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A data-driven traffic steering algorithm for optimizing user experience in multi-tier LTE networks

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***Abstract*—Multi-tier cellular networks are a cost-effective solution for capacity enhancement in urban scenarios. In these networks, effective mobility strategies are required to assign users to the most adequate layer. In this paper, a data-driven self-tuning algorithm for traffic steering is proposed to improve the overall Quality of Experience (QoE) in multi-carrier Long Term Evolution (LTE) networks. Traffic steering is achieved by changing Reference Signal Received Quality (RSRQ)-based inter-frequency handover margins. Unlike classical approaches considering cell-aggregated counters to drive the tuning process, the proposed algorithm relies on a novel indicator, derived from connection traces, showing the impact of handovers on user QoE. Method assessment is carried out in a dynamic system-level simulator implementing a real multi-carrier LTE scenario. Results show that the proposed algorithm significantly improves QoE figures obtained with classical load balancing techniques.**

***Index Terms*—Mobile network, Quality of Experience, Self-Organizing Network, Reference Signal Received Quality, load balancing.**

I. INTRODUCTION

Over the last years, the explosive growth in mobile data traffic has forced cellular operators to increase network capacity and reduce cost per bit delivered [1]. To this end, operators deploy multi-tier (a.k.a. hierarchical or multi-layered) networks, where multiple base stations provide coverage in the same geographical area [2]. In such scenarios, ensuring that users are always connected to the best serving base station is not straight forward.

In parallel, the success of smartphones and tablets has raised user expectations. This fact has led operators to change their network management procedures from a network-centric approach based on network performance to a user-centric approach focused on user satisfaction (Quality of Experience, QoE). Such a trend will continue in 5G systems, where services of very different nature will coexist [3].

As a result of those changes, network management has become a very challenging task. For this purpose, operators seek automatic tools for configuring network parameters during deployment and operational stages, giving rise to Self-Organizing Networks (SON). SON use cases are classified into three groups: self-configuration, self-healing and self-optimization [4]. In particular, self-optimization procedures adjust system parameters to face changes in the network so that optimal performance is guaranteed. Load balancing (a.k.a. traffic steering) is one of the most extended use cases in self-optimization [3]. It aims to alleviate congestion problems due to traffic fluctuations by redistributing users among neighbor cells. For this purpose, base stations parameters are modified. In the literature, several load balancing schemes are proposed based on tuning different physical or logical system parameters, such as transmit power [5], antenna tilt [6], cell reselection offset [7] or handover margins [8]. The latter option of steering traffic by adjusting mobility parameters, known as Mobility Load Balancing (MLB), is the most popular alternative.

Several MLB algorithms have been developed for traffic steering in single-tier networks. Most of them tune handover parameters by using simple proportional controllers [9], fuzzy logic controllers [10] or adaptive controllers with reinforcement learning [11]. MLB can also be combined with other traffic steering techniques, such as power re-planning [12]. In multi-tier networks, traffic steering is much more difficult due to the asymmetric signal and interference levels between cells of different layers (e.g., cells of different bands, macrocells vs small cells...) [13]. For this purpose, several inter-frequency handover schemes have been proposed in the literature. First schemes dealt with user mobility in multi-band (a.k.a. multi-carrier) cellular networks, consisting of co-located cells using different frequency bands [14]. Later schemes deal with user mobility in heterogeneous cellular networks, comprising overlapping cells of different sizes or technologies. A survey of mobility strategies for LTE heterogeneous networks is presented in [15]. In [16], a handover scheme considering User Equipment (UE) speed and requested service is proposed to manage mobility between macrocells and small cells. Such a scheme increases network capacity while maintaining Quality of Service (QoS). In [17], a handover skipping scheme for two-tier cellular networks is proposed to enhance user throughput. For this purpose, an admission controller is implemented in eNodesB (eNBs) to skip some handovers, depending on UE speed and location. In multi-tier networks, a common approach is to address inter-frequency load balancing in the cell (re)selection process. In [18], a heuristic algorithm that assigns cell-specific offsets to low power nodes in a heterogeneous LTE network is proposed so that more users can be associated with them during cell reselection (a.k.a. cell range expansion). In [19], an association

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scheme that jointly maximizes downlink system capacity and minimizes mobile station uplink transmit power is presented. In [20], the parameters in different cell (re)selection strategies are optimized with statistical information of radio propagation to achieve a certain target traffic distribution in a multi-carrier LTE network. Alternatively, other authors tackle traffic steering by adjusting the value of inter-frequency handover (IFHO) parameters. For instance, in [21], the optimal configuration of inter-Radio Access Technology (RAT) handover margins in a multi-RAT multi-layer wireless network is derived by means of a sensitivity analysis. In [22], a self-tuning algorithm based on a fuzzy logic controller adapted with reinforcement learning is proposed to adjust inter-RAT handover margins to reduce call dropping ratio in heterogeneous LTE networks. In [23], cell-specific offsets are adjusted by taking into account target cells and their surroundings, reducing the number of unsatisfied users and the total number of handovers.

All the above-mentioned traffic steering algorithms are driven by simple performance indicators obtained from the aggregation of all connections in a cell. In legacy networks, where voice calls were the predominant service, these approaches achieved the best user performance. However, in current networks supporting services of very different requirements, new traffic steering algorithms driven by end-user data must be designed to optimize QoE. In [24], a throughput-based traffic steering algorithm for heterogeneous LTE-Advanced networks is presented. Traffic steering decisions are evaluated by predicting whether forcing the handover of users may increase the overall system throughput. For this purpose, the maximum radio link throughput that each user could potentially achieve on each neighbor cell is estimated by the Shannon formula with an equal resource sharing scheme. Such an advanced radio resource management algorithm improves the overall user throughput at the expense of increasing the number of handovers (i.e., signaling load). However, in current networks offering multiple services, end-user throughput strongly depends on the traffic mix and the packet scheduling algorithm. Thus, a change in the scheduler or the demanded services might lead to inaccurate throughput estimations. Moreover, a large increase in user throughput does not necessarily lead to a large QoE improvement, due to the non-linear mapping between QoS and QoE (e.g., logarithmic [25] or exponential [26]).

With the latest advances of information technologies, it is now possible to process connection traces collected by the network management system by means of Big Data Analytics (BDA) techniques. Such very detailed information can be used to design new QoE indicators to drive the traffic steering process. For instance, the impact of specific events (e.g., handovers) on service performance on a connection basis can be isolated. For this reason, the combination of SON and BDA has been recognized as the most efficient method to guarantee end-user satisfaction in future 5G networks [27] [28].

In this work, a data-driven algorithm for traffic steering in multi-carrier LTE networks is proposed. The aim of the algorithm is to improve the overall system QoE. For this purpose, traffic steering is carried out by tuning Reference Signal Received Quality (RSRQ)-based handover margins in a classical IFHO scheme. Unlike previous works, where parameter tuning is driven by network performance counters from the aggregation of all connections in a cell, the proposed algorithm is driven by a novel indicator, derived from individual connection traces, that estimates the impact of handovers on end-user QoE. The algorithm is validated in a dynamic system-level simulator implementing a real multi-carrier scenario. The main contributions of this work are: a) a novel indicator, derived from individual connection traces, showing the impact of handovers on end-user QoE, b) a new self-tuning algorithm for steering users among carriers in a classical IFHO scheme to improve the overall system QoE, and c) the validation of the algorithm in a realistic simulation scenario.

The rest of the document is organized as follows. Section II formulates the problem of optimizing the QoE in a multi-carrier LTE network by improving IFHO performance. Section III presents the considered traffic and QoE models. Section IV describes the proposed self-tuning algorithm. Section V presents the assessment process. Finally, Section VI summarizes the main conclusions.

II. Problem formulation

User mobility in LTE is handled by an event-based hard handover procedure assisted by the UE. The UE measures the signal quality received from a set of cells, consisting of a serving cell and active cells (i.e., cells whose received pilot signal level exceeds a predefined threshold). Measurement reports are then sent to the serving eNB either periodically or triggered by an event. Finally, the eNB makes the handover decision based on the predefined handover triggering event [29]. Table I summarizes the events defined for intra-RAT measurement reporting and handover.

Two measurement quantities related to the handover procedure are defined in 3GPP specifications: RSRP and RSRQ [30]. RSRP is defined as the linear average of the received power in the resource elements carrying cell-specific reference signals within the considered measurement frequency bandwidth. RSRQ is defined as the ratio

$$RSRQ = \frac{N_{PRB} \cdot RSRP}{RSSI} , \qquad (1)$$

where N_{PRB} is the number of Physical Resource Blocks (PRBs) over the entire bandwidth and $RSSI$ is the E-UTRA Carrier Received Signal Strength Indicator, providing information about total received wideband power, including all interference and thermal noise. Hence, RSRP is equivalent to signal strength, while RSRQ provides information about received signal quality and cell load. The type of measurement (i.e., RSRP or RSRQ) used to evaluate equations for event triggering is configured by the operator.

In multi-carrier networks, it is essential to set a suitable handover scheme (i.e., triggering events, measurement type and handover parameters) to ensure efficient use of bandwidth and guarantee an adequate level of end-user performance. For this purpose, it is common practice to configure both intra-frequency and inter-frequency handovers based on RSRP measurements [31]. Fig. 1 shows the typical handover scheme

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TABLE I
HANDOVER EVENTS IN LTE

Event	Description
A1	Serving cell becomes better than threshold
A2	Serving cell becomes worse than threshold
A3	Neighbor cell becomes offset better than serving cell
A4	Neighbor cell becomes better than threshold
A5	Serving cell becomes worse than threshold1 and neighbor cell becomes better than threshold2

(hereafter referred to as Signal-Based HandOver scheme, SBHO) for handling mobility in a two-tier network. The bottom layer, comprising large cells (cells 1 and 2) working at a low carrier frequency, represents the coverage layer. The top layer, consisting of small cells (cells 3 and 4) with large bandwidth and a higher carrier frequency, works as a capacity layer. In both layers, intra-frequency handovers are triggered by A3 event, i.e.,

$$RSRP(j) \geq RSRP(i) + HOM_{intra}(i,j) \ , \qquad (2)$$

where $RSRP(i)$ and $RSRP(j)$ are the pilot signal levels received from the serving cell i and neighbor cell j, respectively, and $HOM_{intra}(i,j)$ is the handover margin for intra-frequency handovers, defined on a per-adjacency basis. In contrast, IFHOs are triggered by RSRP-driven A5 event, i.e.,

$$RSRP(i) \leq thresh1 \ , \qquad (3)$$

$$RSRP(j) \geq thresh2 \ , \qquad (4)$$

where $thresh1$ and $thresh2$ are absolute signal level thresholds, and i and j are the inter-frequency neighbor cells (e.g., cells 1 and 3 in Fig. 1).

The set-up in SBHO scheme ensures that users are always connected to a cell with adequate received power, since it is based on RSRP. However, RSRP measurements do not reflect other factors affecting the radio link performance, such as noise, interference or cell congestion. As a consequence, network performance can be severely degraded if the coverage layer becomes congested as a result of its better propagation conditions. This problem can be solved by using RSRQ to trigger IFHOs.

To show the link between cell load and RSRQ, Fig. 2 represents an example of evolution of the RSRQ reported by a LTE user as cell load (measured by the PRB utilization ratio) changes in a simulation tool. Two RSRQ values are shown: instantaneous RSRQ, $RSRQ_{inst}$, and RSRQ averaged over a certain time window, $RSRQ_{avg}$, the latter reported in measurement reports [29]. It is observed that the value of $RSRQ_{inst}$ strongly depends on cell load, i.e., the highest PRB_{util}, the lowest $RSRQ_{inst}$. Likewise, the left side of the figure shows that, even when cell load is constant, $RSRQ_{inst}$ varies due to desired signal strength and interference fluctuations. This rapid variation can turn into instabilities when evaluating handover triggering conditions. Such fluctuations are smoothed out by the averaging operation

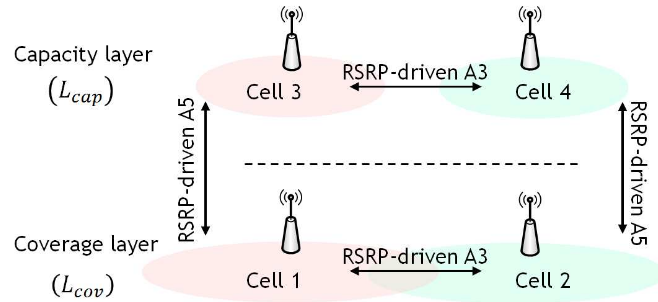

Fig. 1. Typical handover scheme in a two-tier network.

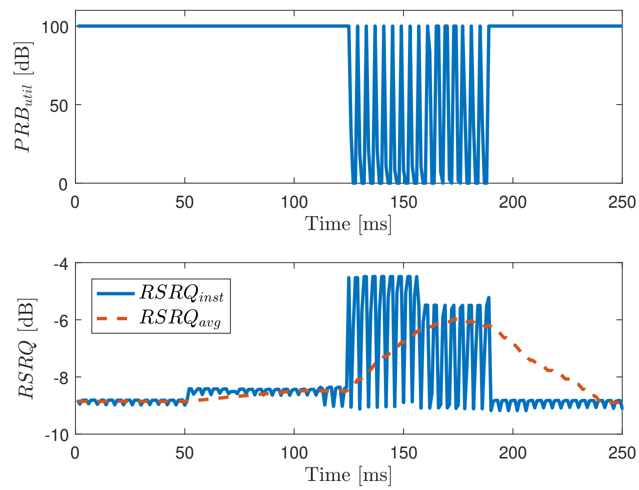

Fig. 2. Impact of cell load on RSRQ.

in $RSRQ_{avg}$. Thus, $RSRQ_{avg}$ may be a convenient measurement for triggering IFHOs in multi-carrier LTE networks, as traffic will be offloaded from coverage layers when capacity layers become underutilized. Some studies [32] [33] state that RSRQ-based IFHOs lead to better performance in terms of packet delay, data throughput, number of handovers and UE power consumption. For this reason, RSRQ-based IFHO has been used as a passive traffic steering solution in multi-carrier scenarios [24]. Nonetheless, proper handover margin settings must still be configured to ensure the best user experience. This is done by the QoE-based MLB algorithm described later.

III. SYSTEM MODEL

This section outlines the traffic and QoE models for the considered services.

A. Traffic models

Four services are considered in this work: Voice over Internet Protocol (VoIP), on-demand videostreaming (VIDEO), file download via File Transfer Protocol (FTP) and web browsing (WEB). Table II summarizes the main features of each service.

B. QoE models

In this work, QoE is estimated by utility functions that map objective QoS measurements into a Mean Opinion Score (MOS) value, ranging from 1 (bad) to 5 (excellent). Likewise,

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TABLE II
TRAFFIC MODEL PARAMETERS

Service	Description
VoIP	Coding rate: 16 kbps
	Duration: exponential (avg. 60 s)
VIDEO	Packet arrival process and file size from H.264/MPEG-4 AVC real traces
	Resolution: 720p
	Duration: uniform [0,540] s
FTP	File size: log-normal (avg. 10 MB)
WEB	HyperText Transfer Protocol (HTTP)
	No. pages per session: log-normal (avg. 30)
	Reading time: exponential (avg. 30 s)

context information is used to differentiate between indoor and outdoor users, so that indoor users are more demanding in terms of QoS. Thus, two utility functions are defined per service, as in [34].

The utility functions used for VoIP service are [35]

$$QoE^{(VoIP_{outdoor})} = 1 + 0.035R + 7{\cdot}10^{-6}(R-60)(100-R)\ , \tag{5}$$

$$QoE^{(VoIP_{indoor})} = 1 + 0.035\tfrac{R}{1.5} + 7\cdot 10^{-6}\tfrac{R}{1.5}(\tfrac{R}{1.5}-60)(100-\tfrac{R}{1.5})\ , \tag{6}$$

where R is a parameter related to packet delay, ranging from 0 to 93. It is assumed that $QoE^{(VoIP_{indoor})} = QoE^{(VoIP_{oudoor})} = 1$ if a VoIP connection is dropped.

For videostreaming service, the utility functions are [36]

$$QoE^{(VIDEO_{outdoor})} = 4.23 - 0.0672T_{init} - 0.742F_{reb} - 0.106T_{reb}\ , \tag{7}$$

$$QoE^{(VIDEO_{indoor})} = 4.23 - 0.0672(1.5T_{init}) - 0.742(1.5F_{reb}) - 0.106(1.5T_{reb})\ , \tag{8}$$

where T_{init} is the initial buffering time (in seconds), F_{reb} is the average stalling frequency (in seconds^{-1}) and T_{reb} is the average stalling duration (in seconds). For both indoor and outdoor users, the QoE value for a video connection is upper limited to 4.23, showing that some users do not score their experience as excellent even with the best possible link conditions. Again, a value of 1 is set if the connection is dropped.

The QoE of FTP users is computed as [37]

$$QoE^{(FTP_{outdoor})} = \max(1, \min(5, 6.5TH - 0.54))\ , \tag{9}$$

$$QoE^{(FTP_{indoor})} = \max(1, \min(5, 6.5\tfrac{TH}{1.5} - 0.54))\ , \tag{10}$$

where TH is the average session throughput in Mbps.

Finally, the utility functions used for WEB users are [37]

$$QoE^{(WEB_{outdoor})} = 5 - \frac{578}{1 + \left(\frac{TH + 541.1}{45.98}\right)^2}\ , \tag{11}$$

$$QoE^{(WEB_{indoor})} = 5 - \frac{578}{1 + \left(\frac{\frac{TH}{1.5} + 541.1}{45.98}\right)^2}\ , \tag{12}$$

where TH is the average session throughput in kbps. Note that, although both FTP and WEB utility functions only depend on session throughput, FTP users are more demanding (i.e., a higher value of TH is required to achieve a certain level of QoE).

IV. TRAFFIC STEERING STRATEGY

In this section, a novel strategy for traffic steering in multi-carrier LTE networks is presented. The aim is to improve the overall system QoE by redistributing the load between carriers. For this purpose, a two-stage optimization process is carried out. First, a mobility scheme combining RSRQ and RSRP measurements to trigger IFHOs is activated. Then, IFHO margins are tuned on a per-adjacency basis with a new MLB algorithm.

A. Stage 1: activation of RSRQ-based IFHOs

First, a handover scheme considering RSRQ measurements for triggering IFHOs is enabled. This scheme, hereafter referred to as Quality-Based HandOver scheme (QBHO), is shown in Fig. 3. Unlike SBHO scheme, presented in Fig. 1, QBHO enables RSRQ-based handovers triggered by A3 event to handle mobility from coverage to capacity layer (hereafter, L_{cov} and L_{cap}, respectively). Handovers in this direction are triggered when

$$RSRQ(j) \geq RSRQ(i) + HOM_{inter}(i,j)\ , \tag{13}$$

where $RSRQ(i)$ and $RSRQ(j)$ are the RSRQ values in serving and neighbor cell, respectively, and $HOM_{inter}(i,j)$ is the IFHO margin.

A default value of $HOM_{inter}(i,j) = 3$ dB is set for all adjacencies $(i,j)|\{i \in L_{cov}, j \in L_{cap}\}$ [38]. Recall that RSRQ values do not only depend on the received signal strength, but also on interference and cell load. Consequently, even if signal strength received from L_{cap} is lower than that received from L_{cov}, some users will be offloaded from L_{cov} to L_{cap} when L_{cap} is underutilized. Moreover, any user experimenting bad coverage at L_{cap} will be reallocated to L_{cov} thanks to the coverage-based handover mechanism set for handovers from L_{cap} to L_{cov}. Hence, QBHO scheme guarantees service continuity while retaining a good quality of service.

Note that QBHO scheme should only be considered as a previous step to the application of the self-tuning algorithm described next, which is the main contribution of this work.

B. Stage 2: optimization of IFHO margins

Once QBHO scheme is activated, a novel MLB algorithm, referred to as Optimized Experience (OE), is executed. The aim of the algorithm is to improve the overall system QoE by finding the best share of users among cells of different carriers. This is achieved by tuning RSRQ-based IFHO margins on an

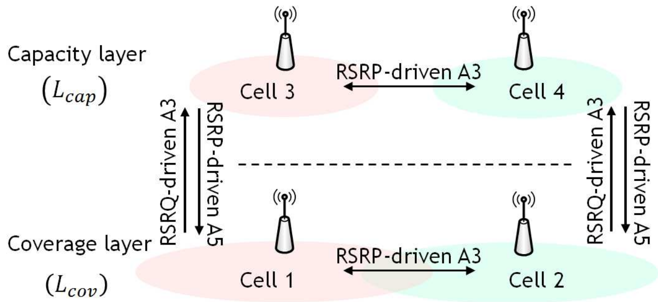

Fig. 3. Quality-based handover scheme for a two-tier network.

adjacency basis. Unlike classical traffic steering algorithms, where parameter tuning is driven by cell-level performance counters (e.g., PRB utilization ratio), the proposed algorithm relies on a new indicator that estimates the impact of handovers on end-user QoE. For clarity, the rationale of the algorithm is explained first, the indicator used to drive the tuning process is then defined and the control algorithm is described later.

1) Rationale of the algorithm: In LTE, each IFHO changes: a) the radio link conditions of the handed-over user, and b) the number of simultaneous users in the source and target cells. These changes have an impact on received signal level of the handed-over user and cell loads, which ultimately affect user throughput (and, hence, QoE) of every user in both cells.

From a QoE perspective, the optimum handover point is that maximizing the overall QoE of users in both source and target cells. Steering a user to the new cell too early might negatively affect the QoE of the handed-over user (e.g., due to low signal in the target cell) and that of users in the target cell (e.g., due to an earlier increase of cell load). In this early case, it is expected that the overall QoE in the adjacency is degraded after the handover event (i.e., the overall QoE is worse when the handed-over user is in the new cell). Conversely, steering a user to the new cell too late might negatively affect the QoE of the handed-over user (e.g., due to low signal in the source cell) and users in the source cell (e.g., due to a later decrease of cell load). In this case, it is expected that the overall QoE in the adjacency is improved after the handover (i.e., the overall QoE is worse when the handed-over user is in the old cell). In the optimal situation, delaying (or bringing forward) the handover point would deteriorate the overall QoE in the adjacency. In this case, the overall QoE in the adjacency should be the same just before and after the handover event.

From the previous observation, it can be inferred that changes of the overall QoE measured after a handover event are an indicator of the impact of displacing the handover point. Since the handover point is displaced by increasing the handover margin, such QoE differences before and after the handover can be used to derive the sign, and approximate the magnitude, of the gradient of the objective function (i.e., the overall system QoE, QoE_T) with respect to the decision variables (i.e., handover margins, $HOM(i,j)$), $\frac{\partial QoE_T}{\partial HOM(i,j)}$. This information can then be used to implement a gradient ascent method to optimize the overall system QoE.

To that end, a self-tuning algorithm is proposed here to adjust handover margins per adjacency so that the overall QoE in the adjacency is the same before and after handover events on average. For this purpose, the QoE of individual connections around the handover events must be estimated from connection traces.

2) Description of the driver: A user u performing a handover k between two neighbor cells experiences a change of QoE defined as

$$\Delta QoE_u^{(k)} = QoE_{afterHO}^{(k)} - QoE_{beforeHO}^{(k)} \, , \tag{14}$$

where $QoE_{beforeHO}^{(k)}$ is the QoE experienced by the user just before the handover and $QoE_{afterHO}^{(k)}$ is the QoE experienced by the user just after the handover. For a user handed over from cell i to cell j, $QoE_{beforeHO}$ is measured in cell i and $QoE_{afterHO}$ is measured in cell j. A positive value of $\Delta QoE_u^{(k)}$ implies that user satisfaction improves after handover.

Both $QoE_{beforeHO}^{(k)}$ and $QoE_{afterHO}^{(k)}$ are computed using the equations introduced in Section III. For the sake of robustness, the time window used to measure the indicators in these equations must be long enough to provide representative information of the user QoE in the serving cell, but short enough to avoid changes in the traffic demand in the source and target cells unrelated to the handover event. In this work, a 500-ms window is established. This value is long enough to reduce the impact of the throughput ramp-up effect due to Transmission Control Protocol slow-start [39] and Outer Loop Link Adaptation convergence [40] for throughput-sensitive services (i.e., web browsing or FTP).

In addition, any handover modifies the number of simultaneous users in both source and target cells (i.e., source cell loses a user, while target cell gains a user). As a result, other users in such cells will also be affected by the handover. The change in the overall QoE in the adjacency due to a handover k can be calculated as

$$\Delta QoE_T^{(k)} = \sum_{u \in \{i,j\}} \Delta QoE_u^{(k)} \, , \tag{15}$$

where $u \in \{i,j\}$ represents all users served by cells i and j when the handover is executed and $\Delta QoE_u^{(k)}$ is the change in QoE of user u, defined in (14). Note that, for the user performing the handover, $QoE_{beforeHO}$ and $QoE_{afterHO}$ in (14) are calculated in different cells, and the performance difference is due to the change of serving cell. In contrast, for the rest of users, both terms are calculated in the same cell (as their serving cell does not change), and the performance difference is originated by the cell load change.

The indicator used as a driver to tune IFHO margins on an adjacency basis is the average QoE change after a handover in the adjacency, defined as

$$\overline{\Delta QoE_T}(i,j) = \frac{1}{N_{HO}(i,j)} \sum_{k=1}^{N_{HO}(i,j)} \Delta QoE_T^{(k)} \, , \tag{16}$$

where $N_{HO}(i,j)$ is the number of handovers performed from cell i to cell j during a certain reporting period (e.g., 15 min).

A negative value of $\overline{\Delta QoE_T}(i,j)$ indicates that, on average, the overall user satisfaction in cells i and j decreases when handovers are performed from i to j, and thus the number of these handovers must be reduced (i.e., handover margins must be more restrictive). In contrast, a positive value of $\overline{\Delta QoE_T}(i,j)$ indicates that user satisfaction increases when handovers are performed from i to j, and thus the number of these handovers must be increased (i.e., handover margins must be less restrictive). The optimal handover point is given by the condition $\overline{\Delta QoE_T}(i,j) = 0$. At that point, on average, QoE does not experience any degradation because of handovers.

3) Control algorithm: The self-tuning algorithm is implemented as shown in Algorithm 1. It is designed as a set of proportional controllers (1 per adjacency) that iteratively modify IFHO margins, $HOM_{inter}(i,j)$, based on the value of the above-described indicator, $\overline{\Delta QoE_T}(i,j)$. In each iteration, the value of $HOM_{inter}(i,j)$ is modified incrementally on a per-adjacency basis. Specifically, the increment/decrement in the handover margin, $\Delta HOM_{inter}(i,j)$, is computed from the value of $\overline{\Delta QoE_T}(i,j)$ as

$$\Delta HOM_{inter}(i,j) = \begin{cases} 1 & \overline{\Delta QoE_T}(i,j) < \beta_1 \,, \\ 0 & \beta_1 \leq \overline{\Delta QoE_T}(i,j) \leq \beta_2 \,, \\ -1 & \overline{\Delta QoE_T}(i,j) > \beta_2 \,, \end{cases} \tag{17}$$

where β_1 and β_2 are thresholds for triggering handover margins changes so as to eliminate random actions due to small fluctuations of drivers. In this work, both thresholds are symmetric, i.e., $\beta_2 = -\beta_1 = 0.05$ MOS points. Such values provide an adequate trade-off between optimality and complexity. Larger absolute values reduce the number of iterations required to reach equilibrium at the expense of deteriorating network performance slightly, since the optimization process stops before $\overline{\Delta QoE_T}(i,j) = 0$.

The chosen 1-dB step in (17) provides an adequate trade-off between fast convergence and stability. Lower values of $\Delta HOM_{inter}(i,j)$ make optimization too slow, while too large values lead to abrupt changes in handover margins, both degrading network performance.

The algorithm is executed a predetermined number of times (referred as to optimization loops). In every loop, connection traces are collected during a predetermined reporting period (e.g., 15 min). Then, the algorithm computes the value of $\overline{\Delta QoE_T}(i,j)$ in each inter-frequency adjacency (i,j) where handovers are RSRQ-based. Finally, the new value of $HOM_{inter}(i,j)$ is computed as

$$HOM_{inter}^{(n+1)}(i,j) = HOM_{inter}^{(n)}(i,j) + \Delta HOM_{inter}^{(n)}(i,j) \,, \tag{18}$$

where superscripts (n) and $(n+1)$ denote iteration numbers.

$HOM_{inter}(i,j)$ values are limited to the interval $[-7, 7]$ dB. The minimum $HOM_{inter}(i,j)$ value avoids too early handovers and ping-pong effect, while the maximum value avoids too late handovers, which can have a negative impact on user experience.

Algorithm 1 Self-tuning algorithm

```
repeat
  Collect connection traces during 15 min
  for all adjacencies (i,j)|{i ∈ L_cov, j ∈ L_cap} do
    Compute ΔQoE_T(i,j)
    if ΔQoE_T(i,j) is lower than β1 then
      ΔHOM_inter(i,j) = 1
    else if ΔQoE_T(i,j) is higher than β2 then
      ΔHOM_inter(i,j) = −1
    else
      ΔHOM_inter(i,j) = 0
    end if
    Update HOM_inter(i,j) value
  end for
until the predetermined number of loops is reached
```

The proposed self-tuning algorithm performs small changes in the value of handover margins iteratively (+/- 1 dB) until equilibrium is reached (i.e., $\overline{\Delta QoE_T}(i,j) = 0$). This equilibrium condition leads to a local maximum of the problem. However, due to the heuristic nature of the controller, convergence is not guaranteed. In practice, feedback loop gain is small enough to avoid oscillations in the system. In addition, thresholds β_1 and β_2 in (17) ensure that the controller stops when the value of $\overline{\Delta QoE_T}(i,j)$ is small in every adjacency.

Note that every change performed by the algorithm only affects IFHOs from the coverage to capacity layer. All other mobility mechanisms keep the default settings during the optimization process (e.g.,$HOM_{intra}^{(n)}(i,j) = 3$ dB $\forall\, i,j,n$). Moreover, these changes only affect the IFHO triggering condition. Neither time-to-trigger nor handover execution procedure are modified at any time. As a consequence, the proposed self-tuning algorithm does not increase latency in the IFHO procedure, but just change the condition that must be fulfilled to initiate the handover.

V. PERFORMANCE ASSESSMENT

The proposed traffic steering strategy is validated in a dynamic system-level simulator [41]. For clarity, the assessment methodology is first described and results are presented later.

A. Assessment methodology

A live LTE network scenario is implemented. The scenario consists of 48 cells located in a dense urban area working at 2 different carriers: 700 MHz and 2100 MHz (denoted as L_{700} and L_{2100}, respectively). Cells are distributed in 8 sites, each including 2 co-located sets (1 per carrier) of 3 tri-sectorized antennas. Thus, half of the cells work at L_{700} (cells 1-24) and the other half work at L_{2100} (cells 25-48). To reduce computational load, only the downlink is simulated.

Table III summarizes the main simulation parameters, taken from the live network settings. Path loss in L_{700} is estimated by the empirical Okumura-Hata model, widely used for urban macrocells working from 500 to 1500 MHz. Path loss in L_{2100} is modeled with Hata-COST 231 model, its extension for

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TABLE III
SIMULATION PARAMETERS

Time resolution	10 ms
Carrier frequencies	736 MHz (L_{700}), 2100 MHz (L_{2100})
System bandwidth	1.4 MHz (L_{700}), 5 MHz (L_{2100})
Propagation model	Path loss: Okumura-Hata (L_{700}), Hata COST-231 (L_{2100}) Slow-fading: log-normal σ = 8 dB, d_c = 40 m Fast fading: ETU model
eNB model	Tri-sectorized antennas, MIMO 2x2, transmit power 47.8 dBm (L_{700}), 49 dBm (L_{2100})
Inter-site distance	620 m
Traffic model	Irregular user distribution at cell level adjusted with real statistics, evenly distributed within a cell
Scheduler	Classical exponential/proportional fair [44]
UE location	Case A: 70 % indoor, 30 % outdoor Case B: 100 % outdoor
UE speed	3 km/h (outdoor), 0 km/h (indoor)
Default handover settings	A3 $HOM_{intra}(i,j)$ = 3 dB A5 $tresh1$ = -115 dBm A5 $tresh2$ = -108 dBm

frequencies up to 2 GHz [42]. Slow fading follows a log-normal distribution. Finally, fast fading due to multi-path is modeled with the Extended Typical Urban (ETU) channel model [43]. Note that the coverage layer, L_{700}, offers better propagation conditions, as it works at a lower frequency, but reduced bandwidth (1.4 MHz). In contrast, the capacity layer, L_{2100}, offers worse propagation conditions due to a higher frequency, but a higher bandwidth (5 MHz).

In the above-described scenario, four different mobility management methods are tested. A first method, referred to as Operator Solution (OS), considers mobility procedures currently configured in the live network, namely: a) idle users select carrier based on a token algorithm, b) cell (re)selection is then performed to select the best cell according to RSRP measurements, and finally, c) connected users are handed over according to the SBHO scheme shown in Fig. 1 with the parameters in Table III. No traffic steering algorithm is enabled. This method is considered as a baseline. The other three methods consist of combinations of handover scheme and self-tuning algorithm. A first combination, denoted as SBHO+LB (Load Balancing), tackles traffic steering by executing a classical load balancing algorithm [45] to adjust $HOM_{inter}(i,j)$ values in the SBHO scheme (i.e., RSRP-based IFHOs). A second combination, denoted as QBHO+LB, executes the same load balancing algorithm to adjust $HOM_{inter}(i,j)$ in the quality-based mobility scheme (i.e., RSRQ-based IFHOs) presented in Section IV-A. Finally, the third combination, denoted as QBHO+OE, is the two-stage strategy proposed in this work, modifying $HOM_{inter}(i,j)$ values in QBHO scheme with the OE algorithm described in Section IV-B. In all combinations, 10 optimization loops are simulated. Each loop consists of 15 minutes of network activity, which is the minimum reporting period to collect traces in current LTE networks. It is checked a posteriori that 10 loops are enough to ensure that control system reaches steady state with the different self-tuning algorithms. For a fair comparison, every optimization loop is carried out under identical conditions by pre-generating all random variables. Thus, performance differences between loops are only due to the different mobility settings, and not to the stochastic nature of simulation.

As shown in Table III, two use cases, referred to as cases A and B, are considered to check the impact of user context on the proposed strategy. In case A, 70 % of users are indoors and 30 % are outdoors. In case B, all users are outdoors. Note that, as explained in Section III-B, indoor users have higher expectations than outdoor users, leading to completely different QoE figures. The three analyzed methods (SBHO+LB, QBHO+LB and QBHO+OE) are tested in both scenarios.

The main figure of merit to assess the methods is the global QoE, computed as the average user QoE in the scenario,

$$QoE_{global} = \frac{1}{N_u}\sum_{u} QoE(u) \; , \tag{19}$$

where N_u is the number of users in the scenario and $QoE(u)$ is the session QoE experienced by user u, computed with the QoE models in (5)–(12).

Two secondary indicators are measured for a more detailed assessment. The first one is the average cell load in terms of PRB utilization ratio, $\overline{PRB_{util}}$, measured globally or on a per-layer basis. The second one is the average handover margin deviation from the initial default settings caused by the corresponding MLB algorithm (i.e., LB or OE), computed as

$$\overline{\delta HOM_{inter}} = \frac{\sum\limits_{(i,j)} \delta HOM_{inter}(i,j)}{N_{adjs}} = \frac{\sum\limits_{(i,j)} |HOM_{inter}(i,j) - HOM^{(0)}_{inter}(i,j)|}{N_{adjs}} \; , \tag{20}$$

where N_{adjs} is the total number of adjacencies in the network where parameters self-tuning is performed, and $HOM^{(0)}_{inter}(i,j)$ is the default IFHO margin value at the beginning of the optimization process (i.e., iteration 0). As mentioned before, $HOM^{(0)}_{inter}(i,j)$=3 dB $\forall(i,j)$ for both traffic steering algorithms, LB and OE.

B. Results

Table IV shows some relevant performance metrics obtained with the initial handover settings (OS) in cases A and B. Recall that simulation parameters are set so that network performance resembles that of the live network. With the token-based cell (re)selection mechanism used by the operator, approximately 60 % of users are served by cells at L_{2100} and 40 % of users are served by cells at L_{700}, even when L_{2100} has much larger bandwidth than L_{700}. Moreover, traffic demand is dominated by VIDEO users, followed by FTP users [1]. In both cases, average cell load in L_{2100} is less than that of L_{700} (about 30 % in case A and 40 % in case B). As a consequence of

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TABLE IV
INITIAL PERFORMANCE

Indicator	L_{700}	L_{2100}	L_{700}+L_{2100}
Share of connections [%]	40.27	59.73	100
Data volume ratio VoIP [%]	$1.5 \cdot 10^{-5}$	$6 \cdot 10^{-5}$	$2.4 \cdot 10^{-3}$
Data volume ratio VIDEO [%]	26.51	57.27	53.86
Data volume ratio FTP [%]	50.98	32.11	32.14
Data volume ratio WEB [%]	22.50	10.62	13.99
$\overline{PRB_{util}}$ case A [%]	87.71	52.70	59.48
QoE_{global} case A	1.91	4.35	3.32
$\overline{PRB_{util}}$ case B [%]	88.1	46.9	54.87
QoE_{global} case B	2.49	4.38	3.57

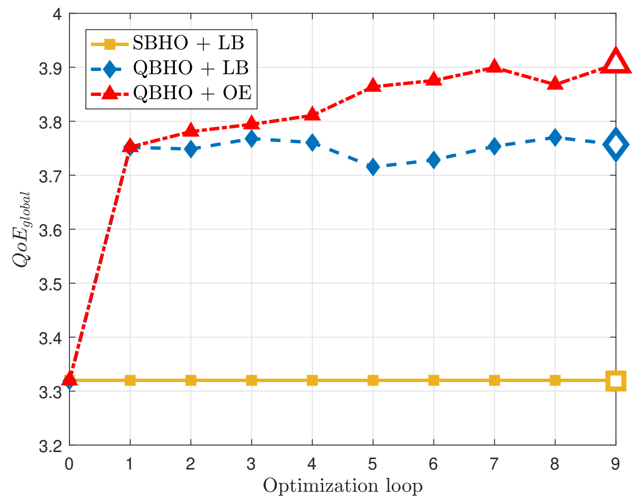

Fig. 4. Evolution of the overall QoE in the scenario.

the high load in L_{700}, many users in this carrier experience poor QoE (on average, 1.91 MOS points in case A, and 2.49 MOS points in case B). These results point out the need for steering users from L_{700} to L_{2100}.

1) Case A (indoor/outdoor users): Fig. 4 shows the evolution of QoE_{global} across iterations in the tuning process. In all methods, loop 0 represents OS performance. In SBHO+LB, loops 1 to 9 shows the behavior when executing a classical LB algorithm in a SBHO scheme. In QBHO+LB curve, loop 1 shows the impact of enabling RSRQ-based IFHOs and loops 2 to 9 show the impact of adjusting IFHO margins by LB in a QBHO scheme. Similarly, in QBHO+OE, loop 1 shows the effect of enabling RSRQ-based IFHOs and loops 2 to 9 show the impact of adjusting IFHO margins based on the novel trace-based indicator in OE. Large markers indicates the final QoE_{global} achieved with each method. It is observed that SBHO+LB does not have a significant impact on QoE. However, QBHO+LB and QBHO+OE improve QoE_{global} compared to OS (3.75 and 3.91 vs 3.32 MOS points, respectively). The improvement obtained by QBHO+LB is essentially due to the activation of RSRQ-based IFHOs, since no significant improvement on QoE_{global} is shown from loop 1 onwards (i.e., again, LB does not improve QoE_{global}). This result is consistent with the fact that the aim of LB is not

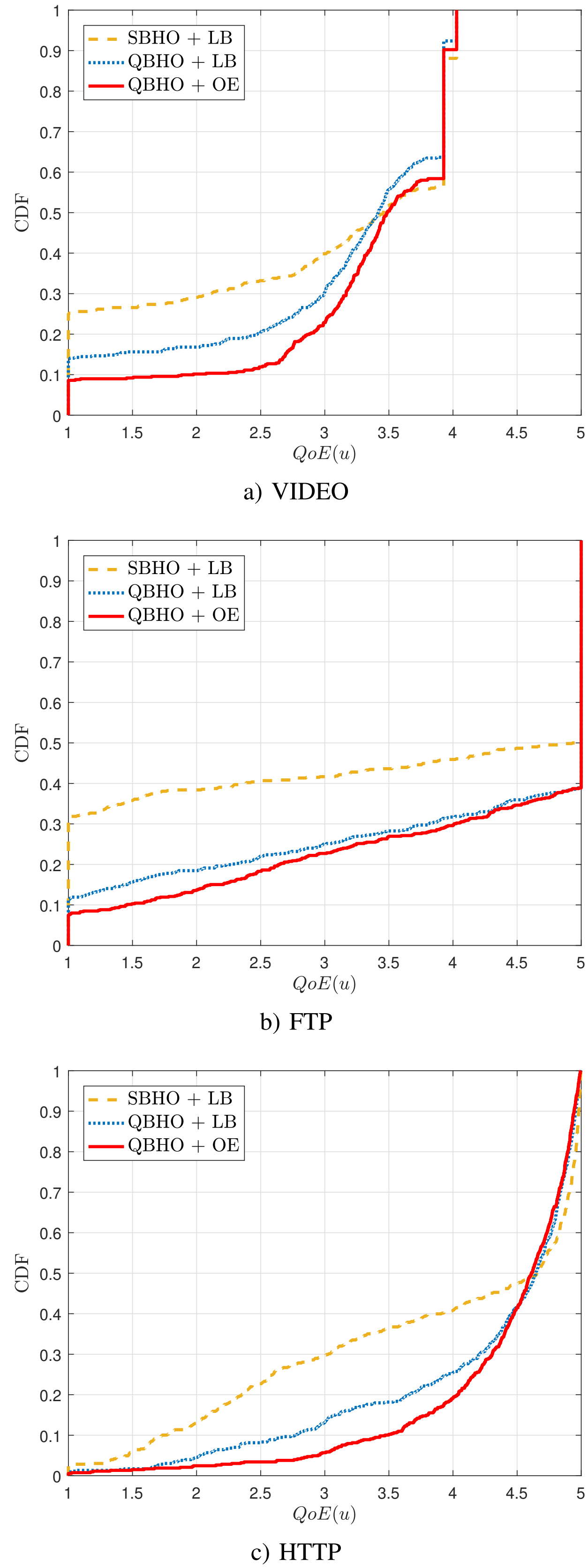

Fig. 5. Cumulative distribution function of user QoE.

TABLE V
PERFORMANCE COMPARISON IN CASE A (INDOOR/OUTDOOR)

Indicator	OS	SBHO+LB	QBHO+LB	QBHO+OE
QoE_{global}	3.32	3.32	3.75	3.91
Global $\overline{PRB_{util}}$ [%]	59.48	59.48	79.36	72.22
$\overline{PRB_{util}}$ L_{700} [%]	87.71	87.71	79.73	26.29
$\overline{PRB_{util}}$ L_{2100} [%]	52.70	52.70	77.79	83.25
$\overline{\delta HOM_{inter}}$ [dB]	–	-5.97	-0.35	-3.38

TABLE VI
PERFORMANCE COMPARISON IN CASE B (OUTDOOR)

Indicator	OS	SBHO+LB	QBHO+LB	QBHO+OE
QoE_{global}	3.57	3.57	4.17	4.25
Global $\overline{PRB_{util}}$ [%]	54.87	54.87	70.99	68.11
$\overline{PRB_{util}}$ L_{700} [%]	88.10	88.10	72.59	34.01
$\overline{PRB_{util}}$ L_{2100} [%]	46.90	46.90	70.61	76.30
$\overline{\delta HOM_{inter}}$ [dB]	–	-7.55	0.42	-3.09

to improve QoE, but to equalize cell load between layers. In contrast, QBHO+OE obtains an additional gain thanks to the OE algorithm, resulting in the highest QoE_{global}.

It should be pointed out that, even if OE aims to optimize user experience, a decrease of 0.03 MOS points in QoE_{global} is observed from loop 7 to loop 8 in QBHO+OE, due to the iterative nature of the controller. As in most closed-loop control systems, small oscillations in system performance are observed when the controller reaches the steady state. Note that the decrease in QoE_{global} from loop 7 to 8 is negligible (0.03 MOS points), and it is compensated in the following optimization loop.

Fig. 5 a)–c) show the cumulative distribution function of user QoE, $QoE(u)$, for VIDEO, FTP and WEB services with the different methods. VoIP is omitted, since its traffic is negligible. Likewise, OS is not included, as its performance is identical to SBHO+LB. It is observed that, for all services, QBHO+LB and QBHO+OE improve QoE distribution compared to SBHO+LB, with QBHO+OE achieving the best QoE figures. In HTTP and VIDEO services, such an improvement is achieved at the expense of a slight decrease in $QoE(u)$ for the best users. Note that many VIDEO users experience a $QoE(u)$ value of 4.02 and 3.92, corresponding to the upper limiting values in the outdoor and indoor QoE models when T_{init}=3 s (fixed in this work [46]).

For a more detailed analysis, Table V breaks down several statistics for the tested methods at the end of the optimization process (loop 9 in Fig. 4). OS is also included for comparison purposes. Regarding the main figure of merit, QoE_{global}, both QBHO+LB and QBHO+OE outperform OS, with QBHO+OE achieving the largest improvement. (3.91 against 3.32, i.e., a 17.8 % improvement compared to OS). $\overline{PRB_{util}}$ values show that QBHO+OE obtains such a gain by offloading traffic from L_{700} to L_{2100}, since $\overline{PRB_{util}}$ increases in L_{2100} (from 52.70 % to 83.25 %) and decreases in L_{700} (from 87.71 % to 26.29 %). This traffic steering is also confirmed by the negative value of $\overline{\delta HOM_{inter}}$ (i.e., -3.38 dB) at the end of the optimization process. As a side effect, QBHO+OE increases the global $\overline{PRB_{util}}$ from 59.48 % to 72.22 % (i.e., a 12.74 % increase in absolute terms).

2) Case B (outdoor users): Table VI summarizes the results when all users are outdoors. Most indicators show trends similar to those in case A. Again, in terms of QoE_{global}, both QBHO+LB and QBHO+OE outperform OS and SBHO+LB, with QBHO+OE achieving the largest improvement (4.25 vs 3.57, i.e., a 19 % improvement compared to OS). In this case, differences between QBHO+OE and QBHO+LB are lower, since the value of QoE_{global} after enabling RSRQ-based handovers in step 1 is already high (4.16 MOS points). Also note that, from the $\overline{\delta HOM_{inter}}$ figures, it can be deduced that QBHO+LB and QBHO+OE steer traffic in opposite directions, leading to different traffic shares between layers. Specifically, $\overline{\delta HOM_{inter}}$ is negative in QBHO+OE (i.e., traffic is offloaded from L_{700} to L_{2100}), whereas it is positive for QBHO+LB (i.e., traffic is offloaded from L_{2100} to L_{700}).

It is worth noting that, in both cases A and B, even if QBHO+LB achieves a more evenly loaded scenario between the two tiers, it is QBHO+OE that reaches the best QoE. This is clear evidence that an evenly loaded network (which is the aim of classical MLB algorithms) does not lead to the best overall QoE, provided that system bandwidth is not the same in all cells [47]. Finally, it is also remarkable that no improvement in QoE_{global} is achieved with SBHO+LB, even if handover margins are shifted nearly -6 dB in case A and -7.5 dB in case B. This is due to the different propagation conditions in the two carriers that make it extremely difficult to trigger RSRP-based A3 events.

C. Computational complexity

The proposed method is designed as a rule-based control algorithm and therefore has a low computational complexity. The total execution time comprises the time required to process connection traces, the computation of the indicator reflecting the average impact of IFHOs on users QoE per adjacency, $\overline{\Delta QoE_T}(i,j)$, and the computation of the output of the controller. In practice, the total execution time in the above-described scenario in a computer with an Intel Xenon processor with a clock frequency of 2.4 GHz and 64 GB of RAM is 0.022 seconds per optimization loop (note that traces processing is not needed in simulations). The dominant operation is the computation of $\overline{\Delta QoE_T}(i,j)$, with 0.016 seconds per optimization loop. The time taken by this operation grows linear with the number of users affected by handover events. Thus, the worst-case time complexity of the algorithm is $\mathcal{O}(N_{HO} \times N_u)$, where N_{HO} is the total number of handovers and N_u is the average number of active users.

VI. CONCLUSIONS

In this paper, a novel method for traffic steering in multi-tier LTE networks has been proposed to improve the overall system QoE. For this purpose, RSRQ-based inter-frequency handovers are first enabled, and, later, a novel MLB algorithm that adjusts inter-frequency handover margins on an per-adjacency basis driven by QoE measurements is executed. In each adjacency, an independent controller increases (or decreases) the value of handover margins based on an indicator showing the impact of handovers on the overall user satisfaction. Such an indicator is computed by processing data in individual connection traces. The proposed algorithm is conceived as a centralized solution for the network management system, since connection traces are required.

Performance assessment has been carried out in a system-level simulator implementing a realistic scenario. Results have shown that the proposed algorithm outperforms classical load balancing techniques. Specifically, the overall QoE is improved by up to 19 % compared to a traditional load balancing algorithm executed over a legacy RSRP-based inter-frequency handover scheme. Such a performance gain is achieved by offloading traffic from coverage layers to capacity layers, so that users make the most of the large bandwidth available at the capacity layer.

It should be pointed out that the introduction of Carrier Aggregation and Dual Connectivity features in LTE-Advanced may reduce the potential of traffic steering. Nonetheless, the proposed algorithm may still be used to steer legacy terminals or redistribute traffic in multi-carrier LTE networks where those features have not been implemented yet. Likewise, the trace-based MLB algorithm presented here can be extended to perform QoE-driven Carrier Aggregation.

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