

# 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<sup>1</sup>[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.

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<sup>1</sup>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

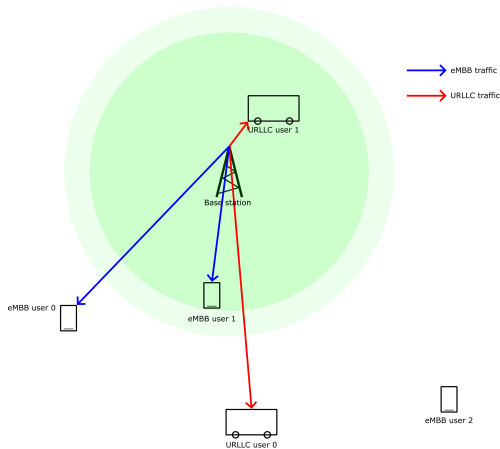


Figure: Singlecell model

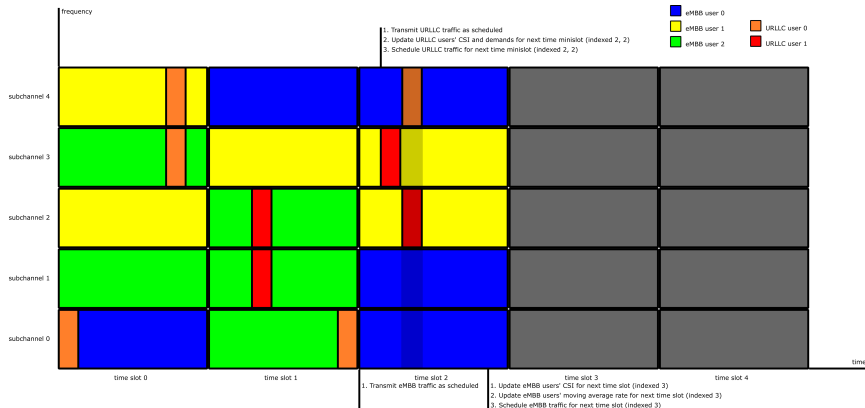


Figure: Singlecell framework

# Multicell

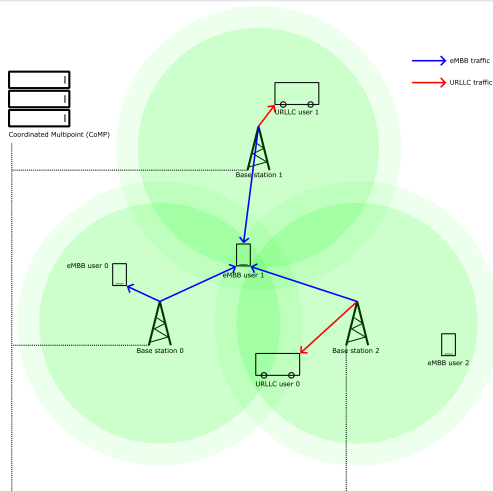


Figure: Multicell model



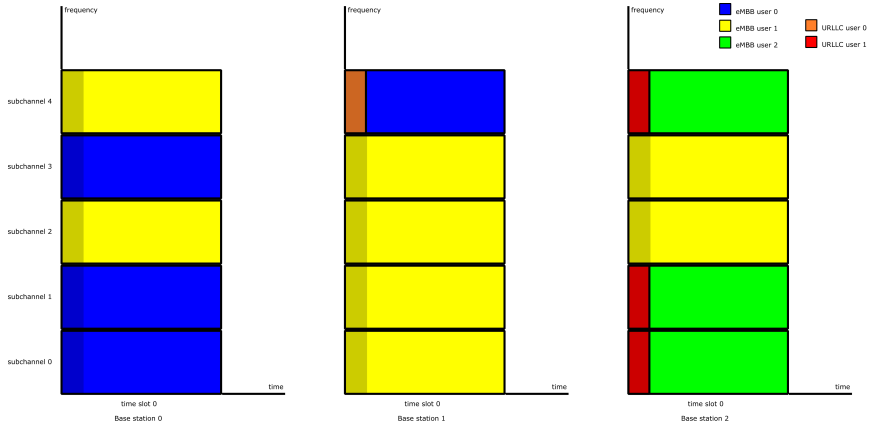


Figure: Multicell framework

# 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 interference 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<sup>2</sup>.

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<sup>2</sup>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.

## Offline

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

$$\text{subject to} \quad \sum_s \gamma_{u,n,s} \leq a_u \quad \forall u \forall n, \quad (1b)$$

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

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

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

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

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

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

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

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

$$r_{v,n,m} \geq R_{v,n,m} \quad \forall v \forall n \forall m, \quad (1k)$$

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

- 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)<sup>3</sup>.
  - serves demands of URLLC users without delays (1k).
  - employs URLLC puncturing scheme instead of superposition (1l).

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<sup>3</sup>Proof in supplementary

- Do note that eMBB users' rate models for URLLC puncturing scheme in the current literature are mostly non-linear [2].
- On the other hand, proposed linear models are either intractable [5] or inappropriate [1] for discrete subchannel scheduling with multiple URLLC users.

## Offline eMBB

$$\begin{aligned} & \underset{\alpha, \gamma}{\text{maximize}} && \sum_u \ln \bar{r}_u && (2a) \end{aligned}$$

$$\begin{aligned} & \text{subject to} && \sum_s \gamma_{u,n,s} \leq \mathbf{a}_u \quad \forall u \forall n, && (2b) \end{aligned}$$

$$\alpha_{u,n,s,l} \leq \gamma_{u,n,s} \quad \forall u \forall n \forall s \forall l, \quad (2c)$$

$$\gamma_{u,n,s} \in \{0, 1\} \quad \forall u \forall n \forall s, \quad (2d)$$

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

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

## Relaxed Offline eMBB

$$\begin{aligned} & \underset{\alpha', \gamma'}{\text{maximize}} && \sum_u \ln \bar{r}'_u && (3a) \end{aligned}$$

$$\begin{aligned} & \text{subject to} && \sum_s \gamma'_{u,n,s} \leq \mathbf{a}_u && \forall u \forall n, && (3b) \end{aligned}$$

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

$$\gamma'_{u,n,s} \leq 1 \quad \forall u \forall n \forall s, \quad (3d)$$

$$\gamma'_{u,n,s} \geq 0 \quad \forall u \forall n \forall s, \quad (3e)$$

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

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

## Relaxed Online eMBB

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

$$\text{subject to} \quad \sum_s \gamma'_{u,n_0,s} \leq \mathbf{a}_u \quad \forall u, \quad (4b)$$

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

$$\gamma'_{u,n_0,s} \leq 1 \quad \forall u \forall s, \quad (4d)$$

$$\gamma'_{u,n_0,s} \geq 0 \quad \forall u \forall s, \quad (4e)$$

$$\sum_u \alpha'_{u,n_0,s,l} \leq 1 \quad \forall s \forall l, \quad (4f)$$

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

# References

- [1] Arjun Anand, Gustavo de Veciana, and Sanjay Shakkottai. "Joint Scheduling of URLLC and eMBB Traffic in 5G Wireless Networks". In: *IEEE/ACM Transactions on Networking* 28.2 (2020), pp. 477–490. DOI: 10.1109/TNET.2020.2968373.
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