

Joint Resource Allocation and Link Association for URLLC Puncturing eMBB Traffic in Multicell Networks

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December 14, 2022

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Introduction

Scenario

- mmWave
 - Multicell¹
- Downlink eMBB and URLLC
 - Puncturing²
 - Hybrid³

¹mitigate path loss and shadowing

²improve spectrum efficiency for sparse URLLC traffic

³accommodate demands for bursty URLLC traffic

Sparse URLLC Traffic

- As the adoption of autonomous vehicles⁴ and drone delivery is still minor, URLLC downlink control traffic is rather dispersed.
- In this regard, having a dedicated channel in URLLC service wastes spectral resources, and such waste **scales linearly** with the number of base stations in the network.

⁴include private cars and public transits

- Do note that the discussion is applicable to any wireless systems serving two heterogeneous qualities of service (QoS) using short-wavelength technology.

Contributions

- A novel **linear** model for URLLC puncturing eMBB traffic in multicell networks is introduced, upon which optimality analysis for the multiplexing procedure is conducted.
- The proportional fairness algorithm's asymptotical optimality [5] is generalized for eMBB resource allocation in multiconnectivity-based networks.
- The URLLC problem's optimal substructure is proved.
- Two approximation algorithms, nearest association algorithm and tightest association algorithm, that jointly schedule URLLC resources and links in multicell networks are proposed.
- An optimal variant of the two algorithms for single-cell networks is derived.

Related Work

- Current models for URLLC puncturing scheme in the literature are mostly non-linear [4].
- Whilst proposed linear models are either intractable [7] or inappropriate [3] for discrete subchannel allocation with multiple URLLC users.
- Many [4, 7] heuristically optimize the URLLC problem at each time minislot, without analyzing the optimal substructure.

System Model

- Base stations of separated channel bandwidths, downlink, OFDMA, puncturing, eMBB and URLLC users.
- Saturated eMBB traffic [6]: Each eMBB user has **infinite** amount of data to be transmitted.
- Strict URLLC constraint: Each URLLC user has an amount of data required to be served within a minislot.
- The system aims to maximize eMBB total average rate and fairness while satisfying URLLC demands.

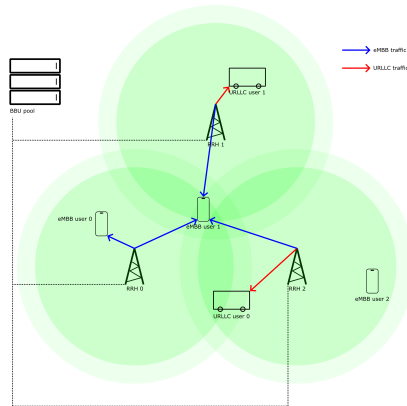


Figure: System model

Stochastic Problem

$$\begin{aligned} & \underset{\alpha, \beta, \delta}{\text{maximize}} && \sum_u \ln \bar{R}_u \end{aligned} \quad (1a)$$

$$\text{subject to} \quad \sum_u \alpha_{u,n,s,l} \leq 1 \quad \forall n \forall s \forall l, \quad (1b)$$

$$\alpha_{u,n,s,l} \in \{0, 1\} \quad \forall u \forall n \forall s \forall l, \quad (1c)$$

$$\sum_s \delta_{v,n,m,s} \leq 1 \quad \forall v \forall n \forall m, \quad (1d)$$

$$\beta_{v,u,n,m,s,l} \leq \delta_{v,n,m,s} \quad \forall v \forall u \forall n \forall m \forall s \forall l, \quad (1e)$$

$$\delta_{v,n,m,s} \in \{0, 1\} \quad \forall v \forall n \forall m \forall s, \quad (1f)$$

$$\sum_v \beta_{v,u,n,m,s,l} \leq \alpha_{u,n,s,l} \quad \forall u \forall n \forall m \forall s \forall l, \quad (1g)$$

$$R_{v,n,m} \geq R_{v,n,m}^{dm} \quad \forall v \forall n \forall m, \quad (1h)$$

$$\beta_{v,u,n,m,s,l} \in \{0, 1\} \quad \forall v \forall u \forall n \forall m \forall s \forall l \quad (1i)$$

- The system maximizes eMBB traffic's total average rate and fairness (1a):

$$\underset{\alpha, \beta, \delta}{\text{maximize}} \quad \sum_u \ln \bar{R}_u.$$

- For each time slot, the system allocates a subchannel to at most one eMBB user (1b):

$$\forall n: \forall s: \forall l: \sum_u \alpha_{u,n,s,l} \leq 1.$$

- For each time slot, the system either un-allocates or allocates a subchannel to an eMBB user (1c):

$$\forall u: \forall n: \forall s: \forall l: \alpha_{u,n,s,l} \in \{0, 1\}.$$

- For each time minislot, the system associates at most one base station to a URLLC user (1d):

$$\forall v: \forall n: \forall m: \sum_s \delta_{v,n,m,s} \leq 1.$$

- For each time minislot, the system allocates a subchannel to a URLLC user only if it associates the corresponding base station to the user (1e):

$$\forall v: \forall u: \forall n: \forall m: \forall s: \forall l: \beta_{v,u,n,m,s,l} \leq \delta_{v,n,m,s}.$$

- For each time minislot, the system either un-associates or associates a base station to a URLLC user (1f):

$$\forall v: \forall n: \forall m: \forall s: \delta_{v,n,m,s} \in \{0, 1\}.$$

- For each time minislot, the system allocates a subchannel to at most one URLLC user, and punctures the subchannel for a URLLC user only if it allocates the subchannel to the corresponding eMBB user (1g)⁵:

$$\forall u: \forall n: \forall m: \forall s: \forall l: \sum_v \beta_{v,u,n,m,s,l} \leq \alpha_{u,n,s,l}.$$

- For each time minislot, the system serves demands of URLLC users without delay (1h):

$$\forall v: \forall n: \forall m: R_{v,n,m} \geq R_{v,n,m}^{dm}.$$

- For each time minislot, the system employs URLLC puncturing scheme (1i):

$$\forall v: \forall u: \forall n: \forall m: \forall s: \forall l: \beta_{v,u,n,m,s,l} \in \{0, 1\}.$$

⁵Proof in supplementary

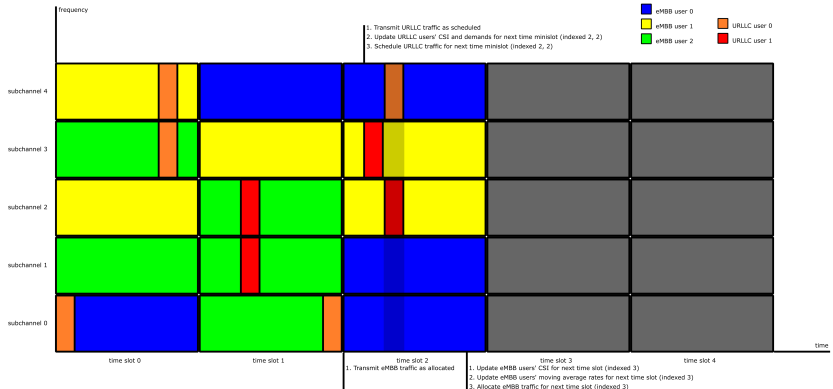


Figure: Multiplexing procedure

eMBB Problem

$$\underset{\alpha}{\text{maximize}} \quad \sum_u \ln \bar{R}_u \quad (2a)$$

$$\text{subject to} \quad \sum_u \alpha_{u,n,s,l} \leq 1 \quad \forall n \forall s \forall l, \quad (2b)$$

$$\alpha_{u,n,s,l} \in \{0, 1\} \forall u \forall n \forall s \forall l \quad (2c)$$

Relaxed eMBB Problem

$$\underset{\alpha'}{\text{maximize}} \quad \sum_u \ln \bar{R}'_u \quad (3a)$$

$$\text{subject to} \quad \sum_u \alpha'_{u,n,s,l} \leq 1 \forall n \forall s \forall l, \quad (3b)$$

$$\alpha'_{u,n,s,l} \geq 0 \forall u \forall n \forall s \forall l \quad (3c)$$

Gradient Problem

$$\begin{aligned} & \underset{\alpha'_{n_0}}{\text{maximize}} && \sum_u \frac{r'_{u,n_0}}{\tilde{r}'_{u,n_0}} && (4a) \end{aligned}$$

$$\begin{aligned} & \text{subject to} && \sum_u \alpha'_{u,n_0,s,l} \leq 1 \forall s \forall l, && (4b) \end{aligned}$$

$$\alpha'_{u,n_0,s,l} \geq 0 \forall u \forall s \forall l \quad (4c)$$

- The relaxed moving average rate of eMBB user is defined based on exponential moving average (EMA) as

$$\forall u: \tilde{r}'_{u,n} = \begin{cases} \frac{1}{n} \sum_{s,l} \frac{1}{u} \mathbf{r}_{u,n,s,l} & n = 0 \\ (1 - \epsilon) \tilde{r}'_{u,n-1} + \epsilon r'_{u,n-1} & n = 1, \dots, n-1 \end{cases} \left[\frac{\text{bits}}{\text{slot}} \right]. \quad (5)$$

- The initial value of which is defined by the feasible policy $\hat{\alpha}'$ for the relaxed eMBB problem where⁶

$$\forall u: \forall s: \forall l: \hat{\alpha}'_{u,n,s,l} = \begin{cases} \frac{1}{u} & n = 0 \\ 0 & n = 1, \dots, n-1 \end{cases}. \quad (6)$$

⁶Proof in supplementary

- To solve the gradient problem, linear programming techniques might be considered.
- Although ellipsoid methods solve by polynomial time in theory, and interior-point methods converge remarkably fast in practice, such solvers do not guarantee a binary solution.
- Fortunately, the gradient problem's totally unimodular property makes simplex methods viable.

- Given a policy $\hat{\alpha}$ where for $n = 0, \dots, N - 1$, $\hat{\alpha}_n$ is a basic optimal point for the n^{th} gradient problem, then $\hat{\alpha}$ is an asymptotically optimal policy for the eMBB problem⁷.

⁷Proof in supplementary

- However, simplex methods run in exponential time in worst-case scenarios, which could not meet the multiplexing procedure's time requirement for allocating eMBB resources.
- By further observations, it is found that the proportional fairness algorithm solves the gradient problem optimally in linear time.

- The following policy is asymptotically optimal with respect to the eMBB problem⁸:

$$\forall n: \forall s: \forall l: \hat{\alpha}_{u,n,s,l} = \begin{cases} 1 & u = \min_{\hat{u}} \arg \max_{\hat{u}} \frac{r_{\hat{u},n,s,l}}{\tilde{r}'_{\hat{u},n}} \\ 0 & \text{otherwise} \end{cases} . \quad (7)$$

⁸Proof in supplementary

URLLC Problem

$$\underset{\beta_{n_0}, \delta_{n_0}}{\text{maximize}} \quad \sum_u \frac{r'_{u,n_0}}{\tilde{r}'_{u,n_0}} \quad (8a)$$

$$\text{subject to} \quad \sum_s \delta_{v,n_0,m,s} \leq 1 \quad \forall v \forall m, \quad (8b)$$

$$\beta_{v,u,n_0,m,s,l} \leq \delta_{v,n_0,m,s} \quad \forall v \forall u \forall m \forall s \forall l, \quad (8c)$$

$$\delta_{v,n_0,m,s} \in \{0, 1\} \quad \forall v \forall m \forall s, \quad (8d)$$

$$\sum_v \beta_{v,u,n_0,m,s,l} \leq \hat{\alpha}_{u,n_0,s,l} \quad \forall u \forall m \forall s \forall l, \quad (8e)$$

$$R_{v,n_0,m} \geq R_{v,n_0,m}^{dm} \quad \forall v \forall m, \quad (8f)$$

$$\beta_{v,u,n_0,m,s,l} \in \{0, 1\} \quad \forall v \forall u \forall m \forall s \forall l \quad (8g)$$

Puncturing Problem

$$\underset{\beta_{n_0, m_0}, \delta_{n_0, m_0}}{\text{minimize}} \quad \sum_{v, u, s, l} \frac{r_{u, n_0, s, l}}{\tilde{r}'_{u, n_0}} \beta_{v, u, n_0, m_0, s, l} \quad (9a)$$

$$\text{subject to} \quad \sum_s \delta_{v, n_0, m_0, s} \leq 1 \quad \forall v, \quad (9b)$$

$$\beta_{v, u, n_0, m_0, s, l} \leq \delta_{v, n_0, m_0, s} \quad \forall v \forall u \forall s \forall l, \quad (9c)$$

$$\delta_{v, n_0, m_0, s} \in \{0, 1\} \quad \forall v \forall s, \quad (9d)$$

$$\sum_v \beta_{v, u, n_0, m_0, s, l} \leq \hat{\alpha}_{u, n_0, s, l} \quad \forall u \forall s \forall l, \quad (9e)$$

$$r_{v, n_0, m_0} \geq r_{v, n_0, m_0}^{dm} \quad \forall v, \quad (9f)$$

$$\beta_{v, u, n_0, m_0, s, l} \in \{0, 1\} \quad \forall v \forall u \forall s \forall l \quad (9g)$$

URLLC Problem's Optimal Substructure

- Given a time slot policy $(\hat{\beta}_{n_0}, \hat{\delta}_{n_0})$ where for $m = 0, \dots, M-1$, $(\hat{\beta}_{n_0, m}, \hat{\delta}_{n_0, m})$ solves the m^{th} puncturing problem, then $(\hat{\beta}_{n_0}, \hat{\delta}_{n_0})$ is an optimal point for the URLLC problem⁹.

⁹Proof in supplementary

Scheduling Problem

$$\underset{\gamma_{n_0, m_0}, \delta_{n_0, m_0}}{\text{minimize}} \quad \sum_{v, s, l} c_{n_0, s, l} \gamma_{v, n_0, m_0, s, l} \quad (10a)$$

$$\text{subject to} \quad \sum_s \delta_{v, n_0, m_0, s} \leq 1 \quad \forall v, \quad (10b)$$

$$\gamma_{v, n_0, m_0, s, l} \leq \delta_{v, n_0, m_0, s} \quad \forall v \forall s \forall l, \quad (10c)$$

$$\delta_{v, n_0, m_0, s} \in \{0, 1\} \quad \forall v \forall s, \quad (10d)$$

$$\sum_v \gamma_{v, n_0, m_0, s, l} \leq 1 \quad \forall s \forall l, \quad (10e)$$

$$\sum_{s, l} \gamma_{v, n_0, m_0, s, l} \mathbf{r}_{v, n_0, m_0, s} \geq \mathbf{r}_{v, n_0, m_0}^{dm} \quad \forall v, \quad (10f)$$

$$\gamma_{v, n_0, m_0, s, l} \in \{0, 1\} \quad \forall v \forall s \forall l \quad (10g)$$

- The puncturing cost of subchannel is defined as

$$\forall n: \forall s: \forall l: c_{n,s,l} = \max_u \frac{\tau_{u,n,s,l}}{\tilde{r}'_{u,n}}. \quad (11)$$

- The scheduling problem is equivalent to the puncturing problem¹⁰.

¹⁰Proof in supplementary

- The scheduling problem is independent from α .

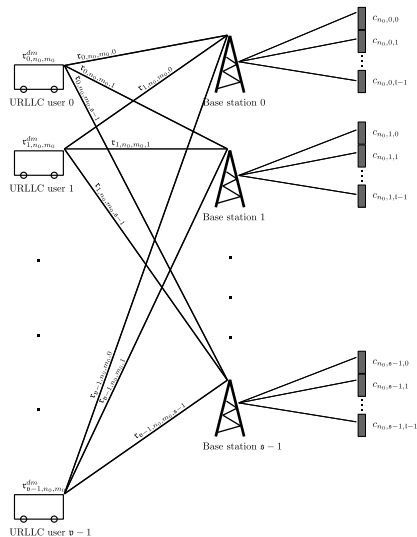


Figure: Scheduling Problem

Homogeneous Problem

$$\underset{\gamma_{n_0, m_0}, \delta_{n_0, m_0}}{\text{minimize}} \quad c_{n_0}^{mn} \sum_{v, s, l} \gamma_{v, n_0, m_0, s, l} \quad (12a)$$

$$\text{subject to} \quad \sum_s \delta_{v, n_0, m_0, s} \leq 1 \quad \forall v, \quad (12b)$$

$$\gamma_{v, n_0, m_0, s, l} \leq \delta_{v, n_0, m_0, s} \quad \forall v \forall s \forall l, \quad (12c)$$

$$\delta_{v, n_0, m_0, s} \in \{0, 1\} \quad \forall v \forall s, \quad (12d)$$

$$\sum_v \gamma_{v, n_0, m_0, s, l} \leq 1 \quad \forall s \forall l, \quad (12e)$$

$$\sum_{s, l} \gamma_{v, n_0, m_0, s, l} \geq \frac{r_{v, n_0, m_0}^{dm}}{r_{v, n_0, m_0}^{mx}} \quad \forall v, \quad (12f)$$

$$\gamma_{v, n_0, m_0, s, l} \in \{0, 1\} \quad \forall v \forall s \forall l \quad (12g)$$

- The minimum puncturing cost is defined as

$$\forall n: c_n^{mn} = \min_{s,l} c_{n,s,l}. \quad (13)$$

- The maximum rate of URLLC user is defined as

$$\forall n: \forall m: \forall v: \tau_{v,n,m}^{mx} = \max_s \tau_{v,n,m,s}. \quad (14)$$

- $c_{n_0}^{mn} \sum_v \left[\frac{\tau_{v,n_0,m_0}^{dm}}{\tau_{v,n_0,m_0}^{mx}} \right]$ is the optimal value for the homogeneous problem.

- The nearest association algorithm defines the following point:

$$\forall v: \hat{\delta}_{v,n_0,m_0,s} = \begin{cases} 1 & s = \min_{\hat{s}} \arg \max_{\hat{s}} \mathbf{r}_{v,n_0,m_0,\hat{s}} \\ 0 & \text{otherwise} \end{cases},$$

$$\forall s: \forall v: \hat{\gamma}_{v,n_0,m_0,s,l} = \begin{cases} 1 & \sum_{\hat{v}=0}^{v-1} \left\lceil \frac{\mathbf{r}_{\hat{v},n_0,m_0}^{dm}}{\mathbf{r}_{\hat{v},n_0,m_0}^{mx}} \right\rceil \hat{\delta}_{\hat{v},n_0,m_0,s} \leq l \\ \leq \left(\sum_{\hat{v}=0}^v \left\lceil \frac{\mathbf{r}_{\hat{v},n_0,m_0}^{dm}}{\mathbf{r}_{\hat{v},n_0,m_0}^{mx}} \right\rceil \hat{\delta}_{\hat{v},n_0,m_0,s} \right) - 1 & \\ 0 & \text{otherwise} \end{cases}.$$

- The nearest association algorithm is a $\frac{c_{n_0}^{mx}}{c_{n_0}^{mn}}$ -approximation algorithm for the scheduling problem¹¹.

¹¹Proof in supplementary

- The maximum puncturing cost is defined as

$$\forall n: c_n^{mx} = \max_{s,l} c_{n,s,l}. \quad (15)$$

- The opportunistic nearest association algorithm defines the following point:

$$\forall v: \hat{\delta}_{v,n_0,m_0,s} = \begin{cases} 1 & s = \min_{\hat{s}} \arg \max_{\hat{s}} \tau_{v,n_0,m_0,\hat{s}}, \\ 0 & \text{otherwise} \end{cases},$$

$$\forall s: \forall v: \hat{\gamma}_{v,n_0,m_0,s,l} = \begin{cases} 1 & \left(\sum_{\hat{v}=0}^{v-1} \left\lceil \frac{\tau_{\hat{v},n_0,m_0}^{dm}}{\tau_{\hat{v},n_0,m_0}^{mx}} \right\rceil \hat{\delta}_{\hat{v},n_0,m_0,s} \right) + 1 \\ & \leq \text{card} \left\{ \hat{l} \mid c_{n_0,s,l} > c_{n_0,s,\hat{l}} \vee (c_{n_0,s,l} = c_{n_0,s,\hat{l}} \wedge l > \hat{l}) \right\} \\ & \leq \sum_{\hat{v}=0}^v \left\lceil \frac{\tau_{\hat{v},n_0,m_0}^{dm}}{\tau_{\hat{v},n_0,m_0}^{mx}} \right\rceil \hat{\delta}_{\hat{v},n_0,m_0,s} \\ 0 & \text{otherwise} \end{cases}.$$

- The opportunistic nearest association algorithm is an optimal algorithm for the scheduling problem in single-cell networks¹².

¹²Proof in supplementary

- The tightest association algorithm defines the following point:

$$\forall v: \hat{\delta}_{v,n_0,m_0,s} = \begin{cases} 1 & s = \min_{\hat{s}} \arg \min_{\hat{s}} c_{n_0,\hat{s}}^{mn} \left[\frac{\tau_{v,n_0,m_0}^{dm}}{\tau_{v,n_0,m_0,\hat{s}}} \right] , \\ 0 & \text{otherwise} \end{cases}$$

$$\forall s: \forall v: \hat{\gamma}_{v,n_0,m_0,s,l} = \begin{cases} 1 & \leq l \\ & \leq \left(\sum_{\hat{v}=0}^v \left[\frac{\tau_{\hat{v},n_0,m_0}^{dm}}{\tau_{\hat{v},n_0,m_0,s}} \right] \hat{\delta}_{\hat{v},n_0,m_0,s} \right) - 1 \\ 0 & \text{otherwise} \end{cases} .$$

- The tightest association algorithm is a ρ -approximation algorithm for the scheduling problem¹³.

¹³Proof in supplementary

- The opportunistic tightest association algorithm is an optimal algorithm for the scheduling problem in single-cell networks.

Simulation

- Compare performance with dedicated URLLC channel systems?
- Compare performance with [3] in single-cell networks with one URLLC user.
- Compare performance with [7] in single-cell networks with multiple URLLC users?
- Compare performance of nearest association algorithm and opportunistic nearest association algorithm in multicell networks.

Parameters

- 3 base stations
- 132 subchannels per base station [1]
- 100 eMBB users
- 100 time slots
- 7 time minislots per time slot
- URLLC demand 256-1600 bits [2]
- 3 algorithms
 - Opportunistic Nearest Association Algorithm (ONAA)
 - Opportunistic Tightest Association Algorithm (OTAA)
 - Exhaustive Algorithm (EA)

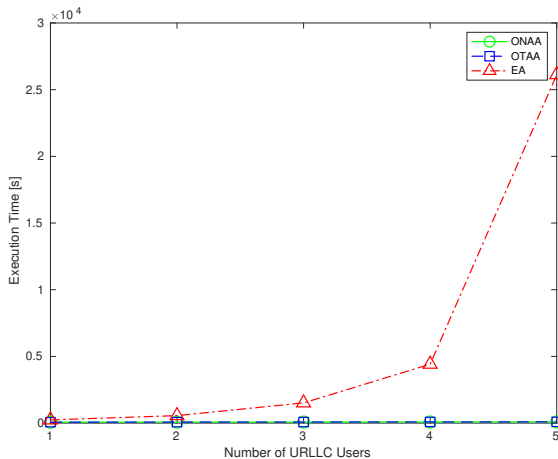


Figure: Optimality execution time

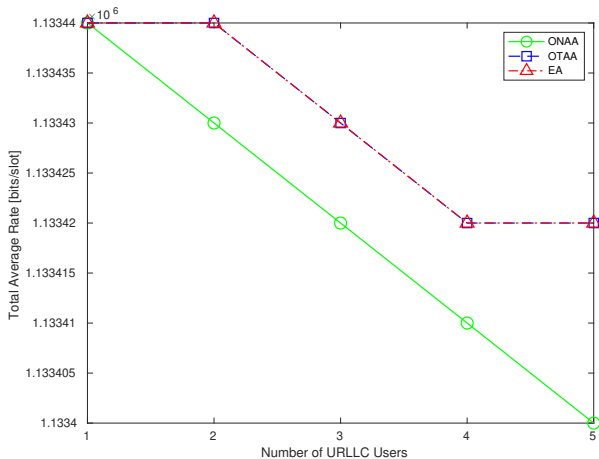


Figure: Optimality total average rates

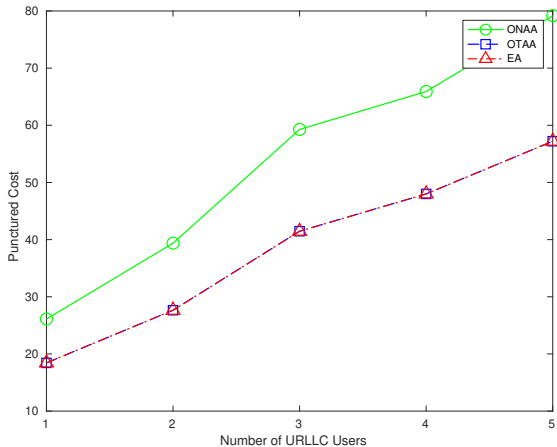


Figure: Optimality punctured costs

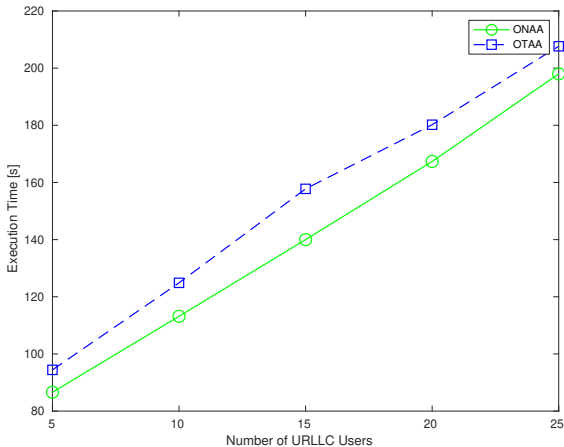


Figure: Heuristics execution time

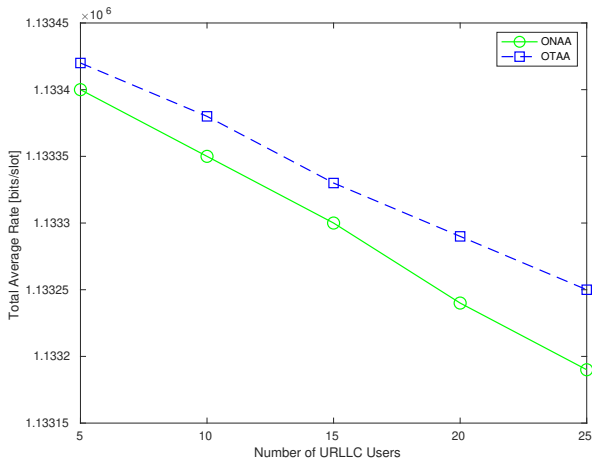


Figure: Heuristics total average rates

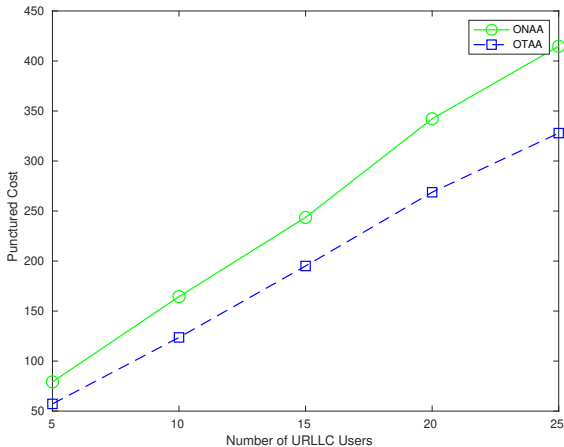


Figure: Heuristics punctured costs

Conclusion

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