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

Hao Yin, Lyutianyang Zhang, Sumit Roy

Department of Electrical and Computer Engineering, University of Washington, Seattle, USA

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System Model

- One base station, downlink transmission, orthogonal frequency-division multiple accses (OFDMA), eMBB and URLLC users.
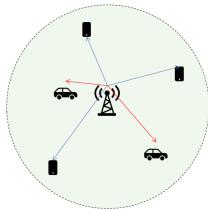- Saturated eMBB traffic [1]: Each eMBB user has infinite amount of data to be served.

Figure: System model

Numerology

- $\mu = 2$ for mmWave 28GHz is used ($\mu \in \{0, 1\}$ is for Sub-6GHz).

- Subchannel bandwidth

$$\mathfrak{w}_{sc} = 2^{\mu} \cdot 15 \qquad [kHz] \qquad (1)$$
$$= 60 \qquad [kHz] \qquad (2)$$
$$= 6 \cdot 10^{4} \qquad [Hz] \qquad (3)$$

- Time slot duration

$$\mathfrak{t}_{sl} = \frac{1}{2^{\mu}} \qquad [ms] \qquad (4)$$
$$= 0.25 \qquad [ms] \qquad (5)$$
$$= 2.5 \cdot 10^{-4} \qquad [s] \qquad (6)$$

Numerology (Continued)

time frame (10ms) = 10 x time subframe

time subframe (1ms) = 4 x time slot

time slot (0.25ms) = 7 x time minislot

subchannel bandwidth (60kHz)

time minislot (1/28ms)

Figure: Numerology

System Framework

- 3 eMBB users $\{0, 1, 2\}$.
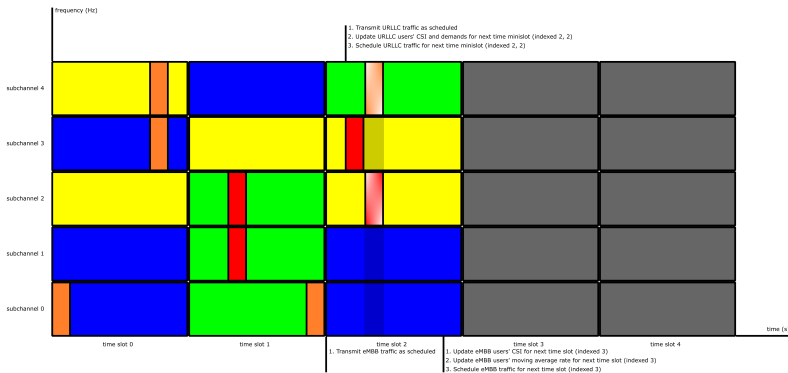- 2 URLLC users $\{0, 1\}$.

Figure: System framework

Offline URLLC Puncturing

- The system maximizes eMBB traffic's total average rate and fairness (7a).

- For each time slot, the system allocates at most one eMBB user to each subchannel (7b).

- For each time slot, the system either schedules or un-schedules a subchannel to each eMBB user (7c).

- For each time minislot, the system allocates at most one URLLC user to each subchannel. Also, it schedules I^{th} subchannel from u^{th} eMBB user to a URLLC user only if it schedules the subchannel to the eMBB user (7d).

- For each time minislot, the system serves URLLC demands without delay (7e).

- For each time minislot, the system employs URLLC puncturing instead of superposition (7f).

$$\underset{\boldsymbol{\alpha}, \boldsymbol{\beta}}{\text{maximize}} \quad \sum_u \ln \bar{r}_u \tag{7a}$$

$$\text{subject to} \quad \sum_u \alpha_{u,n,l} \leq 1, \qquad \forall n, \forall l, \tag{7b}$$

$$\alpha_{u,n,l} \in \{0,1\}, \quad \forall u, \forall n, \forall l, \tag{7c}$$

$$\sum_v \beta_{v,u,n,m,l} \leq \alpha_{u,n,l}, \quad \forall u, \forall n, \forall m, \forall l, \tag{7d}$$

$$r_{v,n,m} \geq R_{v,n,m}, \quad \forall v, \forall n, \forall m, \tag{7e}$$

$$\beta_{v,u,n,m,l} \in \{0,1\}, \quad \forall v, \forall u, \forall n, \forall m, \forall l \tag{7f}$$

where

$$\bar{r}_u = \frac{1}{\mathfrak{n}} \sum_{n,m,l} \left(\alpha_{u,n,l} - \sum_v \beta_{v,u,n,m,l} \right) \frac{\mathfrak{r}_{u,n,l}}{\mathfrak{m}}, \quad \forall u \qquad (8)$$

$$r_{v,n,m} = \sum_{u,l} \beta_{v,u,n,m,l} \mathfrak{r}_{v,n,m}, \quad \forall v, \forall n, \forall m \qquad (9)$$

$$\mathfrak{r}_{v,n,m} = \min_l \{ \mathfrak{r}_{v,n,m,l} \}, \quad \forall v, \forall n, \forall m \qquad (10)$$

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

$$\frac{\mathfrak{p}_{tx}}{p_{rx}(f,d)} = h(f,d) \tag{11}$$

$$p_{rx}^{dB}(f,d) = \mathfrak{p}_{tx}^{dB} - h^{dB}(f,d) \tag{12}$$

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

$$h^{dB}(f,d) = 20 \log_{10} \frac{4\pi f}{3 \cdot 10^8} + 10\epsilon_{pl} \log_{10} d + \sigma_{sd}^{dB} \tag{13}$$

- 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]

$$\epsilon_{pl} = 2 \tag{14}$$

$$\sigma_{sd}^{dB} = 4.6 \tag{15}$$

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

$$\mathfrak{t}_{ms} = \frac{\mathfrak{t}_{sl}}{\mathfrak{m}} \tag{16}$$

- 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.