MEC-aware Cell Association for 5G Heterogeneous Networks

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Abstract—The need for efficient use of network resources is continuously increasing with the grow of traffic demand, however, current mobile systems have been planned and deployed so far with the mere aim of enhancing radio coverage and capacity. Unfortunately, this approach is not sustainable anymore, as 5G communication systems will have to cope with huge amounts of traffic, heterogeneous in terms of latency among other Qualityof-Service (QoS) requirements. Moreover, the advent of Multiaccess Edge Computing (MEC) brings up the need to more efficiently plan and dimension network deployment by means of jointly exploiting the available radio and processing resources. From this standpoint, advanced cell association of users can play a key role for 5G systems. Focusing on a Heterogeneous Network (HetNet), this paper proposes a comparison between state-of-the-art (i.e., radio-only) and MEC-aware cell association rules, taking the scenario of task offloading in the Uplink (UL) as an example. Numerical evaluations show that the proposed cell association rule provides nearly 60% latency reduction, as compared to its standard, radio-exclusive counterpart.

Index Terms—Multi-access edge computing, cell association, packet delay budget

I. INTRODUCTION

A. Motivation

The evolution of mobile networks is characterized by a growing traffic demand (currently dominated by video content [1]) and by a paradigm shift in the consumed services, where content sharing and social behavior are redefining network utilization. Moreover, the introduction of 5G systems in the near future will witness a dramatic increase of Machine-to-machine (M2M) connections [2], due to the progressive introduction of Internet of Things (IoT) traffic and services, that will be dominated by several new vertical business segments [3] (e.g., automotive and mobility, factories of the future, health-care, media and entertainment, energy). As a consequence, 5G networks will need to effectively support huge amounts of traffic streams, both heterogeneous and variable in space and in time.

At the same time, the emergence of Multi-access Edge Computing (MEC) will introduce computing capabilities at the edge of the network and will provide an open environment targeting low packet delays due to close proximity to end users [4]. Such a challenging system scenario, as depicted in Figure 1, also involves a multitude of heterogeneous devices, characterized by dissimilar latency requirements, among others. The heterogeneity of QoS demands creates the need for network operators to efficiently plan and dimension the overall system

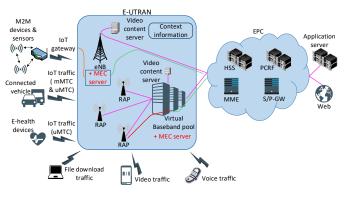


Fig. 1. Envisioned 5G reference system.

by jointly capitalizing on the available communication and computation resources.

From that perspective, the applied rule for user-cell association plays a key role towards efficiently exploiting the entire set of resources. Nevertheless, current mobile systems have been planned and deployed so far by following traditional paradigms of network planning (e.g., based on radio-only coverage). Unfortunately, this approach is not sustainable anymore, as current cell association rules completely discard the aforementioned availability of *processing* resources at the network's edge, hence, they fail to constitute cost-effective and flexible solutions for QoS provisioning.

B. Prior Work

To the best of our knowledge, current technical literature mostly sheds light on the problem of optimally allocating radio and computational resources to already connected users, inherently assuming *conventional* cell association, where the User Equipment (UE) is connected to its serving Evolved NodeB (eNB) based on the maximum Reference Signal Received Power (RSRP) rule. For example, authors in [5] investigated task offloading in a multi-cell scenario, where they showed an enhancement achieved by offloading to multiple eNBs via benefiting from prior knowledge of radio statistics. In [6], the problem of radio and computational resource allocation over connected users was investigated under Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) schemes. The authors optimized the joint allocation and showed the achieved gains, as compared to a baseline round-robin scheme. Moreover, [7] studied the problem of joint radio and processing power allocation under an optimization framework, where the task completion time was minimized subject to energy consumption constraints. It is, thus, evident that none of the above works questioned the effectiveness of the applied cell association rule.

With regards to the design of a cell association rule driven by performance requirements, in [8], a cross-layer, "UE matching" problem was studied for a Cloud Radio Access Network (C-RAN). In this work, the authors proposed a joint matching scheme between the UEs, C-RAN components and MEC hosts, aiming at meeting a task completion deadline at the UE side. Nevertheless, this work did not exploit the multitier resource disparity expected in a HetNet as well as reveal the practicality of the association procedure from a signaling overhead viewpoint.

C. Contribution

Given the above described situation and identified gaps, this paper presents the following:

- Focusing on a MEC-enabled HetNet, we introduce a new, UE-cell association metric, which evaluates the proximity of MEC resources to a UE.
- To highlight the benefits of the proposed association rule, we introduce an Extended-Packet Delay Budget (E-PDB) metric, which is a one-way latency consisting of the radio transmission time of an input packet between the UE and the connected eNB in the UL, along with the execution time of a given task at a MEC host.
- We conduct numerical evaluation to compare the proposed association rule to the conventional RSRP rule, in terms of E-PDB performance for various inter-tier resource disparities, as well as for different network deployment densities.

The remainder of this paper is organized as follows: in Section II, we present an overview of the studied system model; Section III elaborates on the concept of flexible cell association and Section IV shows the relevant numerical results. Finally, Section V concludes the paper.

II. SYSTEM MODEL

A. Modeling Assumptions

Throughout this work, a K-tier cellular network, such as the one illustrated in Figure 2, is studied, where the eNBs and UEs locations are spatially randomized. According to this model, the locations of the eNBs of the *i*-th tier are modeled through a homogeneous Poisson Point Process (PPP) $\Phi_i = \{x_i\}, i = 1, 2, \dots, K$ of density λ_i , where $x_i \in \mathbb{R}^2$ represents the tier-*i* eNB position on a two-dimensional plane. It should be noted that the K PPPs are mutually independent. On the other hand, the UE positions are modeled via a different, independent homogeneous PPP, ψ , of density λ_u . Due to the network's heterogeneity, different tiers are distinguished by the transmit power, P_i , of their eNBs, their spatial density, λ_i , and the total processing power, C_i , of a MEC server colocated with an *i*-th tier eNB. Cross-tier resource disparity can be adjusted by defining the ratio of the transmit powers

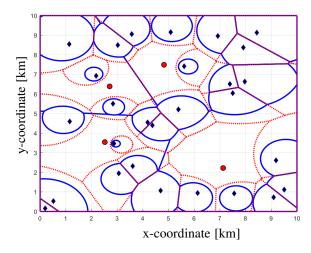


Fig. 2. A two-tier network consisting of macro eNBs (red circles) of spatial density $\lambda_1 = 0.5$ eNBs/km and micro eNBs (black rhombuses) ($\lambda_2 = 6\lambda_1, \rho_1 = 40 \& \gamma_1 = 5$). The solid blue lines represent the boundaries of the radio coverage areas determined by applying the maximum DL RSRP association rule, while the dashed red lines represent the boundaries of the MEC coverage areas when applying the proposed, MEC-aware UE-cell association rule, which will be analyzed in Section III.

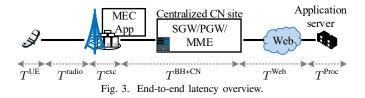
of two consecutive tiers, ρ_i , (i.e., $\rho_i = \frac{P_i}{P_{i+1}} > 1$), as well as the ratio of processing powers of their MEC hosts, γ_i , (i.e., $\gamma_i = \frac{C_i}{C_{i+1}} > 1$). It should be noted that the mentioned ratios are always greater than 1 as a tier $i \in \{1, \dots, K\}$ is assumed to be overlaid with tiers of lower transmit power and processing capabilities. Note that $\rho_K = \gamma_K = 1$.

B. Signal and Channel Model

The pathloss between a given UE and its serving eNB is modeled as inversely proportional to the distance with a given path-loss exponent denoted by α , of common value for all tiers. Small-scale fading is assumed to be Rayleigh distributed with unit average power, i.e., for every UE-eNB link, $|h|^2 \approx \exp(1)$ and the fast fading effects are assumed non-correlated among the various links. Additionally, each UE employs a fixed transmit power, P_{UE} , which is greater than its serving eNB sensitivity. The target eNB belonging to the *i*-th tier is assumed to be placed at the origin [9], thus, for UL communication, the measured Signal to Interference plus Noise Ratio (SINR) at that eNB related to a transmission by the *k*-th UE is

$$\operatorname{SINR}_{k,i} = \frac{P_{UE}|h_k|^2 D^{-\alpha}}{\hat{I}_z + \sigma^2},\tag{1}$$

where σ^2 denotes the noise power, while \hat{I}_z is the interference generated by an interfering set \mathcal{Z} of UEs as $\hat{I}_z = \sum_{z \in \mathcal{Z}} P_{UE} |h_z|^2 R_z^{-\alpha}$. The random variables D and R_z represent the distance between the associated eNB and the focused UE and the distance between the same eNB and the interfering UEs, respectively. Finally, orthogonal channel allocation is assumed to avoid intra-cell interference.



C. Extended Packet Delay Budget

As mentioned earlier, low latency access to cloud infrastructure is foreseen as a critical feature of 5G systems [10]. As a result, the experienced one-way E-PDB at the UE side during task offloading will be the focused metric throughout this work. As shown in Figure 3, the overall end-to-end E-PDB is illustrated [4]. First, T^{UE} represents the time needed for application initiation and packet generation at the UE side, followed by time intervals for data transmission and task execution at the MEC host, denoted by T^{radio} and T^{exc} , respectively. Throughout this work, T^{UE} is implicitly modeled through T^{radio} , via random generation of packets, whereas, the back-haul, web and remote processing latencies, denoted by $T^{\text{BH+CN}}$, T^{Web} and T^{Proc} respectively, are assumed to be negligible. It is also assumed that the eNBs and their corresponding MEC hosts are physically located at the same node and that all deployed UEs concurrently offload their tasks to their chosen MEC host.

As modeled in [6], the E-PDB for the k-th UE associated to an eNB in the *i*-th tier is calculated as follows

$$\text{E-PDB}_{k,i} = T_{k,i}^{\text{radio}} + T_{k,i}^{\text{exc}}, \qquad (2)$$

where $T_{k,i}^{\text{radio}}$ and $T_{k,i}^{\text{exc}}$ stand for the radio propagation time and the task execution time at the MEC host, respectively. The radio propagation latency represents the time needed for a given packet of size of l_k bits to arrive at the serving eNB [11], thus can be calculated as

$$T_{k,i}^{\text{radio}} = \frac{l_k}{r_{k,i}} = \frac{l_k}{B_{k,i} \log_2(1 + \text{SINR}_{k,i})},$$
(3)

where $r_{k,i}$ is the achievable rate of UE k and $B_{k,i}$ represents the bandwidth allocated to UE k when served by an eNB in the *i*-th tier. On the other hand, the execution time can be computed as

$$T_{k,i}^{\text{exc}} = \frac{l_k f_k}{y_{k,i} C_i},\tag{4}$$

where f_k (measured in cycles/bit) is the number of processing operations per input bit for the task to be offloaded by UE kand $y_{k,i}$ represents the fraction of the total processing power of a tier-*i* MEC host dedicated to the k-th UE.

Throughout this work, we assume equal per-user allocation of radio bandwidth and computational (MEC) resources [12], as the design of a more sophisticated resource allocation scheme is beyond the scope of this paper. Thus, for a given eNB belonging to the i-th tier, the number of associated UEs, which is obtained by means of applying a cell association rule, will determine the portion of bandwidth and computational

resources dedicated to each connected UE. In what follows, we present in detail the investigated association rules.

III. FLEXIBLE CELL ASSOCIATION

Radio-based achievable gains, with reference to UL rates, load balancing and system throughput have been shown in [13], [14], however, the UL cell association is achieved based on an eNB proximity criterion, hence, leading to the minimum pathloss experienced by the UE. In this work, we choose to revisit this rule and propose a new, MEC-aware cell association rule, that aims at minimizing the execution time at the MEC host, along with ensuring connectivity to the closest eNB. This is motivated through questioning the optimality of the conventional, maximum Downlink (DL) RSRP-based association rule, when it comes to the task offloading latency experienced by a UE in a HetNet. A mathematical representation of the association problem can be formulated as follows

$$x_{i} = \underset{x \in \boldsymbol{\Phi}_{i}}{\arg \max}(\eta_{i}||x-y||^{-\alpha}), \forall i = 1, 2, \cdots, K, \quad (5)$$
$$x_{o} = \underset{x \in x, i \neq 1, \cdots, K}{\arg \max}(\eta_{i}||x-y||^{-\alpha}),$$

where η_i , $i = 1, \dots, K$ represents a biasing factor for the *i*-th tier imposed to the UEs, *y* is the UE's location and the ||.|| operation denotes the Euclidean distance between two points of the two-dimensional plane. With regards to the choice of values for parameter η_i , the conventional and proposed association rules are discussed in the remainder of this section.

A. Reference Signal Received Power Criterion

According to this cell association rule, a UE is served by the eNB providing it with the maximum RSRP in the DL. This is equivalent to setting η_i to be equal to P_i in Eq. (5).

In a highly heterogeneous HetNet of large radio disparity (i.e., $\rho_i >> 1$), execution of this rule leads to an imbalanced load among the multiple tiers and, as a result, to limited radio performance, since most of the UEs will be associated to eNBs of high total transmit power. This problem is well-known and multiple solutions have been proposed, such as load-aware optimization [10] and cell range extension [15]. In order to quantify the number of UEs associated with a tier-*i* eNB, the association probability of a given UE to an eNB of the *i*-th tier is calculated as $\mathcal{A}_i^{\text{RSRP}} = \frac{\lambda_i}{\Delta_i^{\text{RSRP}}}$, where $\Delta_i^{\text{RSRP}} = P_i^{\frac{-2}{\alpha}} \sum_{j=1}^{K} \lambda_j P_j^{\frac{2}{\alpha}}$ [16]. Consequently, the average number of associated UEs to an eNB of the *i*-th tier, termed as \hat{N}_i^{RSRP} , will affect the experienced E-PDB per UE, as the amount of bandwidth and processing resources allocated per UE is inversely proportional to the achieved E-PDB. Mathematically, quantity \hat{N}_i^{RSRP} is expressed as

$$\hat{N}_i^{\text{RSRP}} = \frac{\mathcal{A}_i^{\text{RSRP}} \lambda_u}{\lambda_i} = \frac{\lambda_u}{\Delta_i^{\text{RSRP}}}.$$
(6)

Assuming equal resource allocation among the UEs connected to an eNB, the bandwidth and processing (MEC) resources

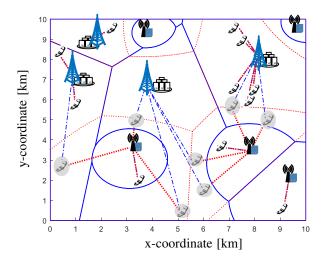


Fig. 4. A zoomed realization of a two-tier network consisting of macro and micro eNBs ($\rho_1 = 40$, $\gamma_1 = 2$, $\omega_1 = 20$). The blue dashed-dotted lines represent UE connectivity following the maximum DL RSRP association rule, while, the red dashed lines represent UE connectivity based on the proposed computational proximity-based rule. The gray shaded users are the ones for which execution of the two cell association rules results to different eNB/ MEC nodes for connectivity.

allocated to the k-th UE associated to an eNB of the i-th tier will be equal to

$$B_{k,i} = \frac{B_i}{\hat{N}_i^{\text{RSRP}}},\tag{7}$$

$$y_{k,i} = \frac{1}{\hat{N}_i^{\text{RSRP}}},\tag{8}$$

where B_i represents the total bandwidth allocated to tier $i, i = 1, \dots, K$.

B. Computational Proximity Criterion

In what follows, we introduce a new, MEC-aware cell association rule, according to which the serving eNB is the one of the maximum computational proximity. In this context, computational proximity refers to the existence of a processing power source in the vicinity of a device of limited computation capabilities that chooses to offload a demanding task to this source. Such resources, as defined in Section II $(C_i, \forall i = 1, \dots, K)$ can be the same for all the tiers, thus, resulting in a homogeneous network from a MEC perspective, or can be varying across the tiers, resulting in a MEC HetNet, thus, affecting the task offloading latency experienced by a UE. As observed from the total E-PDB expression in Eq. (2), the overall E-PDB is jointly affected by the proximity to the connected eNB (i.e., radio part - $T_{k,i}^{\text{radio}}$) as well as by the available processing power (i.e., MEC part - $T_{k,i}^{\text{exc}}$). Our aim is to consider both resource domains through introducing a new association rule for UL communication, by setting the bias factors η_i as functions of the available computational resources (i.e., $\eta_i = C_i$). As a consequence, the association probabilities and the average numbers of connected users can be computed easily by replacing P_i by C_i and computing $\mathcal{A}_i^{\rm MEC},~\Delta_i^{\rm MEC}$ and $\hat{N}_i^{\rm MEC}$, accordingly. Referring to network deployment, as it will be shown, a critical factor affecting the performance of the proposed UE-cell association rule is the ratio of radio/ MEC cross-tier disparities, which is defined as

$$\omega_i = \frac{\rho_i}{\gamma_i}.\tag{9}$$

In order to visualize the influence of parameter ω_i on UE connectivity, focusing on a two-tier network, Figure 4 presents a zoomed overview of a network realization, where UEs are connected to their serving eNBs/MEC hosts via the two discussed rules. One can observe that, assuming a large value of parameter ω_1 , for a fair number of UEs, the maximum DL RSRP association rule indicates a node for connectivity which is different from the one obtained by applying the proposed computational proximity-based association rule. This occurs because large cross-tier radio/ MEC disparities lead towards quite dissimilar radio/ MEC coverage areas. Such an observation paves the way towards a different insight on the network planning process, taking into account the available computational resources together with the radio transmission capabilities, since both of them directly affect the E-PDB experienced by a given UE, when the latter wishes to offload a demanding processing task to a MEC host.

In the following section, we present various simulation results, highlighting key messages regarding the studied association rules, the role of cross-tier parameter disparities, as well as the effect of deployment densities on the achieved E-PDB.

IV. SIMULATION RESULTS

Our objective throughout this section is to provide insight on the E-PDB improvements when applying the new proposed MEC-aware association rule, by means of numerical evaluation, as an analytical E-PDB study is planned for future work. A two-tier HetNet is investigated, where the k-th UE generates a random packet of size of l_k bits that is modeled as a uniform random variable taking values between l_{\min} and l_{max} . Additionally, the number of processing operations per input bit, f_k , is uniformly distributed, as well, between values f_{\min} and f_{\max} . The amount of dedicated bandwidth and computational resources that each eNB assigns to its associated users is computed based on the applied association rules. Due to the utilized random spatial model (i.e., PPP-based), Monte-Carlo simulations were conducted for the eNB/ UE locations and the small-scale fading phenomena. A summary of the adopted simulation parameters is provided in Table I, where the parameter values are fixed throughout the section, unless otherwise stated. It should be noted that, as a two-tier HetNet is considered, the subscript of parameter ω_1 will be dropped for the sake of simplicity.

As mentioned in Section III, the achievable E-PDB is our metric of investigation throughout this work. In Figure 5, the Complementary Cumulative Distribution Function (CCDF) of the E-PDB is shown for the two discussed association rules and for different values of ω . As previously explained, when

TABLE I Simulation Parameters

Parameter	value
Number of tiers	2
(λ_1,λ_2)	(0.5, 3) eNBs/km
(P_1, P_2)	(46, 30) dBm
Relative area	10 km ²
λ_u	30 UEs/km
P_{UE}	23 dBm
σ^2	-90 dBm
(l_{\min}, l_{\max})	(100, 300) kbits
(f_{\min}, f_{\max})	(500, 1500) cycles/bit
Bandwidth	10 MHz
Pathloss exponent (α)	4
Number of realizations	10000

 ω varies away from the value of one, the radio and MEC coverage areas become more dissimilar, hence, resulting in a selection divergence of the associating eNB/MEC server by a UE. It is observed that, for values of ω greater than one $(\omega = 2)$, the proposed computational proximity association rule (denoted by "MEC") provides a lower probability to violate a given E-PDB threshold as compared to the maximum RSRP rule (denoted by "RSRP"), with nearly 60% E-PDB reduction for the 50-th percentile of UEs. This occurs due to the enhanced balance between the proximity and available computational resources at the MEC node. On the other hand, as ω is lower than one ($\omega = 0.5$), the performance is turned over, as the RSRP rule provides a lower experienced E-PDB of the same latency reduction. Consequently, we observe that having the two association metrics at hand, an adaptive, deployment-dependent cell association procedure can be envisioned, in order to fully capture the radio and MEC resource disparities for E-PDB minimization. Under that framework, the UE is ought to only acquire knowledge of the radio and MEC disparities of the HetNet, in order to decide upon which association rule to consider. For the case of $\omega = 1$, since the corresponding coverage areas obtained by the two rules will fully overlap, the experienced E-PDB performance will be identical for the two rules.

With the aim of observing the effect of deployment density on the experienced E-PDB, Figure 6 depicts the probability of violating a target E-PDB of 0.4 seconds for an increasing ratio of micro-over-macro eNB spatial densities when $\omega = 2$. We observe a nearly constant association-based outage reduction in favor of the proposed MEC-aware association rule, similar to the latency reduction observed in Figure 5. The decreasing slope of the two curves is expected as the number of micro eNBs over a unit area increases. This is due to the increasing probability for a UE to be associated with a closer node, thus leading to lower E-PDB values.

Finally, in Figure 7, the percentage of UEs for which the maximum DL RSRP and the proposed MEC-aware cell association rules provide different connectivity recommendations, is illustrated, as a function of the value of parameter

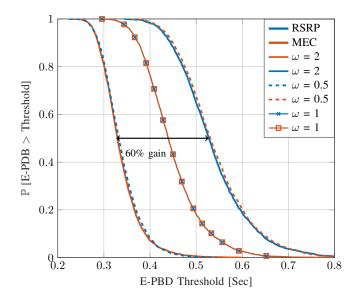


Fig. 5. CCDF of the E-PDB under different radio and MEC resource disparities.

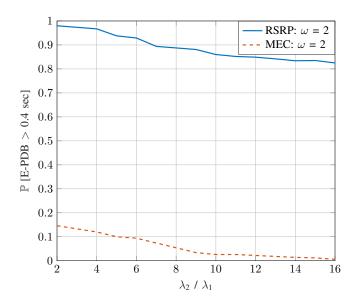


Fig. 6. Probability to violate a target E-PDB (0.4 sec) as a function of the ratio of eNB/MEC deployment densities.

 ω . As anticipated, for the increase of cross-tier disparity between the radio and MEC capabilities (i.e. $\omega \neq 1$), the two coverage areas become highly divergent, thus, leading to a higher probability of a UE being present in this disjoint region (e.g., nearly 40 % of UEs will reach different decisions upon associating to an eNB/ MEC node for large disparities of $\omega = 0.01$ or $\omega = 80$). On the contrary, for the $\omega = 1$ case, the radio and MEC coverage areas will be identical, hence, the application of the two investigated association rules will provide the same preference for UL connectivity.

V. CONCLUSION

In this work we have leveraged the MEC degree of freedom in planning and dimensioning a HetNet, via optimizing the ex-

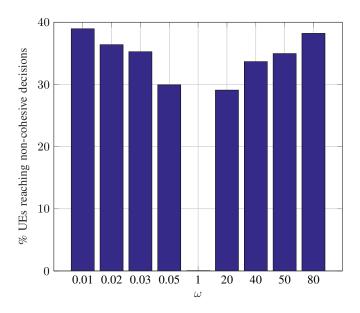


Fig. 7. Fraction of UEs reaching non-cohesive decisions upon cell association, as a function of cross-tier radio and MEC disparity.

ploitation of both communication and computation resources during UE-cell association. Focusing on the task offloading example, a new association metric for UL communication has been proposed, aiming at reducing the experienced E-PDB of a UE. Different scenarios spanning diverse radio and MEC cross-tier disparities have been presented to highlight the cell association decision effect on system performance. It has been shown that, for a range of disparities between radio and MEC capabilities between tiers, the proposed computational proximity rule provided gains in terms of E-PDB, as compared to the conventional maximum RSRP rule. This performance gain degrades as cross-tier radio/ MEC disparities become similar. Also importantly, we have explored the case, in which, for different association rules, a UE would favor associating to different eNB/MEC hosts in the UL.

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