$	mode	slot	mode	slot	mode	slot	mode	slot
0	5	22.0	107.0	6.34	2.09	12.96	**1.63**	**4.24**	1.96	4.89	2.32
0	10	44.6	218.2	77.79	3.93	45.96	3.94	**9.73**	4.00	10.45	**3.79**
0	15	67.2	326.2	164.48	242.04	439.87	242.63	**9.41**	243.74	9.63	**241.06**
0	20	90.0	439.6	195.42	300.38	6000.21	300.09	**9.50**	300.13	10.19	300.36
0	25	112.0	549.8	759.76	300.16	7500.19	300.09	**237.50**	300.25	294.00	300.25
5	0	31.4	198.6	1500.57	300.04	1500.14	300.06	390.88	300.03	**339.86**	300.04
10	0	63.8	405.0	3002.12	300.08	3700.13	300.13	**1249.88**	300.06	1279.68	300.06
15	0	96.4	606.2	4502.34	300.06	4500.43	300.12	1849.59	300.11	**1834.56**	300.05
20	0	129.6	814.6	6003.48	300.07	6000.23	300.07	**2496.88**	300.08	2526.24	300.08
25	0	161.4	1018.2	7504.20	300.07	7500.22	300.07	3137.79	300.10	**3074.31**	300.09
5	5	53.8	311.0	1504.79	300.05	3000.13	300.04	**420.16**	300.09	433.25	300.06
10	10	109.6	627.0	3029.96	300.08	6000.21	300.09	**1206.61**	300.08	2026.38	300.06
15	15	165.2	944.0	8926.65	300.09	9000.24	300.14	**2410.81**	300.10	3530.65	300.08
20	20	219.4	1258.2	12011.00	300.15	12000.43	300.12	**3438.31**	300.16	4494.19	300.10
25	25	274.6	1572.8	15014.64	300.19	15000.44	300.14	**5187.83**	300.17	6019.73	300.11

All methods quickly achieve the slot optimization timeout

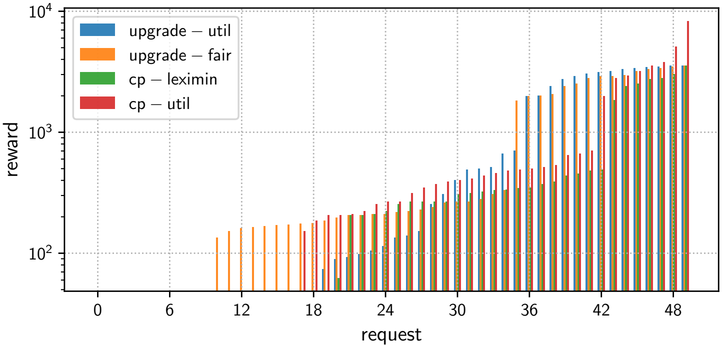
Fairness
Utility profiles an instance with 25 time-tagged allocation requests



- All the methods behave quite **similarly**
- Such problems are **not too constrained**, given the constellation configuration
- The **fair approaches only serve one more request**

Fairness (cont.)

Utility profiles an instance with 25 time-tagged allocation requests and 25 global allocation requests



- The **most rewarding** requests (25 to 49) are the **global allocation** ones
- Some requests **cannot be fulfilled** (even by leximin)
- upgrade — fair **serves more requests** (more than cp — fair, due to time budget)
- upgrade — util **is better than** cp — util on most of the high reward requests
- upgrade — fair and upgrade — util behave very well on the fairness side

Today’s Menu

Conclusions

To Sum Up

- We modeled a **novel problem (OSAP)** for allocating orbit slots
- We considered both **utilitarian and fairness** objectives
- We considered **two types of requests**: time-tagged requests and global requests
- We proposed an iterative **two-level optimization framework**
- We evaluated **four solution methods**
  - **Global allocation requests are the hardest** ones to fulfill
  - $cp - util$ **and** $cp - fair$ **do not scale** on larger instances
  - **Iterative upgrading methods result in good quality solutions** and are **3 times faster** on larger instances

Future Research

- Investigating other types of requests (e.g. areas of interest)
- Investigating other types of mode selection (e.g. searching in the mode space)
- Exploring other iterative schemes (e.g. degrading instead of upgrading)

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