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

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Related Work

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Scenario

- mmWave
  - Multicell[1]
- Downlink eMBB and URLLC
  - Puncturing[2]
  - Hybrid[3]

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[1]mitigate path loss and shadowing

[2]improve spectrum efficiency for sparse URLLC traffic

[3]accommodate demands for bursty URLLC traffic

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Sparse URLLC Traffic

- As the adoption of autonomous vehicles[4] 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.

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[4]include 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.

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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 [4] 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.

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- Current models for URLLC puncturing scheme in the literature are mostly non-linear [3].
- Whilst proposed linear models are either intractable [7] or inappropriate [2] for discrete subchannel allocation with multiple URLLC users.
- Many [3, 7] heuristically optimize the URLLC problem at each time minislot, without analyzing the optimal substructure.

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System Model

- Base stations of separated channel bandwidths, downlink, OFDMA, puncturing, eMBB and URLLC users.
- Saturated eMBB traffic [5]: 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.
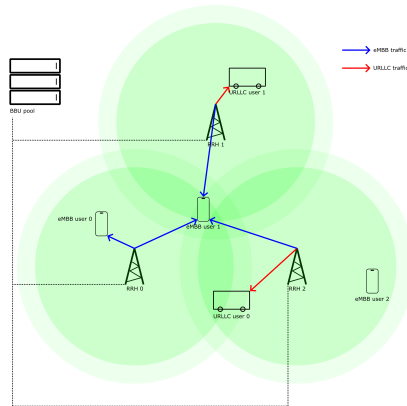
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Figure: System model

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Stochastic Problem

$$\underset{\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\delta}}{\text{maximize}} \quad \sum_u \ln \bar{R}_u \tag{1a}$$

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

$$\alpha_{u,n,s,l} \in \{0,1\} \ \ \forall u \forall n \forall s \forall l, \tag{1c}$$

$$\sum_s \delta_{v,n,m,s} \leq 1 \qquad \forall v \forall n \forall m, \tag{1d}$$

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

$$\delta_{v,n,m,s} \in \{0,1\} \ \ \forall v \forall n \forall m \forall s, \tag{1f}$$

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

$$R_{v,n,m} \geq R_{v,n,m}^{dm} \ \ \forall v \forall n \forall m, \tag{1h}$$

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

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

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

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

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

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

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

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

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

- 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):

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

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

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

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- 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]:

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

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

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

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

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

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[5]Proof in supplementary

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Figure: Multiplexing procedure

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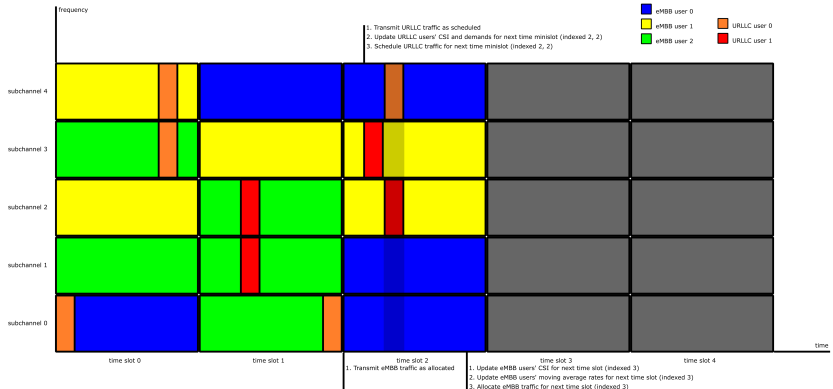
eMBB Problem

$$\underset{\boldsymbol{\alpha}}{\text{maximize}} \quad \sum_{u} \ln \bar{R}_u \tag{2a}$$

$$\text{subject to} \quad \sum_{u} \alpha_{u,n,s,l} \leq 1 \qquad \forall n \forall s \forall l, \tag{2b}$$

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

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Relaxed eMBB Problem

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

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

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

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Gradient Problem

$$\underset{\boldsymbol{\alpha}'_{n_0}}{\text{maximize}} \quad \sum_u \frac{r'_{u,n_0}}{\tilde{r}'_{u,n_0}} \tag{4a}$$

$$\text{subject to} \quad \sum_u \alpha'_{u,n_0,s,l} \leq 1 \forall s \forall l, \tag{4b}$$

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

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

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

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- The initial value of which is defined by the feasible policy $\hat{\alpha}'$ for the relaxed eMBB problem where[6]

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

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[6]Proof in supplementary

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- 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.

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- Given a policy $\hat{\boldsymbol{\alpha}}$ where for $n = 0, \ldots, \mathfrak{n} - 1$, $\hat{\boldsymbol{\alpha}}_n$ is a basic optimal point for the nth gradient problem, then $\hat{\boldsymbol{\alpha}}$ is an asymptotically optimal policy for the eMBB problem[7].

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[7]Proof in supplementary

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- 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.

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- The following policy is asymptotically optimal with respect to the eMBB problem[8]:

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

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[8]Proof in supplementary

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URLLC Problem

$$\underset{\boldsymbol{\beta}_{n_0}, \boldsymbol{\delta}_{n_0}}{\text{maximize}} \quad \sum_u \frac{r'_{u,n_0}}{\tilde{r}'_{u,n_0}} \tag{8a}$$

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

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

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

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

$$R_{v,n_0,m} \geq R^{dm}_{v,n_0,m} \quad \forall v \forall m, \tag{8f}$$

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

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Puncturing Problem

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

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

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

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

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

$$r_{v,n_0,m_0} \geq \mathfrak{r}^{dm}_{v,n_0,m_0} \quad \forall v, \tag{9f}$$

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

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URLLC Problem's Optimal Substructure

- Given a time slot policy $(\hat{\boldsymbol{\beta}}_{n_0}, \hat{\boldsymbol{\delta}}_{n_0})$ where for $m = 0, \ldots, \mathfrak{m} - 1$, $(\hat{\boldsymbol{\beta}}_{n_0,m}, \hat{\boldsymbol{\delta}}_{n_0,m})$ solves the mth puncturing problem, then $(\hat{\boldsymbol{\beta}}_{n_0}, \hat{\boldsymbol{\delta}}_{n_0})$ is an optimal point for the URLLC problem[9].

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[9]Proof in supplementary

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Scheduling Problem

$$\underset{\gamma_{n_0,m_0}, \boldsymbol{\delta}_{n_0,m_0}}{\text{minimize}} \quad \sum_{v,s,l} c_{n_0,s,l} \gamma_{v,n_0,m_0,s,l} \tag{10a}$$

$$\text{subject to} \quad \sum_{s} \delta_{v,n_0,m_0,s} \leq 1 \qquad \forall v, \tag{10b}$$

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

$$\delta_{v,n_0,m_0,s} \in \{0,1\} \qquad \forall v \forall s, \tag{10d}$$

$$\sum_{v} \gamma_{v,n_0,m_0,s,l} \leq 1 \qquad \forall s \forall l, \tag{10e}$$

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

$$\gamma_{v,n_0,m_0,s,l} \in \{0,1\} \qquad \forall v \forall s \forall l \tag{10g}$$

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- The puncturing cost of subchannel is defined as

$$\forall n \colon \forall s \colon \forall l \colon c_{n,s,l} = \max_{u} \frac{\mathfrak{r}_{u,n,s,l}}{\tilde{r}'_{u,n}}. \tag{11}$$

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- The scheduling problem is equivalent to the puncturing problem[10].

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[10]Proof in supplementary

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- The scheduling problem is independent from α.

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Figure: Scheduling Problem

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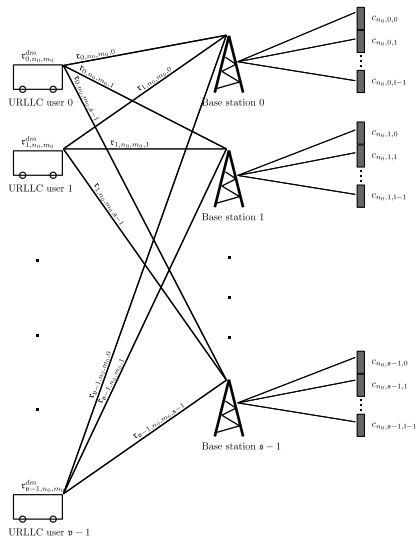
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Homogeneous Problem

$$\underset{\boldsymbol{\gamma}_{n_0,m_0}, \boldsymbol{\delta}_{n_0,m_0}}{\text{minimize}} \quad c_{n_0}^{mn} \sum_{v,s,l} \gamma_{v,n_0,m_0,s,l} \tag{12a}$$

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

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

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

$$\sum_v \gamma_{v,n_0,m_0,s,l} \leq 1 \qquad \forall s \forall l, \tag{12e}$$

$$\sum_{s,l} \gamma_{v,n_0,m_0,s,l} \geq \frac{\mathfrak{r}_{v,n_0,m_0}^{dm}}{\mathfrak{r}_{v,n_0,m_0}^{mx}} \ \forall v, \tag{12f}$$

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

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- The minimum puncturing cost is defined as

$$\forall n \colon c_n^{mn} = \min_{s,l} c_{n,s,l}. \tag{13}$$

- The maximum rate of URLLC user is defined as

$$\forall n \colon \forall m \colon \forall v \colon \mathfrak{r}_{v,n,m}^{mx} = \max_s \mathfrak{r}_{v,n,m,s}. \tag{14}$$

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- $c_{n_0}^{mn} \sum_v \left\lceil \frac{\mathfrak{r}_{v,n_0,m_0}^{dm}}{\mathfrak{r}_{v,n_0,m_0}^{mx}} \right\rceil$ is the optimal value for the homogeneous problem.

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- The nearest association algorithm defines the following point:

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

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

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- The nearest association algorithm is a $\frac{c_{n_0}^{mx}}{c_{n_0}^{mn}}$-approximation algorithm for the scheduling problem[11].

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[11]Proof in supplementary

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- The maximum puncturing cost is defined as

$$\forall n\colon c_n^{mx} = \max_{s,l} c_{n,s,l}. \tag{15}$$

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- The opportunistic nearest association algorithm defines the following point:

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

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

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- The opportunistic nearest association algorithm is an optimal algorithm for the scheduling problem in single-cell networks[12].

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[12]Proof in supplementary

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- The tightest association algorithm defines the following point:

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

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

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- The tightest association algorithm is a ρ-approximation algorithm for the scheduling problem[13].

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[13]Proof in supplementary

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

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Optimality
Heuristics

Simulation

- Compare performance with dedicated URLLC channel systems?
- Compare performance with [2] 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.

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Parameters

- 3 base stations in 24GHz, 72GHz, and 28GHz [6]
- 51 subchannels per base station
- 100 eMBB users
- 100 time slots
- 7 time minislots per time slot
- URLLC demand 0-1000 bits (32-200 bytes [1])
- 3 algorithms
  - Opportunistic Nearest Association Algorithm (ONAA)
  - Opportunistic Tightest Association Algorithm (OTAA)
  - Exhaustive Algorithm (EA)

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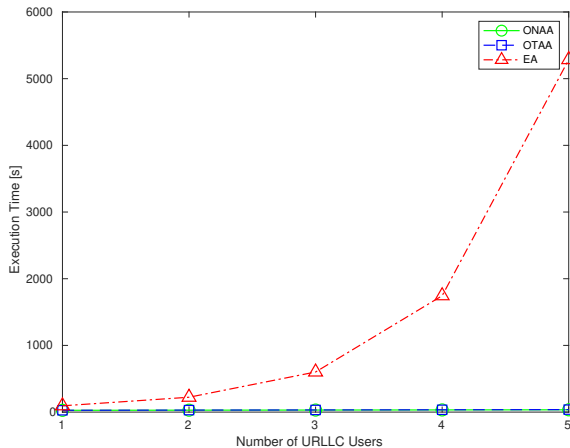
Figure: Optimality execution time

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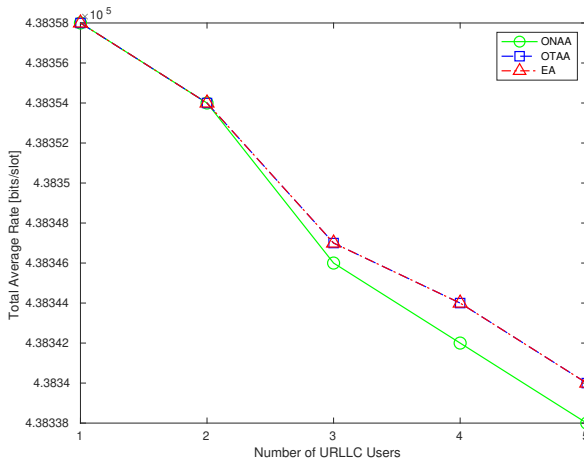
Figure: Optimality total average rates

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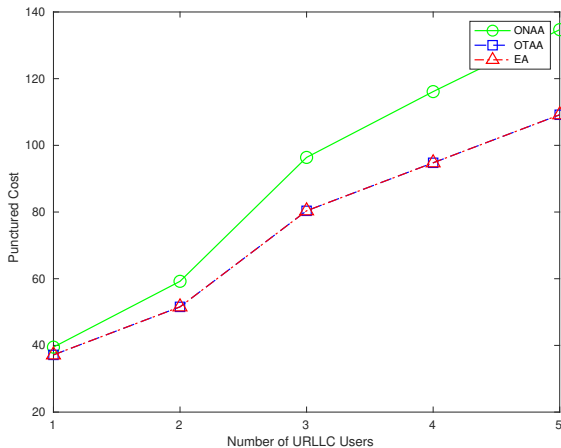
Figure: Optimality punctured costs

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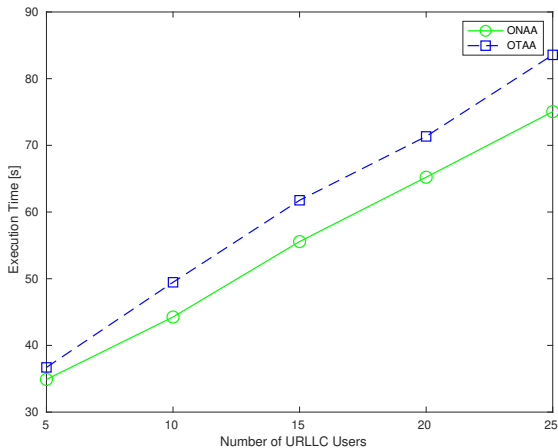
Figure: Heuristics execution time

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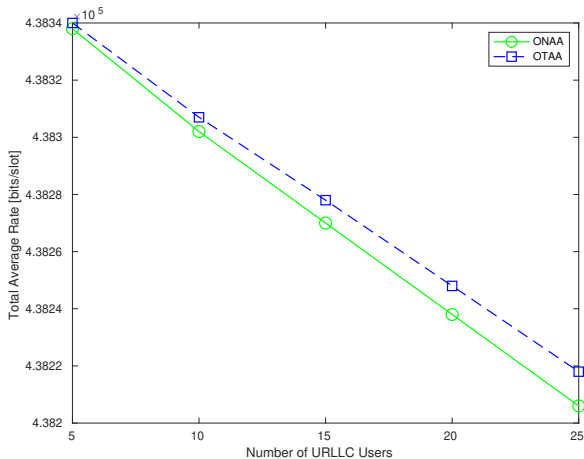
Figure: Heuristics total average rates

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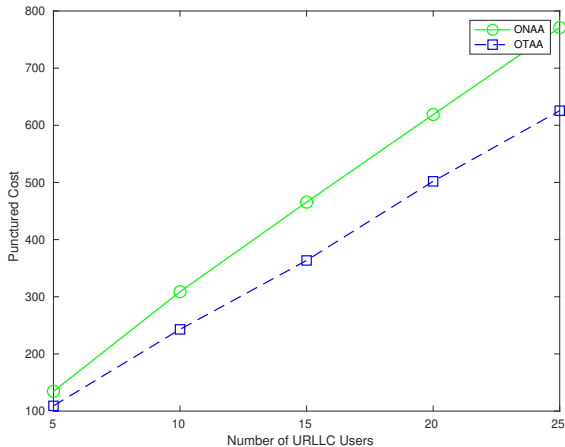
Figure: Heuristics punctured costs

Conclusion

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