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

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Introduction

Scenario

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

[1] mitigate path loss and shadowing
[2] improve spectrum efficiency for sparse URLLC traffic
[3] accommodate demands for bursty URLLC traffic

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.

[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.

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 [3] is generalized for eMBB resource allocation in multiconnectivity-based networks.
- The URLLC problem's optimal substructure is proved.
- A $\frac{c_{n_0}^{mx}}{c_{n_0}^{mn}}$-approximation algorithm, the nearest association algorithm, that jointly schedules URLLC resources and links in multicell networks is proposed.
- An optimal algorithm, the opportunistic nearest association algorithm, which allocates URLLC resources in single-cell networks is derived.

Related Work

- Current models for URLLC puncturing scheme in the literature are mostly non-linear [2].
- Whilst proposed linear models are either intractable [5] or inappropriate [1] for discrete subchannel allocation with multiple URLLC users.
- Many [2, 5] 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 [4]: 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.

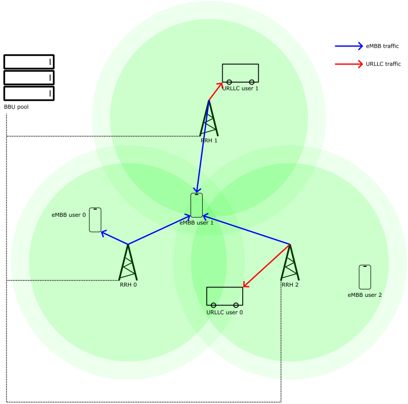

Figure: System model

Stochastic Problem

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

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

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

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

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

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

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

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

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

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

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

- 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):

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

- 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):

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

- 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):

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

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

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

[5] Proof in supplementary

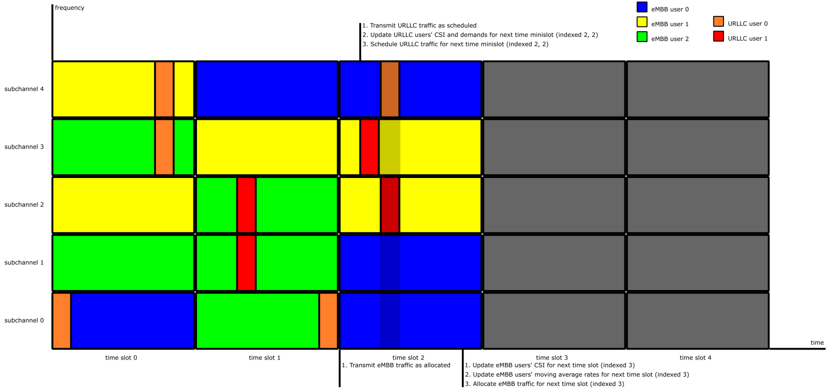

Figure: Multiplexing procedure

eMBB Problem

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

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

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

Relaxed eMBB Problem

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

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

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

Gradient Problem

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

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

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

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

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

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

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

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

[7] Proof 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 problem[8]:

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

[8] Proof in supplementary

URLLC Problem

$$
\begin{aligned}
\underset{\boldsymbol{\beta}_{n_0},\,\boldsymbol{\delta}_{n_0}}{\text{maximize}} \quad & \sum_{u} \frac{r'_{u,n_0}}{\tilde{r}'_{u,n_0}} && \text{(8a)} \\
\text{subject to} \quad & \sum_{s} \delta_{v,n_0,m,s} \leq 1 \qquad \forall v \forall m, && \text{(8b)} \\
& \beta_{v,u,n_0,m,s,l} \leq \delta_{v,n_0,m,s} \forall v \forall u \forall m \forall s \forall l, && \text{(8c)} \\
& \delta_{v,n_0,m,s} \in \{0,1\} \quad \forall v \forall m \forall s, && \text{(8d)} \\
& \sum_{v} \beta_{v,u,n_0,m,s,l} \leq \hat{\alpha}_{u,n_0,s,l} \forall u \forall m \forall s \forall l, && \text{(8e)} \\
& R_{v,n_0,m} \geq R^{dm}_{v,n_0,m} \ \forall v \forall m, && \text{(8f)} \\
& \beta_{v,u,n_0,m,s,l} \in \{0,1\} \quad \forall v \forall u \forall m \forall s \forall l && \text{(8g)}
\end{aligned}
$$

Puncturing Problem

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

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

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

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

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

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

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

URLLC Problem's Optimal Substructure

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

[9] Proof in supplementary

Scheduling Problem

$$\begin{aligned}
\underset{\gamma_{n_0,m_0},\,\delta_{n_0,m_0}}{\text{minimize}} \quad & \sum_{v,s,l} c_{n_0,s,l}\gamma_{v,n_0,m_0,s,l} && && \text{(10a)}\\
\text{subject to} \quad & \sum_{s} \delta_{v,n_0,m_0,s} \leq 1 && \forall v, && \text{(10b)}\\
& \gamma_{v,n_0,m_0,s,l} \leq \delta_{v,n_0,m_0,s} && \forall v \forall s \forall l, && \text{(10c)}\\
& \delta_{v,n_0,m_0,s} \in \{0,1\} && \forall v \forall s, && \text{(10d)}\\
& \sum_{v} \gamma_{v,n_0,m_0,s,l} \leq 1 && \forall s \forall l, && \text{(10e)}\\
& \sum_{s,l} \gamma_{v,n_0,m_0,s,l}\mathfrak{r}_{v,n_0,m_0,s} \geq \mathfrak{r}^{dm}_{v,n_0,m_0} && \forall v, && \text{(10f)}\\
& \gamma_{v,n_0,m_0,s,l} \in \{0,1\} && \forall v \forall s \forall l && \text{(10g)}
\end{aligned}$$

- The puncturing cost of subchannel is defined as

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

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

[10] Proof in supplementary

- The scheduling problem is independent from α.

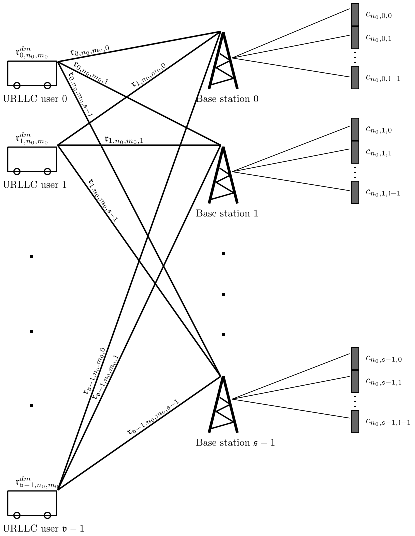

Figure: Scheduling Problem

Homogeneous Problem

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

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

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

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

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

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

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

- 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

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

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

- The nearest association algorithm defines the following point:

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

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

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

[11] Proof in supplementary

- The maximum puncturing cost is defined as

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

- The opportunistic nearest association algorithm defines the following point:

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

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

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

[12] Proof in supplementary

Simulation

- Compare performance with dedicated URLLC channel systems?
- Compare performance with [1] in single-cell networks with one URLLC user.
- Compare performance with [5] in single-cell networks with multiple URLLC users?
- Compare performance of nearest association algorithm and opportunistic nearest association algorithm in multicell networks.

Conclusion

References

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