eMBB Multiconnectivity URLLC Multicell eMBB URLLC Puncturing

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System

- Homogeneous base stations, mmWave, downlink transmission, OFDMA, multiple-input eMBB and single-input URLLC users.
- Saturated eMBB traffic [4]: Each eMBB user has infinite amount of data to be served.
- Strict URLLC constraint: Each URLLC 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.

Scenario

- There are approximately 750 people per 1000 square meters living in suburban area[1][3].
- These are potential eMBB users, who surf the Web, watching videos, and download data.
- During work hours and at night, only a few self-driving vehicles operate that employ URLLC utilities.
  - Uplink transmission (whose bandwidth is independent from that of downlink) is used to upload the vehicles' observations e.g. camera images, sensors data, etc. to the cloud for navigation processing.
  - Downlink transmission accounts for the automobiles' control messages.

[1] Example

Poor Edge Service

- Since mmWave is extremely vulnerable to path loss, URLLC reliability is not guaranteed.
- Similarly, eMBB users at cell edges experience low throughput.

- URLLC multicell and eMBB multiconnectivity are prominent candidates to mitigate this issue.

Singlecell

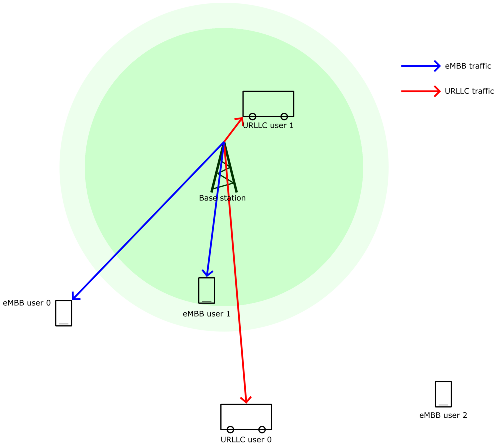

Figure: Singlecell model

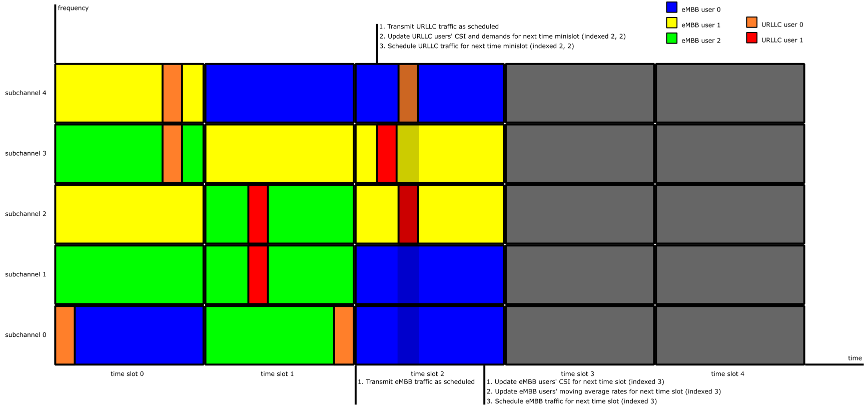

Figure: Singlecell framework

Multicell

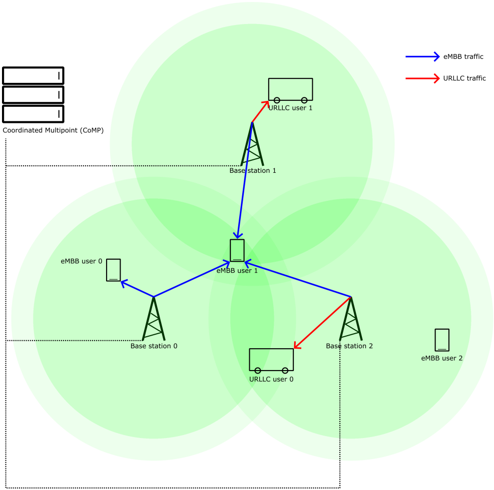

Figure: Multicell model

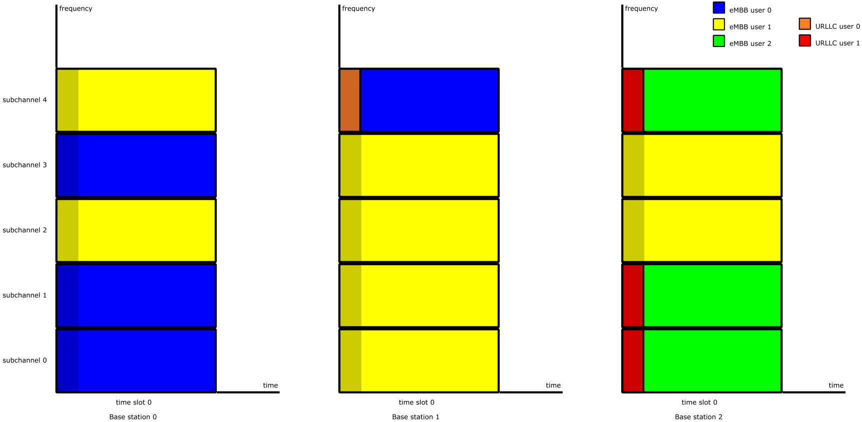

Figure: Multicell framework

Multicell Co-channel Interference

- Since the base stations are homogeneous i.e. use the same frequency band, there exists 3 types of interference:
  - eMBB-eMBB inteference e.g. at subchannel 3, signal from base station 0 to eMBB user 0 interferes with that from base station 1 to eMBB user 1.
  - eMBB-URLLC interference e.g. at subchannel 0, signal from base station 0 to eMBB user 0 interferes with that from base station 2 to URLLC user 1.
  - URLLC-URLLC interference e.g. at subchannel 4, signal from base station 1 to URLLC user 0 interferes with that from base station 2 to URLLC user 1.

- A viable solution might be 5G Non-orthogonal Multiple Access (NOMA) with Successive Interference Cancellation (SIC).
- Inspired by Low-Energy Adaptive Clustering Hierarchy (LEACH), we propose an orthogonal multiple access (OMA) scheme based on 3G Code Division Multiple Access (CDMA) to tackle the problem[2].

[2] Example

- Our scheme works well with the often small number of base stations.
- Our scheme encompasses URLLC multiconnectivity via joint transmission.
- This hence introduces a joint CDMA/OFDMA scheme.

Spectrum Inefficiency

- Dedicated URLLC bandwidth wastes spectral resources significantly in multicell systems.
  - If 2 subchannels of each base station are dedicated to URLLC traffic, then we would have 6 subchannels sitting idle for most of the time in the aforementioned scenario.

- This problem can be addressed by leveraging URLLC superposition/puncturing scheme.
- URLLC superposition scheme employs 5G NOMA SIC, whose performance equals to puncturing when the considered eMBB and URLLC users have the same channel gain.
- URLLC puncturing scheme is discussed here.

Problem

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

subject to

$$\sum_{s} \gamma_{u,n,s} \leq \mathfrak{a}_u \qquad \forall u \forall n, \tag{1b}$$

$$\alpha_{u,n,s,l} \leq \gamma_{u,n,s} \quad \forall u \forall n \forall s \forall l, \tag{1c}$$

$$\gamma_{u,n,s} \in \{0,1\} \quad \forall u \forall n \forall s, \tag{1d}$$

$$\sum_{u} \alpha_{u,n,s,l} \leq 1 \qquad \forall n \forall s \forall l, \tag{1e}$$

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

$$\sum_{s} \delta_{v,n,m,s} \leq 1 \qquad \forall v \forall n \forall m, \tag{1g}$$

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

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

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

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

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

- The system maximizes eMBB traffic's total average rate and fairness (1a).
- For each time slot, the system
  - complies with the multiconnectivity capabilities of eMBB users (1b).
  - schedules a subchannel to an eMBB user only if it associates the corresponding base station to the user (1c).
  - either un-associates or associates a base station to an eMBB user (1d).
  - schedules a subchannel to at most one eMBB user (1e).
  - either un-schedules or schedules a subchannel to an eMBB user (1f).

- For each time minislot, the system
  - associates at most one base station to a URLLC user (1g).
  - schedules a subchannel to a URLLC user only if it associates the corresponding base station to the user (1h).
  - either un-associates or associates a base station to a URLLC user (1i).
  - schedules a subchannel to at most one URLLC user, and punctures the subchannel for a URLLC user only if it schedules the subchannel to the corresponding eMBB user (1j)[3].
  - serves demands of URLLC users without delays (1k).
  - employs URLLC puncturing scheme instead of superposition (1l).

[3] Proof in supplementary

- Do note that current eMBB users' rate 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 scheduling with multiple URLLC users.

eMBB Problem

$$\underset{\boldsymbol{\alpha},\boldsymbol{\gamma}}{\text{maximize}} \quad \sum_u \ln \bar{R}_u \tag{2a}$$

$$\text{subject to} \quad \sum_s \gamma_{u,n,s} \leq \mathfrak{a}_u \quad \forall u \forall n, \tag{2b}$$

$$\alpha_{u,n,s,l} \leq \gamma_{u,n,s} \forall u \forall n \forall s \forall l, \tag{2c}$$

$$\gamma_{u,n,s} \in \{0,1\} \forall u \forall n \forall s, \tag{2d}$$

$$\sum_u \alpha_{u,n,s,l} \leq 1 \quad \forall n \forall s \forall l, \tag{2e}$$

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

Relaxed eMBB Problem

$$
\begin{aligned}
\underset{\boldsymbol{\alpha}', \boldsymbol{\gamma}'}{\text{maximize}} \quad & \sum_{u} \ln \bar{R}'_u && \text{(3a)}\\
\text{subject to} \quad & \sum_{s} \gamma'_{u,n,s} \leq \mathfrak{a}_u \quad \forall u \forall n, && \text{(3b)}\\
& \alpha'_{u,n,s,l} \leq \gamma'_{u,n,s} \forall u \forall n \forall s \forall l, && \text{(3c)}\\
& \gamma'_{u,n,s} \leq 1 \quad \forall u \forall n \forall s, && \text{(3d)}\\
& \gamma'_{u,n,s} \geq 0 \quad \forall u \forall n \forall s, && \text{(3e)}\\
& \sum_{u} \alpha'_{u,n,s,l} \leq 1 \quad \forall n \forall s \forall l, && \text{(3f)}\\
& \alpha'_{u,n,s,l} \geq 0 \quad \forall u \forall n \forall s \forall l && \text{(3g)}
\end{aligned}
$$

Gradient Problem

$$
\begin{aligned}
\underset{\boldsymbol{\alpha}'_{n_0}, \boldsymbol{\gamma}'_{n_0}}{\text{maximize}} \quad & \sum_u \frac{r'_{u,n_0}}{\tilde{r}'_{u,n_0}} && (4a)\\
\text{subject to} \quad & \sum_s \gamma'_{u,n_0,s} \leq \mathfrak{a}_u \quad \forall u, && (4b)\\
& \alpha'_{u,n_0,s,l} \leq \gamma'_{u,n_0,s} \forall u \forall s \forall l, && (4c)\\
& \gamma'_{u,n_0,s} \leq 1 \quad \forall u \forall s, && (4d)\\
& \gamma'_{u,n_0,s} \geq 0 \quad \forall u \forall s, && (4e)\\
& \sum_u \alpha'_{u,n_0,s,l} \leq 1 \quad \forall s \forall l, && (4f)\\
& \alpha'_{u,n_0,s,l} \geq 0 \quad \forall u \forall s \forall l && (4g)
\end{aligned}
$$

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

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

- The initial value of which is defined by the feasible policy $(\hat{\boldsymbol{\alpha}}', \hat{\boldsymbol{\gamma}}')$ for the relaxed eMBB problem where[4]

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

$$\hat{\gamma}'_{u,n,s} = \begin{cases} \frac{\mathfrak{a}_u}{\mathfrak{s}} & n = 0 \\ 0 & n = 1, \ldots, \mathfrak{n} - 1 \end{cases} \qquad \forall u \forall s. \tag{7}$$

[4] Proof in supplementary

- Our set of policy(ies) is defined as

$$\mathcal{P} = \left\{ (\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\gamma}}) \middle| \begin{array}{r} \forall n\colon (\hat{\boldsymbol{\alpha}}_n, \hat{\boldsymbol{\gamma}}_n) \text{ is a basic optimal point} \\ \text{of } n^{th} \text{ gradient problem} \end{array} \right\}. \tag{8}$$

- $\forall(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\gamma}}) \in \mathcal{P}$: $(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\gamma}})$ is an asymptotically optimal policy for the eMBB problem[5].

[5] Proof in supplementary

References

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[3] Richard Florida. *How Should We Define the Suburbs?* 2019. URL: https://www.bloomberg.com/news/articles/2019-06-12/why-we-need-a-standard-definition-of-the-suburbs (visited on 07/13/2022).

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