Optimal Split Bearer Control and Resource Allocation for Multi-Connectivity in 5G New Radio

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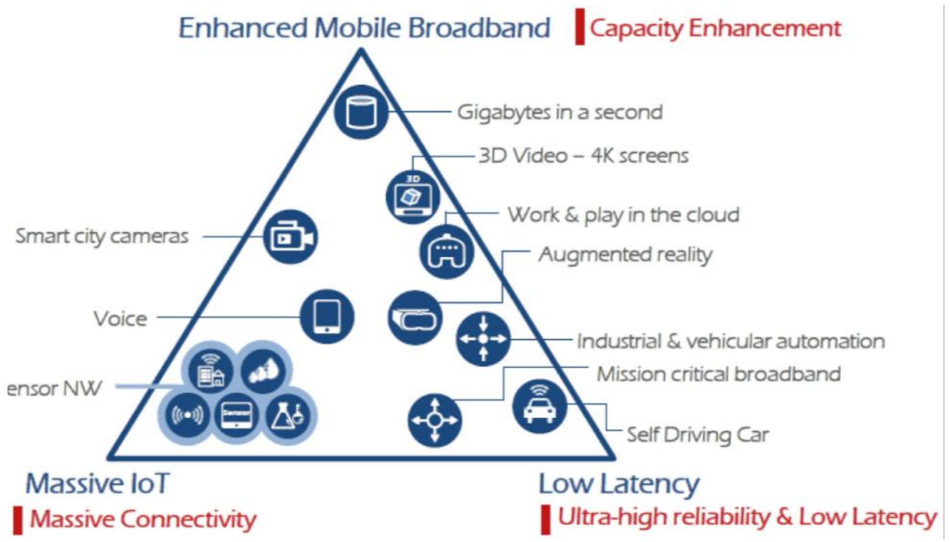
Introduction – 5G and Beyond

- Three directions for RAN development:

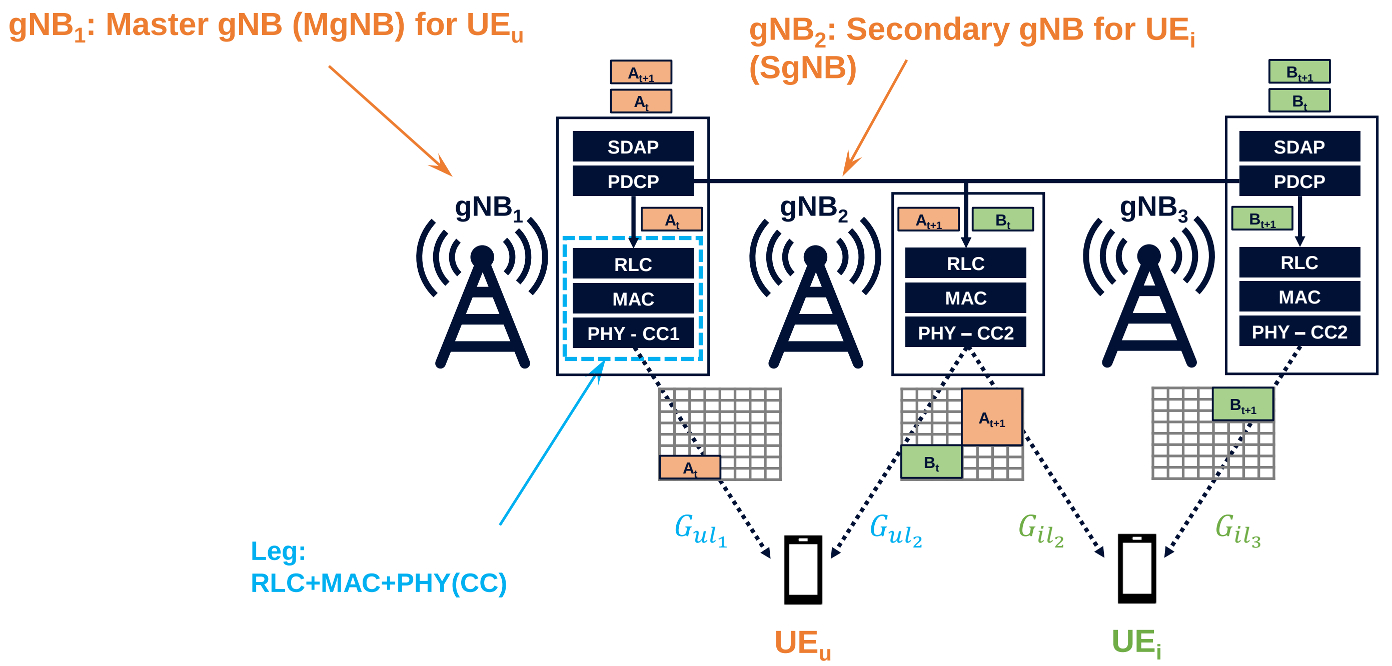
1) Increase network **capacity** (up to 10 Gbit/s)
   - *enhanced Mobile Broad Band (*eMBB)
2) Increase **reliability** and reduce **latency** (in the order of 1-2 ms)
   - *Ultra Reliable Low Latency Communications (*URLLC)
3) Increase consistently **number/density of connected objects** (up to 1 mln devices per km^2)
   - *massive Machine Type Communications (*mMTC).



Source: ETRI graphic, from ITU-R IMT 2020 requirements

Multi Connectivity (MC)

- MC has been introduced to improve capacity, reliability and latency
- Each UE (User Equipment) can be connected to multiple cells hosted by multiple gNBs (Next-generation NodeBs)



Trade-off:
- Higher performance for UE
- Higher system interference

Multi Connectivity (MC) – Problems

- Two distinct problems:

1) **PDCP Split-Bearer Decision** → Increase capacity
   - Targeting enhanced Mobile Broadband (eMBB) service
2) **PDCP Duplication Decision** → Improve reliability
   - Targeting Ultra Reliable Low Latency Communications (uRLLC) service

We will illustrate and solve both problems, (PDCP Split-Bearer Decision Problem – **PSD**, and PDCP Duplication Decision, **PDD**)

PDCP Split-Bearer Decision (PSD) Problem

Parameter	Definition
U	Set of UEs
L	Set of legs (small cells)
M	Set if MCSs
P_{ul}	Power used by leg l to serve UE u
G_{ul}	Channel gain for UE u on leg l
N_0	Noise
γ_m	Minimum SINR threshold for using MCS m
R_m	Rate for MCS m [bit/s]

Parameter	Definition
D_u	Data rate of UE u
$l_0\ (u)$	Primary leg of UE u

Variable	Definition
z_u	whether UE u is fully served
y_{ul}	whether leg l is used to serve UE u
x_{ulm}	whether the MCS m of the leg l is used to serve user u

- Optimization problem:

1. Decide which UEs to serve
2. Decide whether and how to split the traffic of admitted users on multiple cells (also referred to as *legs*)

PSD Problem – MILP Formulation

$\alpha = \frac{1}{|L||U|+1}$: served user priority > resource utilization priority

$$\max \sum_{u \in \mathcal{U}} z_u - \alpha \sum_{u \in \mathcal{U}, l \in \mathcal{L}_u} y_{ul} \quad \text{s. t.:} \tag{1}$$

Max served UEs and min active legs (interference)

$$\sum_{l \in \mathcal{L}_u} y_{ul} \geq z_u \qquad \forall u \in \mathcal{U} \tag{2}$$

Activate ≥1 leg for each served UE

$$\sum_{m \in \mathcal{M}} x_{ul_0(u)m} \leq y_{ul_0(u)} \qquad \forall u \in \mathcal{U} \tag{3}$$

Select a MCS for primary leg

$$\sum_{m \in \mathcal{M}} x_{ulm} \leq y_{ul} \qquad \forall u \in \mathcal{U}, l \in \mathcal{L}_u \setminus \{l_0(u)\} \tag{4}$$

Select a MCS for each secondary leg

$$y_{ul_0(u)} \geq y_{ul} \qquad \forall u \in \mathcal{U}, l \in \mathcal{L}_u \setminus \{l_0(u)\} \tag{5}$$

Secondary leg can be activated after master leg

$$\frac{P_{ul} G_{ul}}{N_0 + \sum_{j \in \mathcal{L}_l, k \in \mathcal{U}_j : k \neq u} P_{kj} G_{uj} y_{kj}} \geq \gamma_m x_{ulm}$$
$$\forall u \in \mathcal{U}, l \in \mathcal{L}_u, m \in \mathcal{M} \tag{6}$$

SINR constraint (it can be linearized)

$$\sum_{l \in \mathcal{L}_u} \sum_{m \in \mathcal{M}} R_m x_{ulm} \geq D_u z_u \qquad \forall u \in \mathcal{U} \tag{7}$$

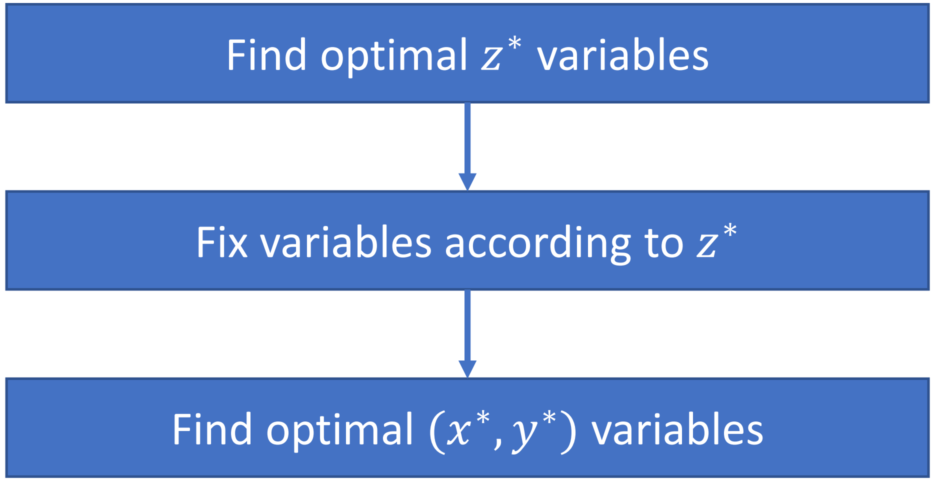
Serving rate must be larger than UE's data rate

$$x_{ulm}, y_{ul}, z_u \in \{0, 1\} \qquad \forall u \in \mathcal{U}, l \in \mathcal{L}_u, m \in \mathcal{M}. \tag{8}$$

Sets of decision variables

PSD Problem – Resolution

- Problem can be decomposed into two subproblems:
  1. *Users' admission problem*
  2. *Radio resource allocation problem*
- If $\alpha = \frac{1}{|L||U|+1}$, then solving sequentially (1) and (2) provides the optimal solution of the PSD problem:



PDD Problem – MILP Formulation

The objective function and constraints (2)-(7) are the same

New Variable/ Parameters	Definition
x_{ulms}	whether the MCS m of the leg l is used to serve user u when the SINR index is s
ϕ_{ms}	BLER (BLock Error Rate) when using MCS m ∈ M with SINR γ_s
Φ_u	BLER target for UE u
γ_s	SINR value corresponding to index s

$$\sum_{m \in \mathcal{M}} \sum_{s \in \mathcal{S}} R_m x_{ulms} \geq D_u y_{ul} \qquad \forall u \in \mathcal{U}, l \in \mathcal{L}_u, \tag{18}$$

Guarantees that each leg selected for user u can serve its traffic demand

$$-\sum_{l \in \mathcal{L}_u} \sum_{m \in \mathcal{M}} \sum_{s \in \mathcal{S}} log_{10}\left(\phi_{ms}\right) x_{ulms} \geq -log_{10}\left(\Phi_u\right) z_u \quad \forall u \in \mathcal{U}, \tag{19}$$

Guarantees that the target error probability of user u is met.

$$x_{ulms}, y_{ul}, z_u \in \{0,1\} \; \forall u \in \mathcal{U}, l \in \mathcal{L}_u, m \in \mathcal{M}, s \in \mathcal{S}. \tag{20}$$

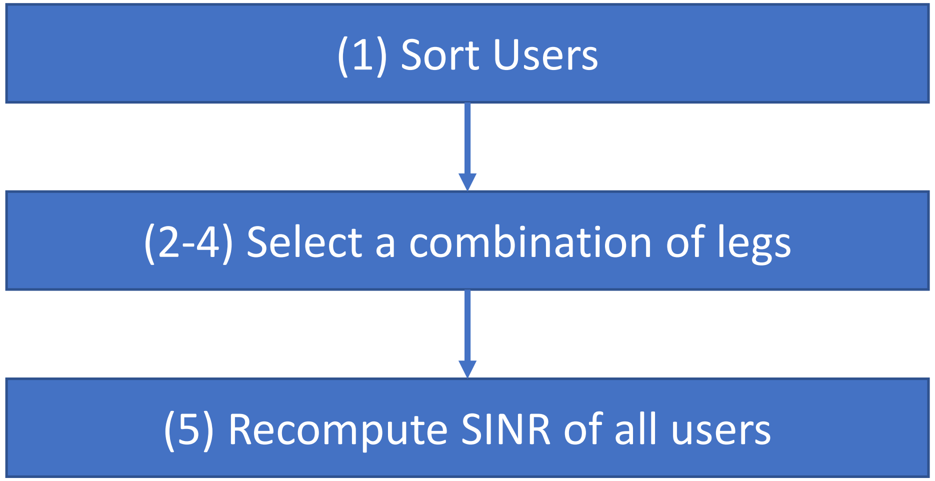
Sets of decision variables

New contraints (18)-(20)

- The set of constraints (18) guarantees that each leg selected for user u can serve its traffic demand.
  - The left-hand-side of the constraint defines the transmission rate used to serve user u on leg l, while the right-hand-side represents the requested user’s data rate Du.
  - Note that the right-hand-side of the inequality is set to zero if the user is not admitted and the left-hand-side can take any value.
- Similarly, the set of constraints (19) guarantees that the target error probability of user u is met.
  - Here, the left-hand-side of the constraint defines the joint error probability of all legs assuming independent errors,
  - while the right-hand-side represents the BLER target for UE u. Constraints (18) and (19) represent therefore the QoS requirements of the users.
- Finally, constraints (20) define the range of the decision variables.

PDD Problem – Heuristic Approach

- We use a *greedy* approach composed of the following steps:
  1. *We sort the users according to a certain metric (to simplify the admission decision in the next step)*
  2. *for each user u we select a combination of legs that meets the user requirements in terms of rate D_u and BLER target Φ_u*
  3. *Finally, in step 5 we recompute the SINR of all legs according to the new solution and we reorder the remaining user*



Step 1 - Sorting

- We first compute the SINR γ_{ul} perceived by each user *u* on every leg *l* assuming that all users are fully connected using all their available legs.
- Then, we compute the combined SINR Γ_u for each user as the product of all SINR values across all legs that can be used to serve a user *u* (i.e., all legs in Lu).
- Once the combined SINRs have been computed, we sort users in ascending order of the ratio between the demanded data rate D_u and the combined SINR Γ_u .
- In this way, we first serve users with <u>small data rate </u>and <u>good channel conditions</u>.
- The rationale behind such choice is that these users are usually close to gNBs and generate low interference, hence their allocation is rather simple and slightly affects allocation decisions of users at the edge.

Steps 2 - 4

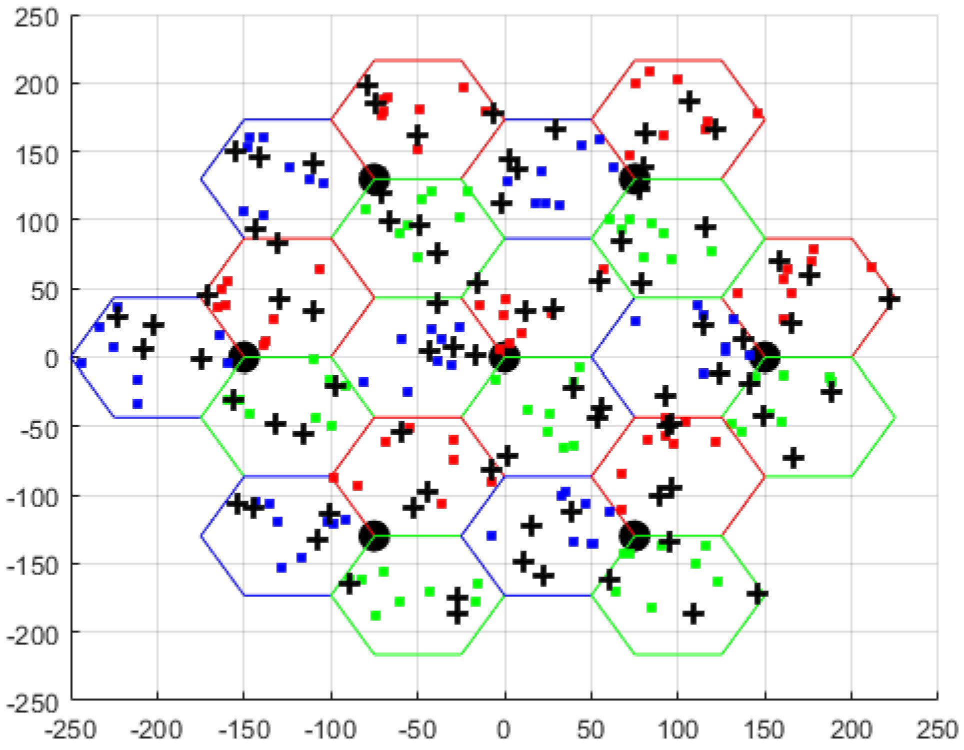
- *for each user u we select a combination of legs that meets the user requirements in terms of rate D_u and BLER target Φ_u*
- To this end, we first generate a set that contains all possible combinations of legs of size smaller than or equal to the input parameter L.
- For each combination of legs $M_u \in T_u$, we first check if it can satisfy the user requirements (step 3) and if it improves the solution (relation $\succ$ in step 4).
- If both conditions hold, the combination M_u is selected as new best candidate solution for user u if either the percentage of users that have activated more than one leg in the solution computed so far is smaller than η or it contains one leg.

Step 5

- Finally, in step 5 we recompute the SINR of all legs according to the new solution and we reorder the remaining user

Numerical Results – Scenario

- Deployment: 3GPP *Urban Macro with Macro and Small Cells*
- *Black circles represent the 7 Macro Base Stations (Macro Cells are illustrated as hexagons),*
- *Small Cells are depicted as black crosses.*
- *UEs are represented as colored squared dots (the color corresponds to the sector of the assigned Macro Cell)*



Numerical Results – Scenario

- Deployment: 3GPP *Urban Macro*

Parameter	Value	
Layer	**Macro**	**Small**
Number of cells	21 (7 gNBs with 3 sectors)	{1,2,…,7}
Placement	Hexagonal (ISD: 150 m)	Uniform distribution in each sector
Power	43 dBm	26 dBm
Frequency	4 GHz	
Bandwidth	20 MHz	
MCSs	TS38.214 Table 1 for PDSCH	

Parameter	Value
UEs/sector	{2,4,…, 10}
Placement	Random (uniform) in each sector Even number of UEs/macro cell
Data rate	Two QoS classes: • [1,5] Mbit/s • [5,9] Mbit/s
BLER target	10%

Numerical Results – PSD – Single vs Dual connectivity

Single Connectivity	5 SCs	7 SCs
5 UEs	54.3	58.8
7 UEs	67.6	73.9

TABLE IV: Average number of users accepted in the system for the Single Connectivity case.

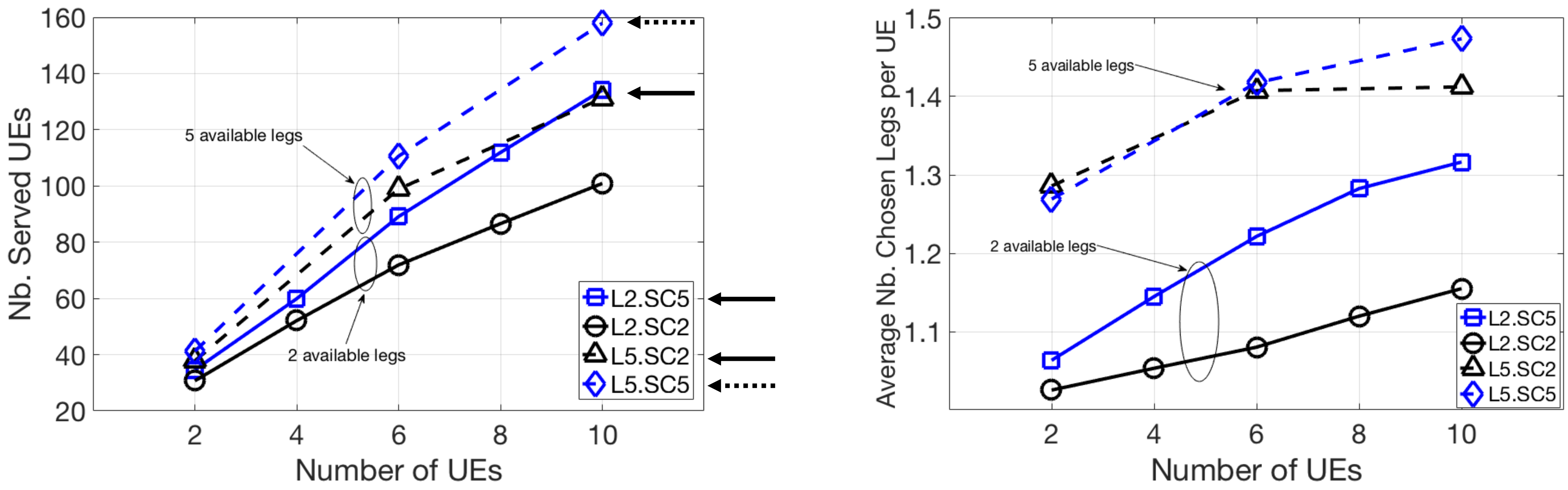
Dual Connectivity	5 SCs	7 SCs
5 UEs	65.5	73.3
7 UEs	87.0	98.3

TABLE V: Average number of users accepted in the system for the Dual Connectivity case (2 legs available per UE).

1) In these scenarios, the number of served users in Dual Connectivity is between **20.6%** (when UEs=Small Cells= 5 per sector) and **33%** (for UEs=Small Cells= 7 per sector) higher than in Single Connectivity.
2) The gain is larger when the number of interfering UEs in the network increases, as well as when a large number of available connections to gNBs exists (either master or small cells)

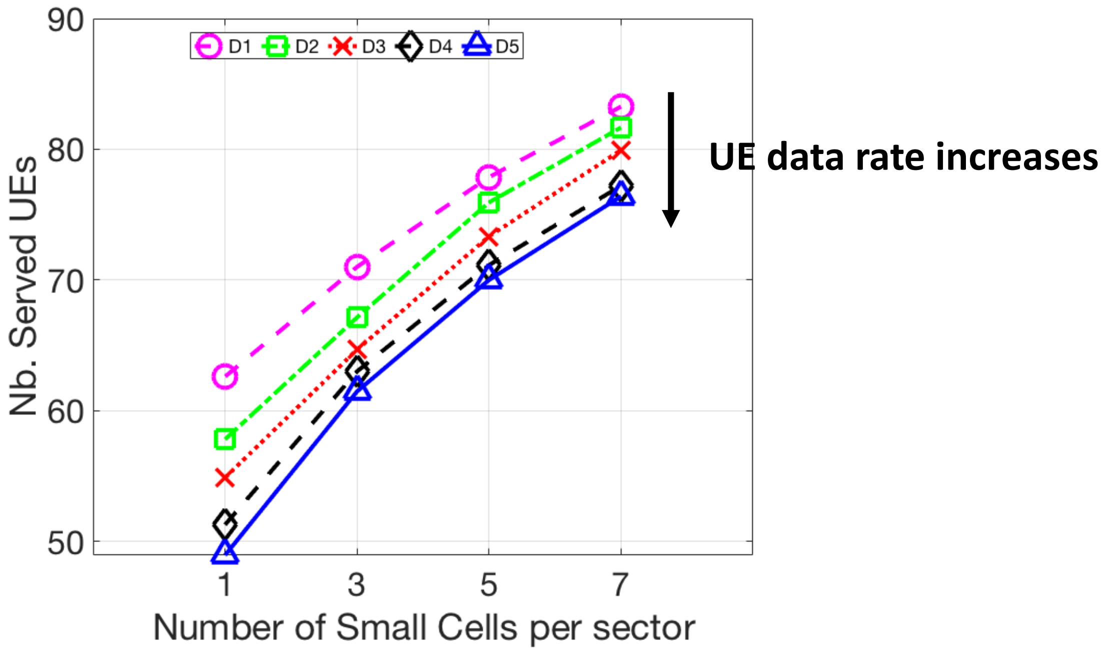
Numerical Results - PSD

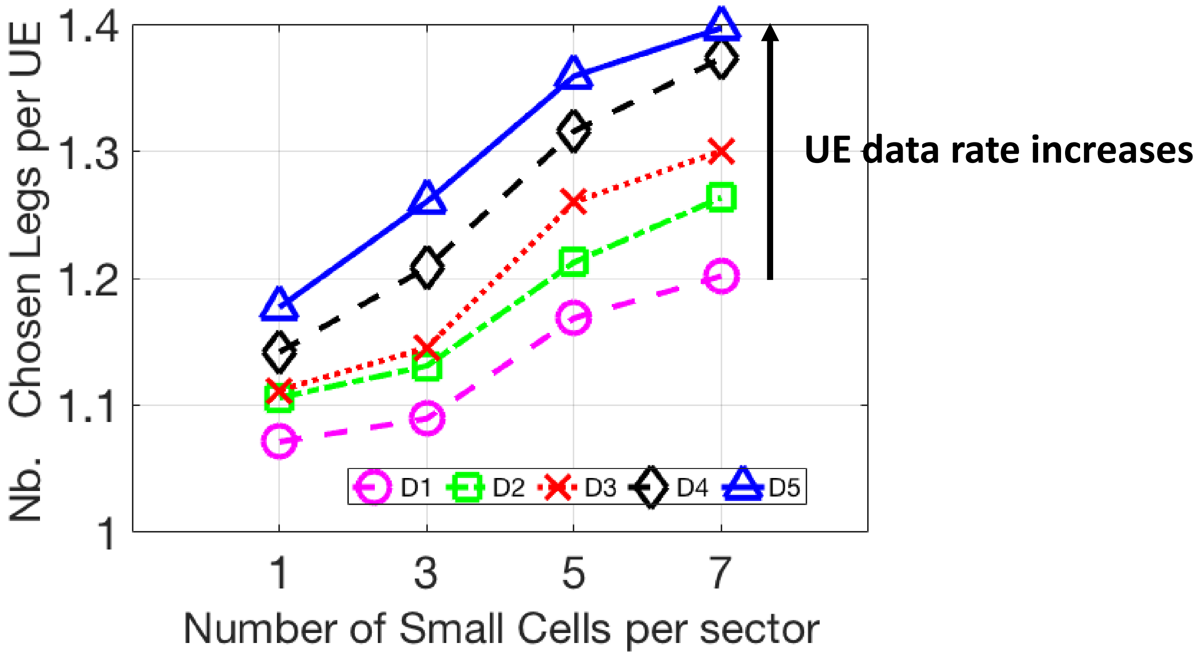
LX.SCY
- X: max #Legs per UE
- Y: # Small Cells per sector



1) Two options to increase capacity in mid-density scenarios:
   1) increasing coverage while keeping the same max #legs per UE (from 2 to 5 small cells per sector)
   2) activating more #legs per UE (from 2 to 5)
2) In “high-density” scenarios it is crucial to install more small cells to maximize capacity

Numerical Results - PSD





- *Number of accepted users* depends on (1) UE's demand and on (2) number of small cells
- The average *# of legs* assigned to each user increases
  - with UE's demand
  - number of available small cells per sector

Numerical Results – PDD – Single vs Multi Connectivity

Single Connectivity	5 SCs	9 SCs
6 UEs	67.7	78.2
8 UEs	81.5	98.7
10 UEs	100.7	116.2

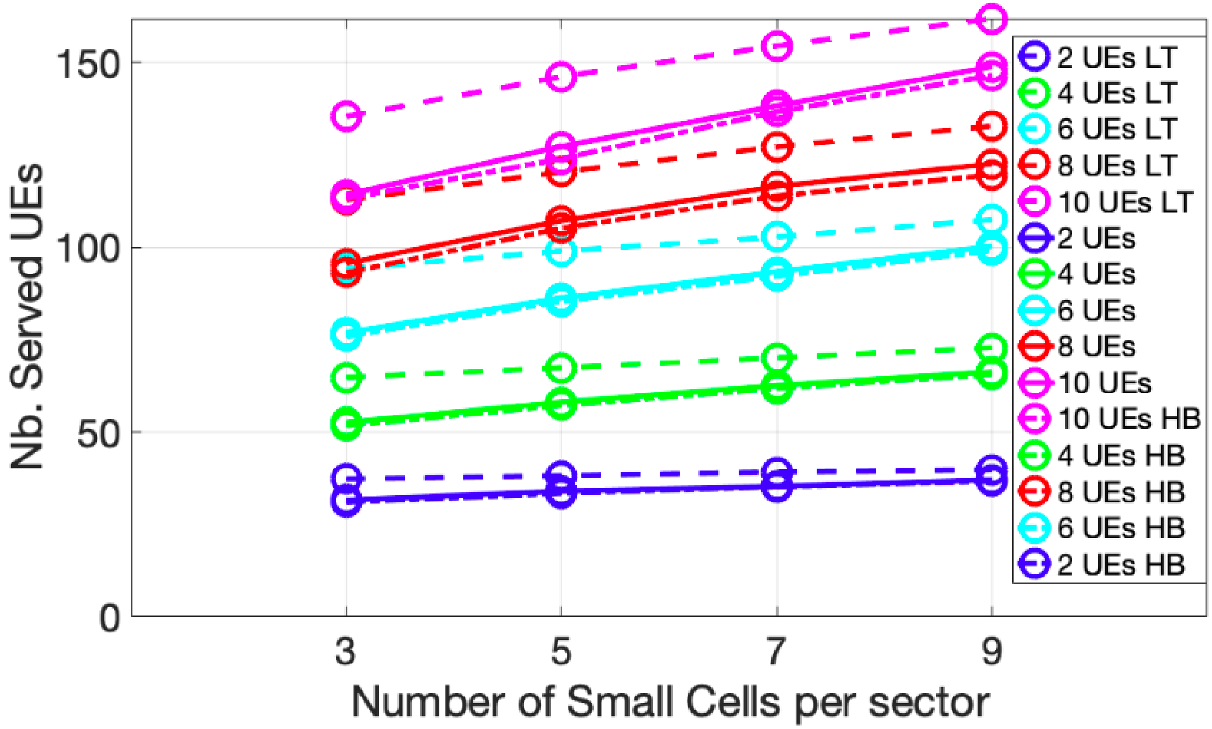
TABLE VI: Average number of accepted users for the Single Connectivity case (with variable numbers of UEs and Small Cells).

Multi Connectivity	5 SCs	9 SCs
6 UEs	86.3	100.3
8 UEs	107.2	123.3
10 UEs	127.3	148.9

TABLE VII: Average number of accepted users for the M Connectivity case (multiple legs available per UEs, with varia numbers of UEs and Small Cells).

1) It can be observed that the number of served users when each UE can activate multiple legs as illustrated in Table VII is **25%** to **31.5%** higher than in the Single Connectivity scenario (Table VI).
2) The gain is hence consistent throughout all network instances

Numerical Results – PDD



- Average number of accepted users, comparing the results obtained using the original data rate for the demands as well as the BLER target (i.e., $10^{[-2;-5]}$), and two scenarios where we reduce the traffic data rate by a factor of 10 (Low Traffic, LT) and increase the BLER target in the range $10^{[-5;-8]}$ (High BLER, HB).

Numerical Results – PDD

- Setting a higher BLER target has a limited impact on the number of accepted users (the HB curves are practically overlapping to the solid ones, especially for a small number of UEs per sector, and only slightly lower for higher UE values).
- This is due to the fact that in such scenarios it is the channel capacity to limit the performance of the system, and not reliability constraints (i.e., the BLER target set for each user).
- For the same reason, a lower traffic demand (LT dashed lines) allows the Mobile network operator to accept more users (up to 19.7% in the best case).

Conclusions

- Optimization framework for solving PDCP Split-Bearer Decision problem in 5G+ networks where Multi-Connectivity is enabled

- We illustrated both a decomposition approach to solve it efficiently
  - Reduces computing time when couple with limitation on maximum number of secondary legs per UE
  - Achieving close-to-optimum solutions (in real-size scenarios)

- Numerical results quantify the trade-off mobile operators face during network planning and operation for capacity expansion:
  - Increasing *max number of legs* is beneficial in *mid-dense* scenarios
  - Increasing *number of small cells* is necessary in *high-dense* scenarios