

# Joint Scheduling of URLLC and eMBB Traffic in 5G Wireless Networks

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# System Model

- Saturated system [1]: Each eMBB user has infinite amount of data to be served.

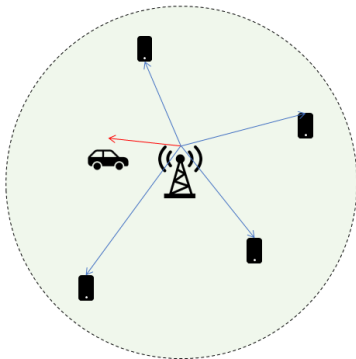


Figure: System model

# System Framework

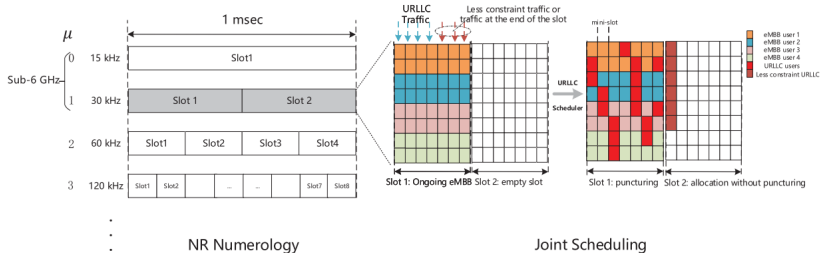


Figure: System framework [2]

# Problem Statement

- URLLC puncturing/superposition commonly used scheduling procedure: allocate *subchannels* for eMBB users in the given time slot first, then schedule *resources* for URLLC users in the respective time minislots accordingly.
- Multiplexing – conducting eMBB resource allocation using only eMBB channel state information (CSI) – has been broadly discussed in the literature.
- However, joint scheduling of eMBB and URLLC traffics has not been well studied.
- That is, in addition to eMBB CSI, could we also leverage URLLC information (e.g. *observed* behavior of URLLC demands, any others?) to schedule eMBB?

- Discussion with Yung-Ching senpai: Reduce eMBB retransmissions of data damaged by URLLC puncturing/superposition.
  - Approach 1: Reserve resources for URLLC traffic.
  - Approach 2: Pre-allocate resources for some URLLC users (less overhead compared to the first method, which increases URLLC reliability).
- However, their paper does not address the aforementioned problems, but aims to tackle two questions:
  - For linear loss model, would the traditional multiplexing procedure be optimal in the long-term?
  - For convex loss model, could we somehow incorporate URLLC demands into eMBB resource allocation formulation?

- The main idea is to perform mathematical analysis on eMBB time slot.
- This is done by their model 'proportion of an eMBB time slot's resource'.
- Linear, convex, and threshold loss models are discussed.

# Linear Loss Model

- A URLLC *puncturing* problem is formulated as follows:

$$\begin{aligned} & \underset{\alpha, \beta}{\text{maximize}} && \sum_u \ln(\bar{r}_u) \\ & \text{subject to} && \sum_u \alpha_{u,n,l} \leq \frac{1}{l}, \quad \forall n, \forall l, \\ & && \alpha_{u,n,l} \in \left\{0, \frac{1}{l}\right\}, \quad \forall u, \forall n, \forall l, \\ & && \sum_u \sum_l \beta_{v_0,u,n,m,l} = D_{v_0,n,m}, \quad \forall n, \forall m, \\ & && \beta_{v_0,u,n,m,l} \leq \alpha_{u,n,m,l}, \quad \forall u, \forall n, \forall m, \forall l, \\ & && \beta_{v_0,u,n,m,l} \in \left\{0, \frac{1}{ml}\right\}, \quad \forall u, \forall n, \forall m, \forall l \end{aligned} \tag{1}$$

- where

$$\alpha_{u,n,m,l} = \frac{\alpha_{u,n,l}}{m}, \quad \forall u, \forall n, \forall m, \forall l \tag{2}$$

# Linear Loss Model (Continued)

- The average rate is calculated as follows.

$$\bar{r}_u = \frac{r_{u,0} + r_{u,1} + \dots + r_{u,n-1}}{n} \quad (3)$$

$$= \frac{1}{n} \sum_n r_{u,n} \quad (4)$$

$$= \frac{1}{n} \sum_n \sum_l r_{u,n,l} \quad (5)$$

$$= \frac{1}{n} \sum_n \sum_l (\alpha_{u,n,l} - \beta_{v_0,u,n,l}) r_{u,n,l}, \quad \forall u \quad (6)$$

- In this paper, subchannel allocation is neglected.

$$\bar{r}_u = \frac{1}{n} \sum_n r_{u,n} \quad (7)$$

$$= \frac{1}{n} \sum_n (\alpha_{u,n} - \beta_{v_0,u,n}) r_{u,n}, \quad \forall u \quad (8)$$



# Linear Loss Model (Continued)

- The first idea that comes to my mind is to give each eMBB user an equal share of URLLC demands.

$$\beta_{v_0,u,n,m} = \frac{D_{v_0,n,m}}{u}, \quad \forall u, \forall n, \forall m \quad (9)$$

- However, this cannot guarantee

$$\beta_{v_0,u,n,m} \leq \alpha_{u,n,m}, \quad \forall u, \forall n, \forall m. \quad (10)$$

- It is then intuitive to give each eMBB user a proportionally equal share of URLLC demands.

$$\beta_{v_0,u,n,m} = \frac{\alpha_{u,n,m}}{\frac{1}{m}} D_{v_0,n,m} \quad (11)$$

$$= \alpha_{u,n} D_{v_0,n,m} \quad (12)$$

# Linear Loss Model (Continued)

- Such an allocation guarantees URLLC constraints:

$$\sum_u \beta_{v_0,u,n,m} = D_{v_0,n,m}, \quad \forall n, \forall m, \quad (13)$$

$$\beta_{v_0,u,n,m} \leq \alpha_{u,n,m}, \quad \forall u, \forall n, \forall m. \quad (14)$$

- URLLC allocation in eMBB time slot can then be derived:

$$\beta_{v_0,u,n} = \sum_m \beta_{v_0,u,n,m} \quad (15)$$

$$= \alpha_{u,n} \sum_m D_{v_0,n,m} \quad (16)$$

$$= \alpha_{u,n} D_{v_0,n} \quad (17)$$

# Linear Loss Model (Continued)

## Theorem 1

For a wireless system under the linear superposition/puncturing loss model we have that  $C = C^{LR}$

- By this theorem, the proportionally equal share policy is optimal.

$$\bar{r}_u = \frac{1}{n} \sum_n (\alpha_{u,n} - \alpha_{u,n} D_{v_0,n}) \mathbf{r}_{u,n} \quad (18)$$

$$= \frac{1}{n} \sum_n (1 - D_{v_0,n}) \alpha_{u,n} \mathbf{r}_{u,n}, \quad \forall u \quad (19)$$

- Do note that URLLC allocation disappears from the objective function of Problem 1, and URLLC demands are constants.

# Linear Loss Model (Continued)

- This problem then can be solved with gradient algorithm [1].

$$\begin{aligned} & \underset{\alpha}{\text{maximize}} && \sum_u \ln(\bar{r}_u) \\ & \text{subject to} && \sum_u \alpha_{u,n,l} \leq \frac{1}{l}, \quad \forall n, \forall l, \\ & && \alpha_{u,n,l} \in \{0, \frac{1}{l}\}, \quad \forall u, \forall n, \forall l \end{aligned} \quad (20)$$

- However, this paper does not execute two problem transformations required to apply the above algorithm.

- Recall that

$$\bar{r}_u = \frac{1}{n} \sum_n r_{u,n} \quad (21)$$

$$= \frac{1}{n} \sum_n (\alpha_{u,n} - \alpha_{u,n} f(x)) r_{u,n} \quad (22)$$

- where  $f(\cdot)$  is a convex function, and

$$x = \frac{\beta_{v_0, u, n}}{\alpha_{u, n}} \quad (23)$$

- Thus

$$\bar{r}_u = \frac{1}{n} \sum_n \left( \alpha_{u,n} - \alpha_{u,n} f\left(\frac{\sum_m \beta_{v_0, u, n, m}}{\alpha_{u, n}}\right) \right) r_{u,n}, \quad \forall u \quad (24)$$

# Convex Loss Model (Continued)

- They first fluidize the bandwidth:

$$\begin{aligned} & \underset{\alpha, \beta}{\text{maximize}} && \sum_u \ln(\bar{r}_u) \\ & \text{subject to} && \sum_u \alpha_{u,n} = 1 \quad \forall n, \\ & && \alpha_{u,n} \geq 0 \quad \forall u, \forall n, \\ & && \sum_u \beta_{v_0, u, n, m} = D_{v_0, n, m} \quad \forall n, \forall m, \\ & && \beta_{v_0, u, n, m} \leq \alpha_{u, n, m} \quad \forall u, \forall n, \forall m, \\ & && \beta_{v_0, u, n, m} \geq 0 \quad \forall u, \forall n, \forall m \end{aligned} \tag{25}$$

- where

$$\alpha_{u, n, m} = \frac{\alpha_{u, n}}{m}, \quad \forall u, \forall n, \forall m \tag{26}$$

# Convex Loss Model (Continued)

- I can prove the objective function is concave (by perspective function), and that this is a convex optimization problem.
- Nevertheless, how can we allocate eMBB *resources* for the current eMBB time slot if the problem depends on unknown URLLC demands in the future?



# Convex Loss Model (Continued)

- Assume minislot-homogeneous policy:

$$\beta_{v_0,u,n,m} = \frac{\frac{\gamma_{v_0,u,n}}{m}}{\frac{1}{m}} D_{v_0,n,m} \quad (27)$$

$$= \gamma_{v_0,u,n} D_{v_0,n,m}, \quad \forall u, \forall n, \forall m, \quad (28)$$

- where

$$\gamma_{v_0,u,n} \geq 0, \quad \forall u, \forall n \quad (29)$$

$$\sum_u \gamma_{v_0,u,n} = 1, \quad \forall n. \quad (30)$$

- Thus

$$\sum_u \beta_{v_0,u,n,m} = D_{v_0,n,m}, \quad \forall n, \forall m \quad (31)$$

# Convex Loss Model (Continued)

- If

$$\frac{\alpha_{u,n}}{\gamma_{v_0,u,n}} \geq 1, \quad \forall u, \forall n \quad (32)$$

- then combining with  $mD_{v_0,n,m} \leq 1, \forall n, \forall m,$

$$\frac{\alpha_{u,n}}{\gamma_{v_0,u,n}} \geq mD_{v_0,n,m}, \quad \forall u, \forall n, \forall m \quad (33)$$

- which materializes

$$\beta_{v_0,u,n,m} \leq \alpha_{u,n,m}, \quad \forall u, \forall n, \forall m \quad (34)$$

# Convex Loss Model (Continued)

- However, this implies that

$$\gamma_{v_0,u,n} = \alpha_{u,n}, \quad \forall u, \forall n \quad (35)$$

- Proof by contradiction: Assume  $\exists u : \exists n : \gamma_{v_0,u,n} > \alpha_{u,n}$ , then at that  $n$ :

$$\sum_u \gamma_{v_0,u,n} > \sum_u \alpha_{u,n} \quad (36)$$

$$1 > 1 \quad (37)$$

# Convex Loss Model (Continued)

- But such an assumption materializes

$$\sum_u \gamma_{v_0, u, n} = \sum_u \alpha_{u, n} = 1, \quad \forall n \quad (38)$$

- They introduce the notation of  $(1 - \delta)$  factor to argue away some fundamental issues.

# Convex Loss Model (Continued)

- Such an assignment eliminates the URLLC constraints.
- The average rate is then

$$\bar{r}_u = \frac{1}{u} \sum_n \left( \alpha_{u,n} - \alpha_{u,n} f\left(\frac{\gamma_{v_0,u,n} D_{v_0,n}}{\alpha_{u,n}}\right) \right) \tau_{u,n}, \quad \forall u \quad (39)$$

- Finally, they hide the  $D_{v_0,n}$  from their problem formulation and state that it is a convex optimization problem.

$$\max_{\phi^s, \gamma^s} \sum_{u \in \mathcal{U}} U'_u(\bar{\tau}_u(t-1)) g_u^s(\phi_u^s, \gamma_u^s), \quad (9)$$

$$\text{s.t. } \phi^s \geq (1 - \delta) \gamma^s, \quad (10)$$

$$\sum_{u \in \mathcal{U}} \phi_u^s = 1 \text{ and } \sum_{u \in \mathcal{U}} \gamma_u^s = 1, \quad (11)$$

$$\phi^s \in [0, 1]^{|\mathcal{U}|} \text{ and } \gamma^s \in [0, 1]^{|\mathcal{U}|}. \quad (12)$$

Figure: Problem

- Multiple URLLC users scenario is neglected.
- Subchannel-wise rate is neglected.
- Physical resource block allocation of eMBB (in linear loss model *analysis* and convex loss model) and URLLC (in linear and convex loss models) is neglected.
- Superposition interference in convex loss model is neglected.
- Bandwidth 'fluidizability' in convex loss model is not guaranteed.
- Homogeneity in convex loss model is not guaranteed.

- They incorrectly address Pareto optimality.
- They incorrectly reference gradient algorithm's moving average rate update function (twice).
- They model channel states, but I think it was sufficient to describe channel states using time slot index.
- They hide the formulation of linear loss model.

- [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] [Hao Yin](#), [Lyutianyang Zhang](#), and [Sumit Roy](#). “Multiplexing URLLC Traffic Within eMBB Services in 5G NR: Fair Scheduling”. In: *IEEE Transactions on Communications* 69.2 (2021), pp. 1080–1093. DOI: [10.1109/TCOMM.2020.3035582](#).