Admission Control and Network Slicing for Multi-Numerology 5G Wireless Networks
Vu Nguyen Ha, Member, IEEE, Ti Ti Nguyen, Student Member, IEEE, 
Long Bao Le, Senior Member, IEEE, and Jean-François Frigon, Senior Member, IEEE

Abstract—This letter studies the admission control and network slicing design for 5G New Radio (5G-NR) systems in which the total bandwidth is sliced to support the enhanced mobile broadband (eMBB) and ultra reliable and low latency communication (URLLC) services. We allow traffic from the eMBB bandwidth part to be overflowed to the URLLC bandwidth part in a controlled manner. We develop a mathematical framework to analyze the blocking probabilities of both eMBB and URLLC services based on which the network slicing and admission control is jointly optimized to minimize the blocking probability of the eMBB traffic subject to the blocking probability constraint for the URLLC traffic. An efficient iterative algorithm is proposed to deal with the underlying problem.

Index Terms—Network slicing, 5G, new radio, numerology.

I. INTRODUCTION

Future mobile networks are expected to support a large number of wireless connections from different applications with diverse requirements including massive machine type communications (mMTC), eMBB, and URLLC. To this end, 5G-NR has proposed different types of physical resource blocks (PRBs) via the so-called flexible numerology [1]. As a result, each service can select a suitable numerology whose PRBs are assigned for its transmission to meet the requirements. Flexible numerology, thus, enables the 5G networks to effectively support heterogeneous services [2], [3]; however, it presents new challenges for resource management.

Development of access control mechanisms to effectively utilize the scarce bandwidth resource in 5G wireless systems is a major challenge which has been studied in several recent works [4]–[6]. While Popovski et al. propose network slicing strategies for three services mMTC–eMBB–URLLC in [4], the authors in [5] consider the scenario with mixed eMBB–URLLC traffic. While both papers consider the achievable transmission rates for eMBB and URLLC, only the work [4] imposes the throughput constraint for mMTC. The joint scheduling design for the eMBB and URLLC services is addressed in [6] where the URLLC traffic is scheduled on the eMBB bandwidth to meet the URLLC’s low latency requirement and maximize the utility of eMBB traffic. However, the joint design of network slicing, numerology allocation, and admission control considering the 5G flexible numerology is not yet studied in these existing works.

This letter aims to fill this gap in the literature. In particular, we consider the admission control for the eMBB and URLLC services where the bounding control strategy [8] is employed to enable the eMBB blocked traffic to overflow to the URLLC’s pre-assigned bandwidth. Then, an analytical framework is developed to determine the blocking probabilities (BPs) of the eMBB and URLLC traffic under this admission control strategy. Based on this analysis, we study the joint network slicing, numerology allocation, and admission control problem which aims to minimize the BP of the eMBB traffic subject to the BP constraint for the URLLC traffic. An efficient algorithm is proposed to solve this challenging problem. Finally, numerical studies are performed to validate the analytical model and demonstrate the efficiency of the proposed design. The simulation results also show that the joint design for network slicing, numerology allocation, and admission control can reduce the BP of eMBB traffic significantly while the BP constraint of URLLC traffic can be maintained. For easy reference, key notations used in this letter are summarized in Table I.

II. SYSTEM MODEL

Consider a 5G new radio wireless network serving traffic flows generated from eMBB and URLLC services where a traffic flow represents a transmission request of the corresponding service with a data chunk to be transmitted over the wireless medium. We assume that the eMBB/URLLC traffic flows arrive according to different Poisson processes (PP) [7], [9], [10] with arrival rates \( \lambda_e \) and \( \lambda_u \), respectively. Additionally, the corresponding data lengths of the eMBB and URLLC flows follow general distributions with average values of \( 1/\mu_e \) and \( 1/\mu_u \), respectively.

We assume that the system bandwidth of \( W_{\text{total}} \) (MHz) is sliced into two bandwidth portions (BWP) [11], denoted as \( W_{e} \) and \( W_{u} \), which serve the eMBB and URLLC services, respectively. Let \( W_{e} \) and \( W_{u} \) be the bandwidth of \( W_{e} \) and \( W_{u} \), then \( W_{e} + W_{u} = W_{\text{total}} \). Various possibilities for numerology selection are allowed for the BWP \( W_{e} \) and \( W_{u} \). In particular, PRBs with high sub-carrier spacing

\( 1 \)Typical use cases for URLLC and eMBB services are Internet of Things with small packets [9] and SPEED-5G virtual reality (VR) [10], respectively where the arrivals of their traffic flows are reported to follow the Poisson process.
follows. When a new eMBB flow arrives, one available SC of BWP \( L_\text{e} \) can be assigned to the flow based on an admission control scheme as 

\[
\text{Pr}_{\text{e,blk}} = B(\rho_\text{e}, N_\text{e}) = \left( \frac{\rho_\text{e}^{N_\text{e}}}{N_\text{e}!} \right) / \sum_{i=0}^{N_\text{e}} \frac{\rho_\text{e}^i}{i!}.
\]

1) Overflow Traffic Approximation: Note that the overflow traffic does not follow PF [13]. To analyze the BP, the overflow flows from BWP \( L_\text{e} \) can be represented by an interrupted Poison process (IPP) with the arrival rate \( \lambda_\text{e} \), the mean ON-time and OFF-time of the random switch being \( 1/\gamma \) and \( 1/\omega \), respectively as illustrated in Fig. 1 [14]. In addition, Kuczura in [14] has shown that an accurate approximation can be achieved if \( \lambda_\text{e}, \gamma \), and \( \omega \) are determined as follows:

\[
\begin{align*}
\rho_\text{e} = \frac{\delta_2(\delta_1 - \delta_0) - \delta_0(\delta_2 - \delta_1)}{(\delta_1 - \delta_0)(\delta_2 - \delta_1)}, \\
\omega = \frac{\delta_0}{\lambda_\text{e}} \left( \frac{\lambda_\text{u}}{\lambda_\text{e}} - \rho_\text{e} \delta_0 \right), \quad \gamma = \frac{\lambda_\text{u}}{\rho_\text{e}} \left( \frac{\lambda_\text{u}}{\lambda_\text{e}} - \rho_\text{e} \delta_0 \right),
\end{align*}
\]

2) Blocking Probability Analysis in BWP \( L_\text{e} \): We denote \( n_1 \) and \( n_2 \) as the numbers of eMBB and URLLC flows being served in BWP \( L_\text{e} \), respectively and \( \alpha \) as the state of the random switch taking on the value of 1 or 0 depending on whether the IPP is ON or OFF. We define a three-dimension Markov chain with the state space described as follows:

\[ S_\alpha = \{ x = (n_1, n_2, \alpha) \mid 0 \leq n_1 \leq K_\text{u}, 0 \leq n_2 \leq K_\text{u} - n_1, \alpha = 1 \text{ or } 0 \} \]
where \( Q_0 \) and \( Q_1 \) are the transition matrices described as

\[
Q_0 = \begin{bmatrix}
Q_{0,1} & U_{0,1} & \cdots & \cdots & 0 \\
0 & Q_{0,1} & U_{0,1} & \cdots & \cdots \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & Q_{0,0} & \ldots \ldots \ldots \ldots \\
\end{bmatrix},
\]

(6)

\[
Q_1 = \begin{bmatrix}
Q_{1,1} & U_{1,1} & \cdots & \cdots & 0 \\
L_{1,1} & Q_{1,1} & U_{1,1} & \cdots & \cdots \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & L_{1,0} & \ldots \ldots \ldots \ldots \\
\end{bmatrix},
\]

(7)

with \( Q_{0,m}, Q_{1,m} \in \mathbb{R}^{m \times m}, U_{0,m}, U_{1,m} \in \mathbb{R}^{m \times (m-1)}, L_{1,m} \in \mathbb{R}^{(m-1) \times m}, m^* = N_u + 1 - m \), and

\[
Q_{0,m} = \frac{m + \lambda_u}{\nu} - \frac{1}{\tau_u} \cdot \ldots \cdot 0,
\]

(8)

\[
Q_{1,m} = Q_{0,m} + \text{diag}(\lambda_u^0, \ldots, \lambda_u^0), \text{ if } m < K_u,
\]

(9)

\[
U_{0,m} = -\text{diag}(\frac{m + 1}{\nu}, \ldots, \frac{m + 1}{\nu}),
\]

(10)

\[
L_{1,m} = -\text{diag}(\lambda_u^0, \ldots, \lambda_u^0).
\]

(11)

From (5), \( p_0 \) and \( p_1 \) can be obtained by employing the iterative algorithm described in Algorithm 1.

### Algorithm 1 Iterative Algorithm

1. Initialize: Choose \( p_0^{(0)} \neq 0 \), a convergence criterion \( \varepsilon \), and set \( \ell = 0 \).
2. repeat
3. \( p_1^{(\ell+1)} = \frac{Q_0 + \omega - \omega_p}{\gamma} p_0^{(\ell)} \) and \( p_0^{(\ell+1)} = Q_1 + \omega p_1^{(\ell+1)} \).
4. \( \ell = \ell + 1 \).
5. until \( \max(|p_1^{(\ell+1)}| - |p_2^{(\ell)}|) < \varepsilon \).

b) Blocking probability: With stationary probabilities obtained from Algorithm 1, we can derive the BPs of data flows in BWPs \( L_u \) as

\[
Pr_{u,blk} = \sum_{m=0}^{K_u} p_u(m, N_u - m, 0) + p_u(m, N_u - m, 1), \quad (12)
\]

\[
Pr_{u,blk}^U = \sum_{m=0}^{K_u} p_u(m, N_u - m, 1) + \sum_{n=0}^{N_u - K_u - 1} p_u(K_u, n, 1), \quad (13)
\]

where \( Pr_{u,blk} \) and \( Pr_{u,blk}^U \) are the BPs of URLLC and eMMB flows in \( L_u \), respectively. Then, the overall BP of an eMBB flow can be calculated as

\[
Pr_{e,blk} = Pr_{e,blk}^E + Pr_{e,blk}^U. \quad (14)
\]

3) Blocking Probability Characteristics: From (12)–(14), some specific characteristics of system BPs can be stated in the following propositions.

**Proposition 1:** \( Pr_{e,blk} \) decreases with the traffic intensity if \( Pr_{e,blk}^E \) decreases.

**Proof:** As can be seen in (14), the smaller value of \( Pr_{e,blk}^E \) results in the reduction of \( Pr_{e,blk} \). In addition, depreciating \( Pr_{e,blk}^E \) also lessens the intensity of the overflow traffic which, therefore, reduces its BP in BWPs \( L_u \). \( Pr_{e,blk}^U \) and hence the overall BP of an eMBB flow, \( Pr_{e,blk} \).

**Proposition 2:** Let \( \rho_u = \bar{\nu} u \) and \( \rho_u^0 = \bar{\nu} u^0 \) for given \( \lambda_u^0 \) and \( N_u \), the bounds of \( Pr_{u,blk} \) can be defined as follows:

\[
B(\rho_u, N_u) \leq Pr_{u,blk} \leq B(\rho_u^0, N_u). \quad (15)
\]

**Proof:** As can be seen, the lower bound of \( Pr_{u,blk} \) can be obtained when there is no overflow traffic from BWPs \( L_u \). Hence, the BP in such a scenario can be obtained from the Erlang B formula \( B(\rho_u, N_u) \). For the upper bound, the overflow traffic exercises its strongest influence on URLLC flows when \( \gamma \approx 0 \) and \( \omega \approx \infty \) and \( K_u = N_u \). In this scenario, there are two PPs with intensity \( \rho_u \) and \( \rho_u^0 \) in BWPs \( L_u \). Thus, the upper bound can be defined as \( B(\rho_u^0, N_u) \).

IV. JOINT ADMISSION CONTROL AND NETWORK SLICING OPTIMIZATION

We study the joint network slicing, numerology allocation, and admission control optimization problem for BWPs \( L_u \) and \( L_0 \) to minimize the BP of eMBB flows while protecting the QoS of URLLC flows. This problem can be stated as

\[
\min_{\Omega} \Omega \text{ s.t. } Pr_{u,blk} \leq \varepsilon_u, \quad (16a)
\]

\[
W_e + W_u \leq W_{total}. \quad (16b)
\]

where \( \Omega = \{ W_e, W_u, g_e, g_u, K_u, g_u \} \in \{1, 2, 3, 4\}, g_e \in \{5, 6\}, 0 \leq K_u \leq N_u \}, \varepsilon_u \) is the required minimum BP of the
URLLC service. Problem (P0) optimizes three design issues with their corresponding decision variables: network slicing (\(\Omega_1 = [W_u,W_0]\)), numerology allocation (\(\Omega_2 = [g_b,g_0]\)), and admission control design (\(K_u\)). Joint optimization of these variables results in a challenging mixed integer programming problem. Hence, we propose to decompose this problem into several low-complexity sub-problems as follows.

1) Numerology Allocation for BWP \(L_0\): Thanks to Proposition 1, \(Pr_{e,blk}(\Omega)\) can be reduced by minimizing \(\text{Pr}_e\). Therefore, the optimal numerology for BWP \(L_0\) for given \(N_b\) can be determined as follows:

\[
g_b^* = \arg \min_{g_b \in \{1,2,3,4\}} \text{Pr}_e = \arg \min_{g_b \in \{1,2,3,4\}} B \left( \frac{\lambda_b}{R(g_b)\mu_b}, N_b \right). \tag{17}\]

2) Admission Control Parameter Design: It can be verified that for given \(N_b\) and \(g_b\), increasing \(K_u\) results in a challenging mixed integer programming problem. Hence, we propose to decompose this problem into several low-complexity sub-problems as follows.

3) Network Slicing Design: For given \(\Omega_2\) and \(K_u\), the network slicing problem can be stated as

\[
\min_{\Omega_1} \text{Pr}_{e,blk}(\Omega) \text{ s.t. constraints (16a) and (16b).} \tag{19}\]

From (16b), the upper bounds of \(N_e\) and \(N_b\) can be given as

\[
N_e \leq \lfloor W_{ttotal}/(W_02^{g_0}) \rfloor \text{ and } N_b \leq \lfloor W_{ttotal}/(W_02^{g_0}) \rfloor. \tag{20}\]

Let \(B^{-1}(\rho,\alpha)\) be the inverse function of \(B(\rho, n)\), i.e., \(B^{-1}(\rho, n) = \min \{ n \in \mathbb{N} : B(\rho, n) \leq \alpha \}\). It is worth noting that \(B^{-1}(\rho, \alpha)\) is a monotonic decreasing function with respect to \(n\) for given \(\rho\); hence, \(B^{-1}(\rho, \alpha)\) is a one-to-one function for given \(\rho\) and \(\alpha\).

Proposition 3: For given \(g_b\), the required bandwidth of \(L_0\) can be bounded as

\[
B_n^{-1}(\rho_u, \bar{\alpha}_b) \leq N_u = \frac{W_u}{W_02^{g_0}} \leq B_n^{-1}(\rho_u, \mu_b), \bar{\alpha}_u). \tag{21}\]

Proof: It can be verified that the lower and upper bounds given in this proposition can be obtained directly from Proposition 2 to satisfy the constraint (16a) and \(\rho_u + \rho_b^u = \lambda_b/\mu_b + \lambda_b^u,\mu_b/\bar{R}(g_b)\mu_b\).\(\star\)

The result given in Proposition 3 enables us reduce the research range for \(N_u\) from \([0, W_{ttotal}/2^{g_0}/0.18]\) to

\[
N_u = \{ N \in \mathbb{N} : B_n^{-1}(\rho_u, \bar{\alpha}_b) \leq N \leq B_n^{-1}(\rho_u, \bar{\alpha}_b) \}, \tag{22}\]

where \(\rho_u, \bar{\alpha}_b = \rho_u + \rho_b^u\). Additionally, for a given \(N_u\), the optimal value of \(N_b\) can be expressed as

\[
N_b = \lfloor (W_{ttotal} - W_0N_u2^{g_0})/(W_02^{g_0}) \rfloor, \tag{23}\]

because the larger bandwidth is allocated for \(L_b\), the smaller values of \(Pr_{e,blk}\) and \(Pr_{e,blk}\) that can be achieved. The required range of \(W_b\) becomes smaller once \(N_b\) is updated so that the intensity of the overflow traffic decreases. Thanks to this observation, the optimal value of \(\Omega_1\) can be obtained by iteratively updating \(N_b\) and \(N_u\), based on which we propose an efficient searching algorithm as summarized in Algorithm 2 to obtain the optimal solution of (P0).

\[\text{Algorithm 2 Proposed Searching Algorithm}\]

1. \text{Initialize: Set } \text{Pr}_{e,blk}^* = 1.
2. \text{for } g_b \in \{5, 6\} \text{ do}
3. \text{Set } \lambda_b^U = \lambda_b.
4. \text{repeat}
5. \text{Choose } N_b = B_n^{-1}(\rho_u, \bar{\alpha}_b).
6. \text{Update } N_b \text{ as in (23), } g_b \text{ as in (17), and } \lambda_b^U \text{ as in (2).}
7. \text{until } N_b \text{ is unchanged.}
8. \text{Determine } N_{\bar{u}} \text{ as in (22).}
9. \text{for } N_b \neq N_{\bar{u}} \text{ do}
10. \text{Update } N_b \text{ as in (23) and } (\lambda_b^U, \omega, \gamma) \text{ as in (2).}
11. \text{Determine } g_b, \bar{K}_u \text{ as in (17),(18) and calculate } Pr_{e,blk}(\Omega).
12. \text{if } \text{Pr}_{e,blk}(\Omega) \leq \text{Pr}_{e,blk}^* \text{ then}
13. \text{Set } \Omega^* = \Omega \text{ and } \text{Pr}_{e,blk}^* = \text{Pr}_{e,blk}(\Omega).
14. \text{end if}
15. \text{end for}
16. \text{end for}
17. \text{Return } \Omega^*.

\[\text{Fig. 3. BPs of eMBB and URLLC traffic vs } 1/\mu_u (a) \text{ and } K_u (b).\]

V. NUMERICAL RESULTS

In this section, we first validate the accuracy of the proposed analytical framework presented in Section III via simulation, then, we study the efficiency of Algorithm 2 under different parameter settings. In the simulation, we consider the 5G-NR wireless system operating at the frequency band 3.6–3.8 GHz, i.e., \(W_{ttotal} = 200 \text{ MHz}\) [16]. Assume that the 16-QAM modulation scheme is employed by all traffic flows, i.e., \(n_{tf} = 4 \text{ bits/Hz}\) [11]. Unless stated otherwise, the parameters are set as: \(\lambda_b = 0.4\), \(1/\mu_b = 1/\mu_u = 1 \text{ Mbits/s}\), \(\bar{\alpha}_u = 10^{-3}\). To obtain simulation results for some specific values of \(\lambda_b, \lambda_u, \mu_b, \mu_u\) and \(\Omega\), we generate over \(10^8\) traffic flow samples for the eMBB and URLLC services following the corresponding Poisson processes as follows. The arrival time of a new flow is determined based on the arrival time of its immediately preceding flow and a random inter-arrival time that is generated from MATLAB according to an exponential distribution with the corresponding values of \(\lambda_b, \lambda_u\). Similarly, the data length brought by a new flow is also generated randomly according to the exponential distribution with the corresponding values of \(\mu_b, \mu_u\). The obtained data length is then used to estimate the completed transmission time. A traffic flow is assumed to occupy one sub-channel during the interval between the flow’s arrival instant and the completed transmission instant. Then, the bounding admission control strategy described in Section II is implemented and the number of blocked flows is counted during the simulation based on which we calculate the blocking probability.

Fig. 3 illustrates the BPs of eMBB and URLLC traffic, obtained by the proposed analytical framework and simulation for different values of \(1/\mu_u\) and \(K_u\), respectively. As
can be seen, results achieved by the proposed analysis are in good agreement with the simulation results which confirms the accuracy of the IPP approximation. With $K_u = N_u$, Fig. 3-(a) shows that increasing the average data length of the URLLC flow results in higher BPs for both services. In addition, Fig. 3-(b) demonstrates that adopting the overflow strategy can help mitigate the overload of the eMBB BWP but it degrades the BP of the URLLC service. Interestingly, both BPs saturate when $K_u$ becomes sufficiently large.

Fig. 4 shows the BP of eMBB versus the arrival rate $\lambda_u$ and target blocking probability of URLLC traffic $\alpha_u$ for two schemes, namely our optimized design using Algorithm 2 with overflow and the conventional scheme with no-overflow (indicated as “Alg. 2” and “No-OF” in these figures, respectively). For the no-overflow scheme, the minimum value of $W_u$ is first determined so that $B(p_u, N_u) \leq \alpha_u$. Then, the remaining bandwidth is allocated to serve the eMBB traffic. The numerical analysis is also optimized in each BWP. As can be observed, the $P_{e,bk}$ achieved by our proposed design is much lower than that due to the no-overflow scheme. In addition, the $P_{e,bk}$ achieved by both schemes increase as $\lambda_u$ increases and decrease as $\alpha_u$ increases. This happens because the higher arrival rate of URLLC traffic and its lower target BP both result in higher traffic load at BWP $L_u$. This may degrade the performance of eMBB data transmission.

The network slicing result is illustrated in Fig. 5 in which the bandwidth of the BWP assigned to eMBB service due to the proposed algorithm and the no-overflow scheme is plotted versus $\alpha_u$. Interestingly, our proposed framework allocates less bandwidth to the eMBB traffic compared to that due to the no-overflow scheme, but it delivers better performance, which again confirms the benefit of adopting our design framework.

VI. CONCLUSION
In this letter, we have proposed a novel design framework for joint network slicing, numerology allocation, and admission control to support the eMBB and URLLC services. Using the bounding admission control strategy, the BPs of eMBB and URLLC traffic have been analyzed and an efficient searching algorithm has been proposed to minimize the BP of eMBB traffic while maintaining the BP requirements of URLLC traffic. Numerical results have confirmed the accuracy of the proposed analytical framework and the benefit of employing the overflow strategy in the admission control.

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