Multiplexing URLLC Traffic Within eMBB Services in 5G NR: Fair Scheduling

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System Model

- One base station, downlink transmission, eMBB and URLLC users.
- Saturated eMBB traffic [1]: Each eMBB user has infinite amount of data to be served.

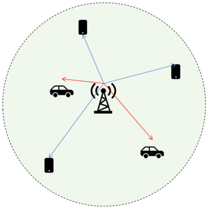

Figure: System model

System Framework

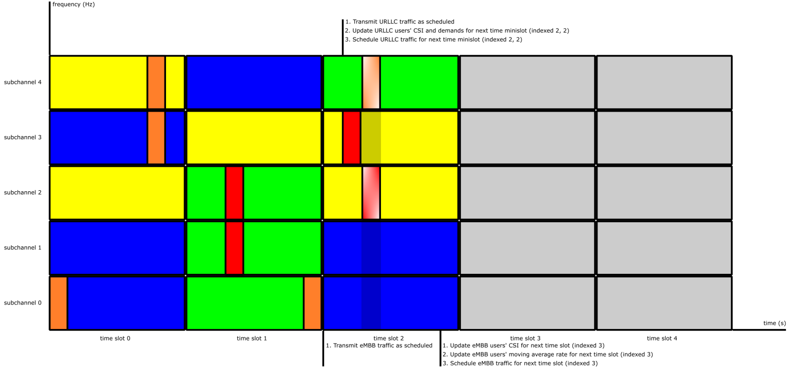

Figure: System framework

Offline URLLC Puncturing

- The system maximizes eMBB traffic's total average rate and fairness (1a).
- For each time slot, the system allocates at most one eMBB user to each subchannel (1b).
- For each time slot, the system either schedules or un-schedules a subchannel to each eMBB user (1c).
- For each time minislot, the system allocates at most one URLLC user to each subchannel. Also, it schedules l^{th} subchannel from u^{th} eMBB user to a URLLC user only if it schedules the subchannel to the eMBB user (1d).
- For each time minislot, the system serves URLLC demands without delay (1e).
- For each time minislot, the system employs URLLC puncturing instead of superposition (1f).

Offline URLLC Puncturing (Continued)

$$
\begin{aligned}
\underset{\boldsymbol{\alpha},\boldsymbol{\beta}}{\text{maximize}} \quad & \sum_u \ln \bar{r}_u && && \text{(1a)}\\
\text{subject to} \quad & \sum_u \alpha_{u,n,l} \le 1, && \forall n, \forall l, && \text{(1b)}\\
& \alpha_{u,n,l} \in \{0,1\}, && \forall u, \forall n, \forall l, && \text{(1c)}\\
& \sum_v \beta_{v,u,n,m,l} \le \alpha_{u,n,l}, && \forall u, \forall n, \forall m, \forall l, && \text{(1d)}\\
& r_{v,n,m} \ge R_{v,n,m}, && \forall v, \forall n, \forall m, && \text{(1e)}\\
& \beta_{v,u,n,m,l} \in \{0,1\}, && \forall v, \forall u, \forall n, \forall m, \forall l && \text{(1f)}
\end{aligned}
$$

Offline URLLC Puncturing (Continued)

where

$$\bar{r}_u = \frac{1}{\mathfrak{n}} \sum_{n,m,l} \left(\alpha_{u,n,l} - \sum_{v} \beta_{v,u,n,m,l} \right) \frac{\mathfrak{r}_{u,n,l}}{\mathfrak{m}}, \quad \forall u \tag{2}$$

$$r_{v,n,m} = \sum_{u,l} \beta_{v,u,n,m,l} \mathfrak{r}_{v,n,m}, \quad \forall v, \forall n, \forall m \tag{3}$$

$$\mathfrak{r}_{v,n,m} = \min_{l} \{\mathfrak{r}_{v,n,m,l}\}, \quad \forall v, \forall n, \forall m \tag{4}$$

Channel Model – Path Loss and Shadowing

- Large-scale propagation path loss model (power in W)

$$\frac{\mathfrak{p}_{tx}}{p_{rx}(f,d)} = h(f,d) \tag{5}$$

$$p_{rx}^{dB}(f,d) = \mathfrak{p}_{tx}^{dB} - h^{dB}(f,d) \tag{6}$$

- Close-in (CI) free space reference distance model

$$h^{dB}(f,d) = 20\log_{10}\frac{4\pi f}{3\cdot 10^8} + 10\epsilon_{pl}\log_{10} d + \sigma_{sd}^{dB} \tag{7}$$

- Path loss exponent and shadowing standard deviation for urban macro-cellular (UMa) line-of-sight (LoS) over frequency and 3D distance ranging from 2 to 73.5GHz and 58 to 930m are derived as [2]

$$\epsilon_{pl} = 2 \tag{8}$$

$$\sigma_{sd}^{dB} = 4.6 \tag{9}$$

Channel Model – Co-channel Interference and Thermal Noise

- Shannon-Hartley theorem (bandwidth in Hz, time in s)

$$\mathfrak{r}_{u,n,l} = \mathfrak{w}_{sc} \log_2 \left(1 + \frac{p_{rx}^{dB}(\mathfrak{f}_l, \mathfrak{d}_{u,n})}{\mathfrak{i}_l^{dB} + \mathfrak{o}_{sc}^{dB}}\right) \mathfrak{t}_{sl} \left[\frac{bits}{slot}\right],$$
$$\forall u, \forall n, \forall l$$
$$\mathfrak{r}_{v,n,m,l} = \mathfrak{w}_{sc} \log_2 \left(1 + \frac{p_{rx}^{dB}(\mathfrak{f}_l, \mathfrak{d}_{v,n,m})}{\mathfrak{i}_l^{dB} + \mathfrak{o}_{sc}^{dB}}\right) \mathfrak{t}_{ms} \left[\frac{bits}{minislot}\right],$$
$$\forall v, \forall n, \forall m, \forall l$$

- where

$$\mathfrak{t}_{ms} = \frac{\mathfrak{t}_{sl}}{\mathfrak{m}} \tag{10}$$

- Channel fading and inter-symbol interference (ISI) are not considered.

References

[1] Alexander L. Stolyar. "On the Asymptotic Optimality of the Gradient Scheduling Algorithm for Multiuser Throughput Allocation". In: *Operations Research* 53.1 (2005), pp. 12–25. DOI: 10.1287/opre.1040.0156.

[2] Shu Sun et al. "Propagation Path Loss Models for 5G Urban Micro- and Macro-Cellular Scenarios". In: *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*. 2016, pp. 1–6. DOI: 10.1109/VTCSpring.2016.7504435.