On the Capacity and Spatial Fairness Trade-off in Planning Sectorization and Frequency Reuse

Ali Imran[1], Elias Yaacoub[1], Zaher Dawy[2], Adnan Abu-Dayya[1]
[1]Qatar Mobility Innovations Center (QMIC), QSTP, Doha, Qatar
[2]American University of Beirut, Department of Electrical and Computer Engineering.
email:{alii, eliasy,adnan}@qmic.com, {zaher.dawy}@aub.edu.lb

***Abstract*—The intrinsic trade-off between the capacity and Quality of Service (QoS) has long been subject of investigation in the design of MAC layer scheduling, power and call admission control mechanisms. However, from prospective of planning a cellular network, while capacity and coverage trade-off has been well studied and capacity and energy trade-off has also received significant attention recently, trade-off between the capacity and spatial fairness of service level in the coverage area is relatively overlooked. In this paper we identify the increasing importance of this trade-off in context of emerging cellular networks and present a set of metrics that can be used to quantify and analyze this trade-off particularly in terms of number of sectors per site and frequency reuse factor. The numerical results presented also provide insights into the relatively under explored advantages of intra-site frequency reuse compared to classic inter site frequency reuse. The key advantage of these metrics is that they can be used as part of the optimization objectives for planning future cellular networks to meet the increasingly pressing requirements both in capacity and QoS.**

***Index Terms*—Cell planning; intra-site frequency reuse; Performance Quantification; Capacity; Quality of Service;**

I. Introduction

Cellular system planning objectives have changed significantly over the past two decades to comply with evolution of the new generations of cellular systems as well as to meet the changing user requirements. The focus has shifted from coverage only, to capacity, and to capacity and QoS together, for GSM, UMTS and LTE respectively. The metrics to quantify these objectives have also undergone revisions for each generation and changing socio-economic eco-system of cellular networks and their users. For example, in classic GSM the planning objective in terms of QoS was to simply ensure the outage is below certain percentage of area i.e. SINR available in the coverage is above the protection ratio of about 9dB to ensure that a voice call can be supported with acceptable audibility. On the other hand capacity in GSM simply meant the number of users that could be supported in the system in conjunction with spectrum reuse efficiency that could be harnessed from frequency reuse concept. With advent of UMTS the notion of soft capacity came into being and cellular system capacity had to be redefined in terms of throughput. At the same time classic concepts of spectrum reuse and threshold protection ratio from GSM also became less relevant.

Emerging OFDM based cellular systems such as LTE and LTE-A again require significantly different if not totally new approach, towards quantifying various aspects of performance. For example, LTE capacity is not soft anymore as it was for UMTS and spectrum reuse efficiency is not irrelevant metric either for LTE. Rather increasing scarcity of spectrum is pushing towards more aggressive frequency reuse in LTE, leading to intra-cell spectrum reuse [1] and fractional frequency reuse [2] that has to be incorporated while defining performance metrics for future cellular systems from planning perspective. Also, QoS is getting new assertions fueled by performance criteria set for LTE by 3GPP where fairness of data rate received among the cell edge and cell centre users is being given increased importance [3]. All these changes are again asking for revamping and revision of metrics to quantify the performance of emerging and future cellular systems. A mechanism to precisely quantify the inherent trade offs among multiple and mutually contradicting facets of the performance is essential in order to plan future cellular networks that can judiciously strike the intended balance among the various conflicting planning goals.

A number of work have recently embarked on various aspects of LTE planning [4]–[13]. However, each of the prior research works on planning uses different definitions of performance metrics while considering different sets of planning parametere. This makes the investigation of the trade-offs among various aspects of the performance and their cross comparison difficult. Furthermore, the capacity and QoS trad-off although well delved into from MAC layer perspective, is not fully investigated from the planning perspective. Given the increasing importance of QoS particularly in spatial fairness context, in this paper we investigate how the different planning layouts in terms of number of sectors per site and frequency reuse, offer a trade off between the capacity oriented performance and QoS oriented performance.

The contributions of this paper are two folds: First, we derive a set of metrics that can characterise the performance of cellular system plan in terms of capacity, spectrum reuse efficiency and QoS. These metrics can be used to quantify the performance of a cellular deployment plan against number of sectors per site and frequency reuse plan. While deriving these metrics we incorporate the impact of modulation and coding schemes that are used in a particular cellular system. This is to ensue that the metrics reflect the performance by taking into account the standard specific features of the system under consideration. The main advantage of proposed metrics is that they can be evaluated semi-analytically through a simple static simulator. Their use can substantially reduce the solution time by avoiding the need for classic dynamic simulators to evaluate metrics such as throughput and rate fairness etc. Second, using our results and subsequent analysis we provide useful insights that can help to address the time-persistent cell edge and cell centre throughput differences by making use of intra-site frequency reuse instead of or in addition to inter-site frequency reuse.

The rest of the paper is organized as follows: Section II describes system model and derivation of the metrics. In Section III we present numerical results and section IV concludes this paper.

II. Deriving Metrics to Analyse Capacity and QoS Trade OFF

Using the definitions given in Table I we consider a system model in which area of interest is divided into bins of equal sizes. The first step to quantify the capacity and QoS related performance of cellular system is to assess SINR's geographical distribution in the system as this not only can help to calculate the achievable link spectral efficiencies but also can be used to determine the spatial fairness among data rates achievable in the service area. Therefore, it is rational to start with derivation of the SINR as function of number of sectors per site and the frequency reuse, that can then be used to derive expressions for these metrics. The SINR perceived in the q^{th} bin from s^{th} sector, can be given as:

$$\gamma_q^s = \frac{P^s G_q^s \alpha \left(d_q^s\right)^{-\beta}}{\sigma^2 + \sum_{\forall \acute{s} \in \mathcal{S}} \left(P^{\acute{s}} G_q^{\acute{s}} \alpha \left(d_q^{\acute{s}}\right)^{-\beta} u\left(\Upsilon_f\right)\right)}, s, \acute{s} \in \mathcal{S}, q \in \mathcal{Q} \quad (1)$$

Where $u\left(\Upsilon_f\right)$ is a unit function that determines wether or not the q^{th} bin will receive interference from a particular sector depending on the frequency reuse. Note that we assume full load scenarios, i.e. each sub-carrier allocated to a cell is simultaneously under use. Therefore, in calculating SINR we have omitted the impact of dynamic scheduling and only static frequency reuse is used to determine the inter carrier collision and hence interference at given location. And d_q^s is distance between the s^{th} sector antenna and q^{th} bin. The antenna gain can be modelled as proposed in [14] and with simplification introduced in [15] as:

$$G_q^s = G(\rho, D) \times 10^{-1.2\left(\frac{\phi_q^s - \phi^s}{\varphi_h^s}\right)^2} \quad (2)$$

The ϕ_q^s is horizontal angle in degrees on s^{th} sector to q^{th} bin with respect to positive x-axis. As indicated the maximum antenna gain G is a function of efficiency of antenna ρ, and directivity D and can be written as $G = \rho D$ where D can be further approximated as : $D = \frac{4\pi}{\varphi_h^s \varphi_v}$. Note that for the practical cellular antennas the relationship between the horizontal beamwidth of sector antenna and the number sectors per site can be modeled as $\varphi_h^s = \frac{360}{\mu * S_b}$. Where μ is a factor representing overlap between the sectors. Thus using (2) in (1) the SINR perceived in q^{th} bin can be determined as in (3). As desired, the SINR derived in (3) is function of the key

TABLE I
Notation for System Model

Symbol	Description
b	b^{th} base station
$\mathcal{B}$	set of all base stations in systems
B	total number of BS i.e. $\lvert\mathcal{B}\rvert = B$
A	Total area of interest
$\mathcal{Q}$	set of Q bins that constitute A
q	q^{th} bin, $\sum_{i=1}^{Q} q_i = A$, & $\frac{A}{Q} = q, \forall q \in \mathcal{Q}$
$\mathcal{Q}_b$	set of bins in which BS are located, $\mathcal{Q}_b \subseteq \mathcal{Q}$
$\mathcal{S}$	set of all sectors in the systems
S	total number of sectors in system i.e. $\lvert\mathcal{S}\rvert = S$
s	denotes s^{th} sector
S_b	total number of sectors b^{th} BS has
$\mathcal{S}_b$	$\mathcal{S}_b = \{S_1, S_2, S_3 ... S_B\}$, $S = \lvert\mathcal{S}\rvert = \sum_{b=1}^{B} S_b$
Υ_f	Number of times spectrum is reused within a given area
G_q^s	gain from the s^{th} sector antenna to q^{th} bin.
α	path loss co-efficient
β	pathloss exponent
φ_h^s	horizontal beamwidth of s^{th} sector antenna
Υ_c	capacity wise metric
Λ	service area fairness wise metric
σ^2	noise power

parameters we are interested in i.e number of sectors per site and frequency reuse. Note that, (3) can be used to calculate SINR anywhere in the area of interest with respect to a best serving sector denoted by s, therefore to mark its generality for onward use we have dropped the superscirpt s from the SINR symbol in (3).

A. Quantifying Capacity from Planning Perspective

Our basic aim here is to assess the long term performance of a cellular system plan by incorporating its dependencies on the planning parameters listed above rather than short term dynamics of cellular eco-system. Therefore, conventional throughput based metrics are not exact match to our purpose mainly because of their dependency on short term dynamics such as scheduling and fast fading, as well as their complexity of evaluation. To this end, here we present a metric to quantify the capacity wise performance of cellular system from planning perspective, denoted by Υ_{MCE}. This metric has semantics similar to the area spectral efficiency but it does not require throughput estimation for its calculation, rather it can be determined through simple semi-analytical approach with help of static less time consuming simulator. A key advantage of this metric is that it can also serve as the basis for calculation of QoS wise metric for planning i.e. Λ as we will show later. Below we explain calculation of Υ_{MCE}.

Since the sub carrier bandwidth in emerging cellular system (e.g. LTE) is fixed so the throughput on single sub-carrier in a given BS-user link and hence the total throughput of the system depends on Modulation and Coding Efficiency (MCE) on each link. The MCE in turn depends on SINR available on that link given by (3). Thus, with total bandwidth fixed, the actual long term average spectral efficiency of a BS-user link depends on the SINR's geographical distribution in the coverage area that in turn depends mainly on planning parameters as given by (3). Therefore, the long term average SINR available at point n is mainly dependent on the location of n. Thus, the SINR in (3) at a point n can be abstracted as

$$\gamma_q\left(\mathcal{S}_b,\Upsilon_f\right)=\frac{P^s\alpha(d_k^n)^{-\beta}\times\left(\frac{4\pi\rho}{\left(\frac{360}{\mu*S_b}\right)\varphi_v}\right)\times 10^{-1.2\left(\frac{\phi_q^s-\phi^s}{\left(\frac{360}{\mu*S_b}\right)}\right)^2}}{\sigma^2+\sum_{\forall\acute{s}\in\mathcal{S}}\left(P^{\acute{s}}\alpha\left(d_q^{\acute{s}}\right)^{-\beta}\times\left(\frac{4\pi\rho}{\left(\frac{360}{\mu*\acute{S}_b}\right)\varphi_v}\right)\times 10^{-1.2\left(\frac{\phi_q^{\acute{s}}-\phi^{\acute{s}}}{\left(\frac{360}{\mu*\acute{S}_b}\right)}\right)^2}\times u\left(\Upsilon_f\right)\right)} \tag{3}$$

function of point's distance d_n^s and angle ϕ_n^s from the BS in cylindrical coordinate system and can be simply written as:

$$\gamma_n=f\left(\phi_n^s,d_n^s\right) \tag{4}$$

This SINR then can be mapped to MCE using theoretical Shannon bound or using practical SINR thresholds of the MCSs used in LTE as given in Table II.

TABLE II
MODULATION CODING SCHEMES IN LTE ALONG WITH THEIR RESPECTIVE MCES AND SINR THRESHOLDS [3]

MCS Index(l)	Modulation	Coding Rate	SINR	MCE(b/s/Hz)
0	N/A	N/A	-5.1>	0
1	QPSK	1/8	-5.1	0.25
2	QPSK	1/5	-2.9	0.4
3	QPSK	1/4	-1.7	0.5
4	QPSK	1/3	-1	0.667
5	QPSK	1/2	2	1
6	QPSK	2/3	4.3	1.33
7	QPSK	3/4	5.5	1.5
8	QPSK	4/5	6.2	1.6
9	16QAM	1/2	7.9	2
10	16QAM	2/3	11.3	2.667
11	16QAM	3/4	12.2	3
12	16QAM	4/5	12.8	3.2
13	64QAM	2/3	15.3	4
14	64QAM	3/4	17.5	4.5
15	64QAM	4/5	18.6	4.8

Now the average modulation and coding efficiency theocratically achievable in a cell can be given as:

$$\bar{MCE}_{cell}=\frac{1}{A_{cell}}\int_\phi\int_d \log_2\left(1+\gamma_n(\phi_n^s,d_n^s)\right)d\phi dd \tag{5}$$

Where A_{cell} is the total coverage area of a cell. In order to evaluate the system wide theoretical area spectral efficiency in more practical manner, let's consider $\mathcal{N}=\{1,2,3...N\}$ is set of all points in the coverage area. Then (5) extended for whole coverage area can be written as:

$$\bar{MCE}_{area}=\frac{1}{|\mathcal{N}|}\sum_{n=1}^{N}\log_2\left(1+\gamma_n\right) \tag{6}$$

In order to have an actual area measure $N\longrightarrow\infty$. For ease of evaluation we invoke our bin-grid concept introduced above i.e. area is divided into finite set of Q virtual bins of equal size, so small that within each bin the long term average SINR can be assumed to be constant. Now (6) can be written as:

$$\bar{MCE}_{area}=\frac{1}{Q}\sum_{q=1}^{Q}\log_2\left(1+\gamma_q\right) \tag{7}$$

Let $\mathcal{L}=\{0,1,2,3,...L\}$ is set of modulation and coding schemes available to be used in the given standard (e.g. in LTE with L=15) and MCE_l denotes the respective modulation and efficiency of l^{th} scheme. Where $l=0$ means modulation and coding scheme with zero spectral efficiency i.e. no link representing outage and L is modulation and coding scheme with highest spectral efficiency. Now the pdf of MCE can be estimated as:

$$f\left(MCE_l\right)=\frac{Q_l}{Q} \tag{8}$$

where

$$Q_l=\sum_{\forall q\in\mathcal{Q}}U_l\left(\gamma_q\right) \tag{9}$$

and $U_l(\gamma_q)$ is defined as follows.

For $l\in\mathcal{L}\setminus\{0,L\}\,L: U_l(\gamma_q)=\begin{cases}1 & T_l<\gamma_q<T_{l+1}\\ 0 & otherwise\end{cases}$

For $l=L: U_l(\gamma_q)=\begin{cases}1 & T_l<\gamma_q\\ 0 & otherwise\end{cases}$

And for $l=0: U_l(\gamma_q)=\begin{cases}1 & \gamma_q<T_0\\ 0 & otherwise\end{cases}$

T_l is the threshold SINR required to use l^{th} modulation and coding scheme from set $\mathcal{L}$ as given in the right most column of Table II. T_0 is the threshold of minimum γ below which link cannot be maintained with pre-decided performance criterion and all such points in coverage area constitute the outage area.

Similarly CDF of MCE can be given as:

$$F\left(MCE_l\right)=\frac{\sum_{i=0}^{l}Q_i}{Q} \tag{10}$$

While (8) and (10) give PDF and CDF of MCE achievable with given plan, a numeric metric is also required to quantify this MCE. We define this metric to quantify the spectral efficiency achievable through MCE for a given SINR geographical distribution , as follows:

$$\Upsilon_{MCE}=\sum_{l=0}^{L}\left(MCE_l\times\frac{Q_l}{Q}\right) \tag{11}$$

where Q_l is the number of bins in coverage area in which γ_q meets the threshold required to use l^{th} modulation and coding scheme.

Note that Υ_{MCE} reflects average BS-user link spectral efficiency achievable with a particular cellular plan/design and can be used as capacity wise metric. However, for holistic quantification of capacity from planning perspective, an important means of cellular capacity i.e. spectrum reuse also has to be taken into account.

TABLE III
MODELLING PARAMETERS

Parameters	Values
System topology	19 sites (1-6 sector/site)
BS Transmission Power	39 dBm
BS Inter site distance	1200 meters
BS height	32 meters
User antenna	0 dB (Omini directional)
BS antenna maximum gain, G_{max}	18 dB
BS antenna maximum attenuation, A_{max}	20 dB
Frequency	2 GHz
Pathloss model	Cost Hata
Shadowing STD	8 dB

B. Quantifying Reuse Gain from Planning Perspective

In the backdrop of need for aggressive frequency reuse we propose to reuse spectrum within a site. By exploiting the fact that sectorisation provides significant isolation among cells projected from same base station, spectrum can be reused within a site among sectors pointing in opposite directions as well as among alternative sectors pointing in different directions. To quantify the spectrum reuse gain in capacity obtained from such intra-site spectrum reuse we define Υ_f as 'number of times spectrum is reused within a site'. Thus Υ_f can be calculated as:

$$\Upsilon_f = \frac{S}{\text{Number parts spectrum is divided in}} \tag{12}$$

Although intra-site spectrum reuse is expected to increase interference thus decrease Υ_{MCE} it would be interesting to investigate how gain in capacity through higher Υ_f trades against lower Υ_{MCE} as well as the QoS wise performance.

C. Quantifying QoS from LTE Planning Perspective

A measure of QoS from planning perspective needs to capture the data rate levels offered by a cellular system design to users in the coverage area in both the spatial and temporal context. However, while planning a cellular system, all short term temporal dynamics that impact data rates such as fast fading can be neglected as they are averaged out. The long term average data rates are already captured in calculation of Υ_{MCE}. However, one key aspect of QoS remains uncaptured that is increasingly becoming very important from planning perspective i.e. service area fairness or in other words homogeneity of the level of service that can be provided throughout the coverage area. Building on above derivations and we define a metric for the service area fairness as:

$$\Lambda = 1/\sqrt{\frac{1}{Q}\sum_{q=1}^{Q}\left(MCE_q - \sum_{l=0}^{L}\left(MCE_l \times \frac{Q_l}{Q}\right)\right)^2} \tag{13}$$

The advantage of this metric of QoS is that it exclusively captures geographical variation of the BS-user link spectral efficiency and hence achievable data rates in area of coverage which is key factor to be considered in cellular system planning. Furthermore, Λ is also capable to implicitly take into account the cell-center and cell-edge rate differences. This is because, having spatial connotation instead of temporal, Λ gives the cell edge users higher importance because area is square function of radius, thus more area lies farther from the cell center.

III. NUMERICAL RESULTS AND DISCUSSION

Figure 1 plots CDF given by (10) for the geographical distribution of SINR using the system model parameters listed in Table III. The SINR is obtained through (3) as function of two important planning parameters i.e. 'number of sectors per site' S and the 'number of times spectrum is reused per site' i.e Υ_f. Thus, for example the notation '11. S=6,Υ_f=2' that denotes plan number 11 means there are six sectors per site and spectrum is used two times within a site. i.e. the spectrum is divided in three equal parts, each part is allocated to three adjacent sectors and the pattern is repeated for other three sectors on the site such that sectors using the same spectrum are apposite to each other. A comparison of SINR distributions for range of possible S and Υ_f is made. First observation in Figure 1 is quite intuitive that with less aggressive frequency reuse SINR distribution improves. For example, plan no. 12 (S=6,Υ_f=1) has much better SINR distribution and thus is expected to have capacity wise better performance compared to plan no. 9 (S=6,Υ_f=6). However, two important underlying trade-offs are to be observed here. First, obviously, plan no. 12 (S=6,Υ_f=1) has too low spectrum reuse efficiency that will undermine the over-all capacity of cellular system for given spectrum. Second, and relatively less intuitive observation is that the spread of CDF curves for plans with highΥ_f i.e aggressive intra-site reuse is much narrower then those with low Υ_f. The reason for that is, with intra-site frequency reuse, the cell centre users are also interfered with almost same magnitude as cell edge users, compared to conventional inter-site reuse where cell edge users are interfered much more aggressively than cell centre users. In other words the intra-site frequency reuse can help to improve cell edge cell centre disparity to some extent. For example, in plan no. 12 (S=6,Υ_f=1) the range of SINR a user perceives, varies from -20dB to 60dB leading to huge spatial disparity in service area. On the other hand, in plan no. 9 (S=6,Υ_f=6), SINR varies from -20dB to 20dB only. For planning cellular networks judiciously and optimally with respect to QoS and capacity priorities, in addition to identification of these trade-offs, their precise quantification is also required. This objective can be achieved by using the metrics proposed in previous section. Figure 2 plots values of these metrics Λ, Υ_{MCE} and Υ_f. Trade off among the average link spectral efficiency Υ_{MCE}, spectrum reuse efficiency Υ_f and the spatial fairness Λ can be clearly observed in Figure 2. For example, plan no. 9 (S=6,Υ_f=6) offers the maximum service area fairness and highest spectrum reuse efficiency but the average BS-user link spectral efficiency achievable with this plan is the worst among all the twelve plans evaluated. On the other hand, plan no. 12 (S=6,Υ_f=1) offers maximum average BS-user link spectral efficiency but with lowest service area fairness and spectrum reuse efficiency. Whereas, plan no. 10 (S=6,Υ_f=3) does not maximise performance in any of the three aspects but rather offers medium level performance in all the three metrics. The detailed analysis of these tradeoffs is beyond the scope of this paper and will be covered in future work. Here, the key observation to be made is that the proposed metrics' capability to precisely quantify this tradeoff with computation efficiency can actually help to design a cell plan that is optimal to simulatnesouly meet the multiple planning objectives closely. Also insights obtained through presented analysis, particulary the identification and quantification of trade-offs of intra-site frequency reuse can help to plan better cellular system design in future to cope with cell-edge and cell centre disparities.

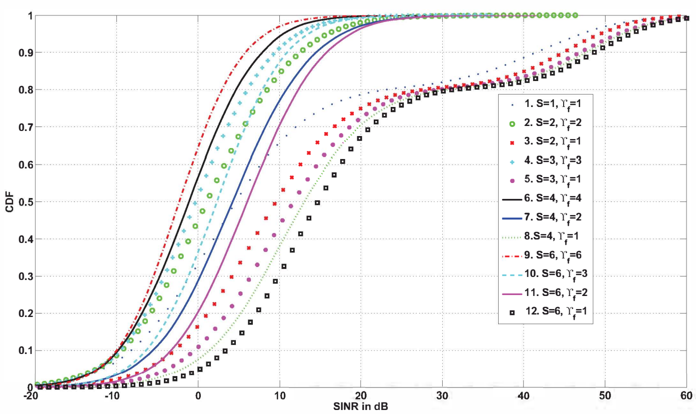

Fig. 1. CDFs of SINR geographical distribution in the coverage area for different number of sectors per site and frequency reuse.

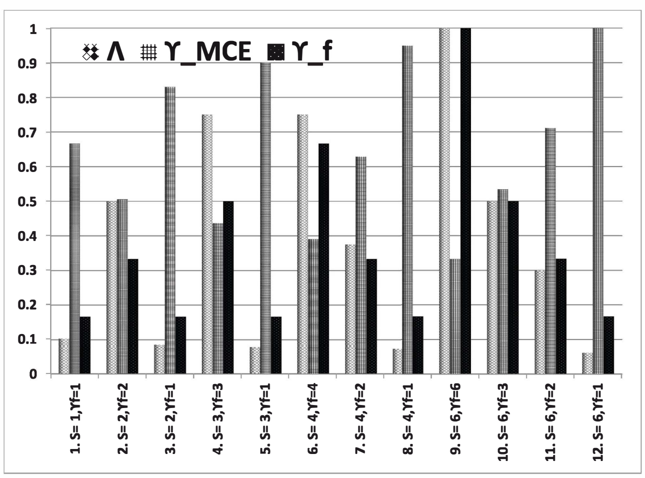

Fig. 2. Quantification of the trade-off between capacity and QoS using proposed metrics. For comparison on same scale, each metric is normalised by its maximum value.

IV. Conclusions

In this paper we present a set of metrics to quantify the cellular system performance in terms of capacity and QoS from planning perspective. We present and analyse a notion of spatial fairness of service area to represent QoS exclusively from planning perspective. We also present the concept of intra-site frequency reuse and analyse its impact on the performance of cell plans with different number of sectors per site using the proposed metrics. The obtained numerical results provide insights into the underlying trade-offs between spectrum reuse efficiency, spectral efficiency and service area fairness. Particularly, the analysis presented have helped to identify and quantify, an otherwise non-intuitive advantage the intra-cell frequency reuse offers compared to classic inter-site frequency reuse, i.e. potential to obtain better balance between cell edge and cell centre prefromance. The extension of the presented analysis to relay enhanced cellular networks in the context of LTE-Advanced will be the focus of our future work.

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