An Advanced Bandwidth Adaptation Mechanism for LTE Systems

Mehdi Khabazian†, Osama Kubbar† and Hossam Hassanein‡

† Qatar Mobility Innovations Center (QMIC), Doha, Qatar.
‡ Queens University, Kingston, Canada.
Email: {mehdik, osamak}@qmic.com, hossam@cs.queensu.ca

***Abstract*—In this paper, we propose a bandwidth adaptation mechanism for 3GPP LTE which partially releases bearers' resources for admission of a new bearer during congestion periods. Each active bearer may contribute into the downgrading mechanism up to its minimum resource requirement according to a bearer contribution attribute called the "downgrading index". This index incorporates three attributes of an active bearer into the downgrading process. These attributes are the bearer priority, QoS over-provisioning and communication channel quality. The performance of the proposed mechanism is evaluated using simulation. Numerical results show that the probabilities of bearer blocking and handoff bearer dropping improve significantly when employing our proposed mechanism. Further, the results show the capability of the proposed mechanism in fine-tuning the service provider's generated revenue.**

***Index Terms*—Bandwidth adaptation, Call admission control, LTE, Handoff.**

I. Introduction

Congestion management techniques such as *bandwidth adaptation* (BA) and *call admission control* (CAC) have recently become some challenging techniques in radio resource management of cellular networks. Unlike legacy applications such as GSM voice which was consuming a fix network resource per call, recent multimedia applications take advantage of scalable coding and adaptive rate techniques mainly to cope with inherent variations in channel quality and network traffic [1]. In 3GPP LTE release 8 [2], the resource assignment of some multimedia bearers is specified by a range which is controlled by two limiting parameters of guaranteed bit rate and maximum bit rate. Although these two parameters are assumed equal in the current version of LTE, they are considered as two main QoS parameters in later 3GPP releases where they can be employed to effectively manage the congestion periods by adopting an appropriate BA mechanism.

Briefly, a BA mechanism is an algorithm which takes advantage of such a data-rate flexibility to partially release the active bearers' resources toward admission of a new or a handoff bearer during congestion periods. The proposed BA techniques in the literature are mostly primitive or are not customized for LTE with such advanced QoS requirements. [3] and [4] are two studies which aim to optimize the BA process with the target of handoff dropping minimization. In both studies, this has been done by assigning some sort of priorities to the handoff calls. [5] proposes a BA scheme which aims to maximize the system capacity while maintaining the guaranteed data rate of the admitted bearers. Their scheme first sorts the bearers according to their priority levels. Then, it selects the bearers with the lowest priority one-by-one to be downgraded to their guaranteed data rate until the target load is released.

A major approach to design BA mechanisms is through the concept of utility function. In this method, the bearer's dedicated bandwidth range is mapped to an interval from 0 to 1 according to a function called utility. The curvature and slope of an utility function represent corresponding bearer sensitivity to the bandwidth downgrading process. The objective is to guarantee resource allocation fairness for all bearers by assigning them the same utility value when they are downgraded. [6] and [7] are two highlighted studies which discuss the fairness issue in utility-based BA mechanism for a single-class and multi-class networks, respectively.

We note that most of the relevant studies including the above ones consider only one QoS attribute, mainly traffic priority, into bandwidth adaptation process; thus, they cannot provide an optimum or a flexible solution for a complex system such as LTE with a wide QoS settings. Authors in [8] discuss about the required parameters which are needed to be considered in an appropriate BA mechanism. Some key parameters mentioned there are traffic priorities, degradation thresholds and call delay. In [9], we studied the issue of fairness in a proposed BA mechanism which jointly considers traffic priority and the amount of allocated resources to a bearer in a single cell scenario.

In this study, we propose a multi-objective and distributed BA mechanism for LTE which takes into account three bearer attributes namely priority, QoS over-provisioning and communication channel quality into the BA process. Through a simulation approach, we evaluate the performance of the proposed BA mechanism. Thus, we consider three classes of multimedia traffic and we measure three performance metrics of the system, i.e. new bearer blocking probability, handoff bearer dropping probability and the service provider's generated revenue. We will show the capability of the proposed

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BA in enhancing the generated revenue and reaching a trade-off between performance measurements.

The remainder of the paper is organized as follows: Section II presents the preliminaries and system modeling of the study, Section III describes the proposed BA mechanism, Section IV presents the performance evaluation of the study and the final section concludes the paper.

II. System Model

In 3GPP standardization, several LTE bearer classes are defined and each class is assigned a *priority*. Bearers are classified into two types, guaranteed bit rate (GBR-bearers) and non guaranteed bit rate (nonGBR-bearers). Resource assignment of GBR-bearers is associated with two system parameters of maximum bit rate (MBR) and guaranteed bit rate (GBR). MBR specifies the maximum sustained data rate that a GBR-bearer can achieve while GBR presents the minimum data rate which is guaranteed (reserved) for that GBR-bearer. As a result, a bearer may achieve a data rate from its GBR rate up to its MBR rate depending on resource availability. On the other hand, resource allocation of nonGBR-bearers is associated with an aggregate MBR parameter (AMBR) which determines the total resources which can be assigned to a group of nonGBR-bearers [2].

In the physical layer, on the other hand, *adaptive modulation and coding* (AMC) technique is used to manage the channel resources among the UEs with different channel conditions. When the channel condition is good, AMC allows UE to employ a higher order modulation format e.g. 64QAM with less redundancy bits, consequently, more information is carried in the allocated resources. On the other hand, when the channel condition is poor, a combination of a lower order modulation format, e.g., QPSK with more redundancy may be used to improve the reception probability, consequently, less information can be carried in the allocated channel resources. AMC uses a channel quality feedback mechanism between eNodeB and UE and a reference target error rate[1] to maximize the overall throughput. This feedback mechanism allows eNodeB to be informed from the channel quality experienced by the UE and this is done by sending a *channel quality indicator* (CQI) by UE in the *uplink control information* (UCI). CQI is an index ranging from 0 to 15 and it corresponds to a combination of a specific modulation and code rate. In general, CQI can be sent periodically or apperiodically depending on the use mode defined in CQI reporting period [10]. CQI plays an important role in LTE link adaptation and scheduling techniques; however, as it is shown in this study, it can also be used in higher layers' techniques such as CAC or BA in a cross layer fashion to better manage the allocated resources to the bearers. Next, let us define the notations which will be used in the rest of this paper:

i: priority of a bearer, $1 \leq i \leq N$, where N is the number of priority levels.

[1]A reference packet error rate of 10% is often used as the target error rate [10].

C: total capacity of the LTE cell in OFDM physical resource block (PRB).

n_i: number of active bearers with priority i.

b_{gi} [b_{mi}]: guaranteed bit rate [maximum bit rate] of GBR-bearers with priority i. In this study, the definition of b_{gi} and b_{mi} will be extended for nonGBR-bearers, thus, they, respectively, denote the minimum rate at which a nonGBR-bearer with priority i can be acceptably maintained and the maximum rate which can be considered for that nonGBR-bearers.

$a_{i,j}(b)$: allocated PRB resources to the j^{th} bearer with priority i to achieve bit rate b. We note that the achievable bit rate depends on the channel quality, consequently, on the employed adaptive coding and modulation scheme.

σ : the amount of resources needed to be released by the BA mechanism for admission of a new bearer with priority i.

A. Handoff Scheme

LTE employs a network-controlled and UE assisted handoff procedure [11]. In this scheme, first a UE measures the received signal strength (RSS) from neighboring EnodeBs and sends a measurement report to the serving eNodeB. A target eNodeB k is chosen by the serving eNodeB as a candidate for handoff procedure if its RSS is measured higher than a threshold value RSS_{th}^{u}. Consequently, the serving eNodeB makes the decision of handoff toward the eNodeB with the highest signal force. The handoff procedure initiates when the signal strength of serving eNodeB drops below a threshold value RSS_{th}^{l}. Since the received RSS of an UE from eNodeB k is directly related to the distance between them, its value can be modeled by $RSS_k = Ptr_k - 10log(d_k) + X_{dB}$ where X_{dB} is a Gaussian random variable with zero mean, d_k is the distance between the UE and eNodeB k and Ptr_k is the transmitted signal power of eNodeB k [12].

B. CAC Scheme

In the following, we briefly describe a CAC scheme from [9] which will be adopted in order to study the performance of the proposed BA mechanism. According to this CAC scheme, a new bearer is admitted if enough resources are available or can be released by a BA mechanism. Let ρ_{i,n_i+1} denote the required resources to establish a new bearer with priority i, i.e., the $(n_i+1)^{\text{th}}$ bearer, $1 \leq i \leq N$. Thus, the CAC policy can be stated as

$$\rho_{i,n_i+1}=\begin{cases} a_{i,n_i+1}(b)|b_{gi}<b<b_{mi}, & \text{if} \sum_{j=1}^{9}\sum_{k=1}^{n_j} \overline{a_{j,k}} \leq C - a_{i,n_i+1}(b) \\ a_{i,n_i+1}(b_{gi}), & \text{if} \sum_{j=1}^{9}\sum_{k=1}^{n_j} \overline{a_{j,k}} - \sigma \leq C - a_{i,n_i+1}(b_{gi}) \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

where in the above, $\overline{a_{i,j}}$ denotes the load contribution of the j^{th} bearer with priority i. A technique such as the one in [13] can be adopted to determine $\overline{a_{i,j}}$. We note that the first and second conditions in (1), respectively, indicate the situations which the needed resource for a bearer admission is enough and the needed resources can be obtained by a BA mechanism.

III. Proposed Bandwidth Adaptation Mechanism

The proposed BA mechanism of this study downgrades the resources of each active bearer up to its guaranteed data rate requirements in a distributed fashion based on a new bearer attribute called *bearer downgrading index*. This index determines the contribution of each active bearer in bandwidth downgrading process based on three parameters. The first parameter is the bearer priority. Intuitively, an active bearer with a lower priority should have a higher contribution in bandwidth downgrading process. The second parameter which affects this index is the bearer's QoS over-provisioning. This parameter can be defined as the amount of the extra resources which is assigned to a bearer with respect to the needed resources to provision its guaranteed data rate. Let $r_{i,j}$ denote the over-provisioned resource for the j^{th} bearer with priority i, it can be measured by

$$r_{i,j} = \overline{a_{i,j}} - a_{i,j}(b_{gi}), \quad 1 \leq i \leq N, \tag{2}$$

where as stated before, $\overline{a_{i,j}}$ denotes the load contribution of that bearer. The third participating parameter in bearer downgrading index is channel quality. We note that a UE which experiences a poor channel condition uses a lower order modulation format with more redundancy bits to improve the reception probability. Thus, compared to an UE which is experiencing a better channel quality, it uses more bandwidth resources to satisfy the same data rate. As a result, downgrading the UE with a poor channel quality will result into releasing more physical resources. As discussed earlier, CQI in AMC process is an appropriate indicator for the channel quality experienced by a UE and it may be invoked from the MAC scheduler. Let CQI_i denote the CQI index of the UE which holds a bearer with priority[2] i. Since CQI_i is an increasing function of channel quality [10], we may define its complement, denoted by q_i as

$$q_i = 16 - CQI_i, \tag{3}$$

which represents a decreasing function of channel quality by returning a higher value for a poorer channel condition.

Next, let $f_{i,j}$ denote the bearer downgrading index for the j^{th} bearer with priority i. Considering the three contribution parameters, we may write this index as

$$f_{i,j} = i^{\alpha} r_{i,j}^{\beta} q_i^{\gamma}, \quad 1 \leq j \leq n_i, \quad 1 \leq i \leq N. \tag{4}$$

With assumption of positive exponents, (4) presents $f_{i,j}$ as an increasing function of the three parameters, i.e. the bearer's priority[3], the bearer's QoS over-provisioning and the complement of the bearer's channel quality indicator. α, β and γ denote some fine-tuning exponents which adjust the contribution level of the three aforementioned parameters. Larger α, β and γ, respectively, result in higher downgrading index for low-priority bearers, highly resource over-provisioned bearers and the bearers whose UEs experience a lower quality channel.

[2] we assume a wideband CQI report mode as described in [10].

[3] Note that a bearer with a higher i has a lower priority.

Next, we define $\bar{f}_{i,j}$ as *normalized bearer downgrading index*. $\bar{f}_{i,j}$ can be written as

$$\bar{f}_{i,j} = f_{i,j} / \sum_{i,j} f_{i,j}, \tag{5}$$

and it presents the normalized contribution of each active bearer in the bandwidth downgrading process. Finally, to release a target load σ for call admission process, we propose the following BA Algorithm:

Algorithm 1 BA Algorithm to Release Load σ

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while load σ was not released do
    Calculate f_{i,j} for all i, j from (4).
    if f_{i,j} = 0 for all i, j then
        Break
    end if
    Calculate f̄_{i,j} for all i, j from (5).
    if ρ_{i,j} − f̄_{i,j}σ > bg_i then
        ρ_{i,j} ← ρ_{i,j} − f̄_{i,j}σ
    end if
end while
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In this algorithm, the first conditional *IF* statement stops the algorithm whenever $f_{i,j}$ approach to zero for all bearers. This happens whenever all bearers are downgraded to their guaranteed data rates. As a result, the target load σ cannot be released by a BA process. In this case, a preemption mechanism may be employed to disable some low-priority bearers completely toward admitting a high priority bearer. The second condition verifies if resource downgrading of an active bearer does not violate its guaranteed bit rate requirements. We note that the proposed BA mechanism not only downgrades the bearers' resources in a fair and distributed scheme, but also it allows the service provider to customize the contribution levels of the three aforementioned parameters in the downgrading process.

IV. Performance Evaluation

A simulation of a seven-cell network model has been considered to evaluate the performance of the proposed BA mechanism. The mobility model of [14] was incorporated to model the UEs' movements and the outer cells hold a wrap-around mobility effect. Only the traffic in the downlink direction of UEs in the center cell was considered in the analysis. In the physical layer, the OFDM channel holds a 5 GHz bandwidth which contains 25 PRBs. The physical layer setting follows the modeling of [15].

Three bearer classes with priorities 1 to 3 were considered from two multimedia traffic types, voice and video whose characteristics, settings and their LTE QoS parameters are shown in Table I[4]. The traffic characteristics were modeled according to the requirements specified by the Next Generation Mobile Networks (NGMN) consortium [16].

[4] As observed in this table, two QoS attributes bearer's preemption vulnerability and preemption capability were disabled for simplicity reasons; however, as expected, the results will be greatly affected when these flags are enabled for some or all bearers.

TABLE I: Traffic distributions and parameters

Voice	
Source rate	Variable rates
Talk spurt length	Exponentially distributed with mean = 147 msec
Silent period length	Exponentially distributed with mean = 167 msec
Service time	Exponentially distributed with mean = 100 Sec
Bearer classes	**GBR-bearer with priority 1**, GBR=32 kb/s, MBR=64 kb/sec, error rate=10^{-2}, preemption vulnerability=0, Preemption capability=0
Video	
Frame inter-arrival time	100msec (Deterministic)
No. of slices (packets) per frame	8 slices/frame (Deterministic)
Packet (Slice) size	Truncated Pareto Distribution with mean = 100 bytes and maximum = 250 bytes
Packet inter-arrival time in a frame	Truncated Pareto Distribution with mean=6 msec and maximum = 12.5 msec
Service time	Exponentially distributed with mean = 100 Sec
Bearer classes	**GBR-bearer with priority 2**, GBR=128 kb/s, MBR=256 kb/sec, error rate=10^{-3}, preemption vulnerability=0, Preemption capability=0
	NonGBR-bearer with priority 3, GBR=10 kb/s, MBR=64 kb/sec, error rate=10^{-2}, preemption vulnerability=0, Preemption capability=0

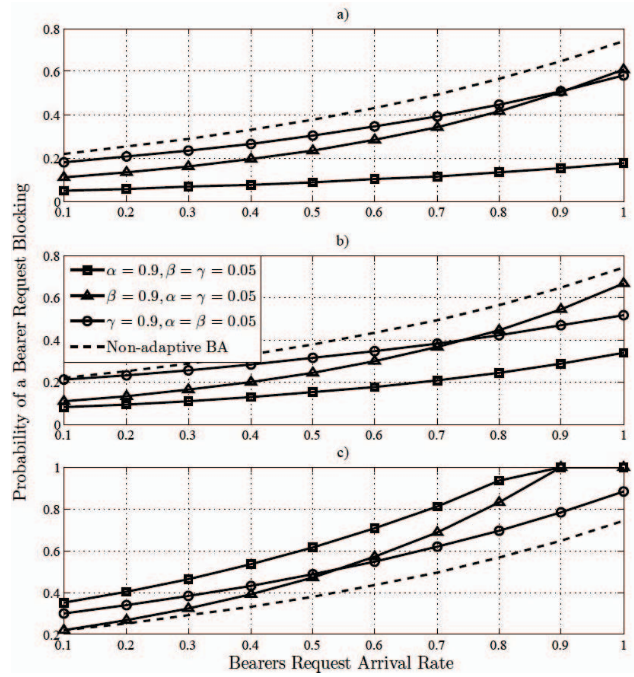

Fig. 1: Probability of a new bearer blocking as a function of bearer request batch arrival rate for (a) GBR voice, (b) GBR video and (c) nonGBR video.

In the following, we assume $\alpha + \beta + \gamma = 1$. To highlight the performance of the proposed BA, we also include the simulation results of a non-adaptive BA scheme in which a bearer is admitted once its required nominal bandwidth is available. This case is similar to 3GPP release 8 in which MBR and GBR parameters are set equal. Thus, in non-adaptive scheme we set the bearer nominal bandwidth requirement as the average of its proposed MBR and GBR values shown in Table I. Figs. 1 (a), (b) and (c) plot the probability of a new bearer blocking as a function of bearer request batch arrival rate for the three bearer priorities, i.e., GBR voice, GBR video and nonGBR video, respectively. Four curves are presented in each figure which correspond to the proposed BA with a dominant priority effect ($\alpha = 0.9$), the BA with a dominant QoS over-provisioning effect ($\beta = 0.9$), the BA with a dominant channel quality effect ($\gamma = 0.9$), and non-adaptive BA, respectively. As it may be observed in Figs. 1 (a) and (b), the employment of the proposed BA scheme reduces the blocking probability for the bearers with priorities one and two. As congestion increases, this improvement becomes significant when $\alpha = 0.9$ while it is almost the same when $\beta = 0.9$ or $\gamma = 0.9$. In other words, priority is a dominant parameter in controlling the new bearer blocking probability. In this simulation run, we note that the exponents α, β and γ were marginally selected to indicate extreme cases; however, they can be fine-tunned to obtain desirable values for the bearer blocking and handoff bearer dropping probabilities.

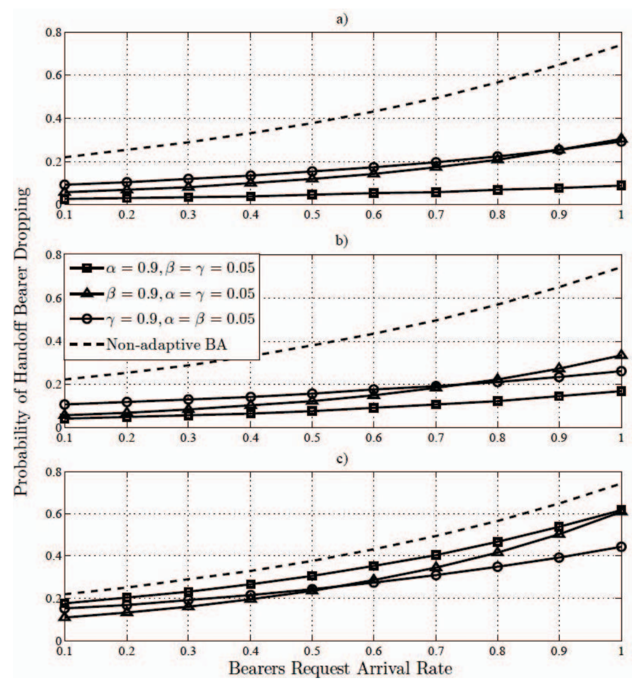

Fig. 2: Probability of handoff bearer dropping as a function of bearer request batch arrival rate for (a) GBR voice, (b) GBR video and (c) nonGBR video.

Figs. 2 (a), (b) and (c) present the probability of a handoff bearer is dropped when it migrates from any of the six adjacent cells to the center cell for the aforementioned three bearer priorities, respectively. Similarly, four curves in each figure, respectively, correspond to the proposed BA with a dominant priority effect ($\alpha = 0.9$), the BA with a dominant QoS over-provisioning effect ($\beta = 0.9$), the BA with a dominant channel quality effect ($\gamma = 0.9$), and non-adaptive BA. For all bearer classes, when the proposed BA is employed, the probability of handoff bearer dropping decreases. This improvement is especially significant for GBR traffics shown in Figs. 2 (a) and (b). Next, we measure the service provider's revenue within an interval of T hours. To do so, we need to consider a time-dependent arrival profile as well as a resource pricing scheme. Thus, we consider a linear bearers batch arrival rate which is increasing from 0.1 to 1 bearers per second within a time frame of $T = 6$ hours. Further, we assume that the services GBR voice, GBR video and nonGBR video are priced as 1, 0.2 and 0.1 money unit/Mb, respectively. Fig. 3 plots a 3D mesh of the generated revenue as a function of two exponents β and γ (note that $\alpha = 1 - \beta - \gamma$). As it may be observed, when $\alpha = 1$ (or equivalently $\gamma = \beta = 0$), the revenue takes its maximum value of 4.17×10^4 money unit. This is due to the fact that $\alpha = 1$ represents the BA with a dominant priority effect in downgrading process where the bearers with lower priorities have a higher chance to be downgraded. In other words, Since the service prices are increasing with their priorities, the generated revenue in this case will take its highest value. Generated revenue reaches to the marginal values 3.93×10^4 and 3.78×10^4, when $\gamma = 1$ and $\beta = 1$, respectively. The latter case indicates that the minimum generated revenue corresponds to the BA mechanism with a dominant QoS over-provisioning parameter.

Although $\alpha = 1$ results into the highest generated revenue, it monopolize the network resources for the high priority bearers. This can be observed in Figs. 1 and 2 where voice bearers experience the minimum blocking and handoff dropping probabilities. Thus, a trade-off is needed based on the service provider policies. Fig. 3 shows the capability of the proposed BA in altering the service provider's generated revenue by 8% during a congestion period.

V. Conclusion

Maximum bit rate and guaranteed bit rate parameters are considered as two important bearers' QoS attributes which are assumed equal in the current version of LTE. However, they provide a great deal of flexibility in bearers' QoS management in future 3GPP releases. In this study, we have shown that bandwidth adaptation as a congestion control technique in LTE radio resource management can play an important role in enhancing system performance measurements such as probability of a bearer blocking and handoff bearer dropping as well as service providers generated revenue. The proposed bandwidth adaptation mechanism takes advantage of three fine-tuning exponents which control the contribution level of the three bearers characteristics, i.e., bearers priorities, bearers' QoS over-provisioning and their communication channel quality into the resource downgrading process. Thus, fine-tuning exponents may be effectively used to reach a tradeoff between performance measurements such as probability of bearer blocking and generated revenue. In our future work, we plan to investigate optimized values for the exponents used in our approach.

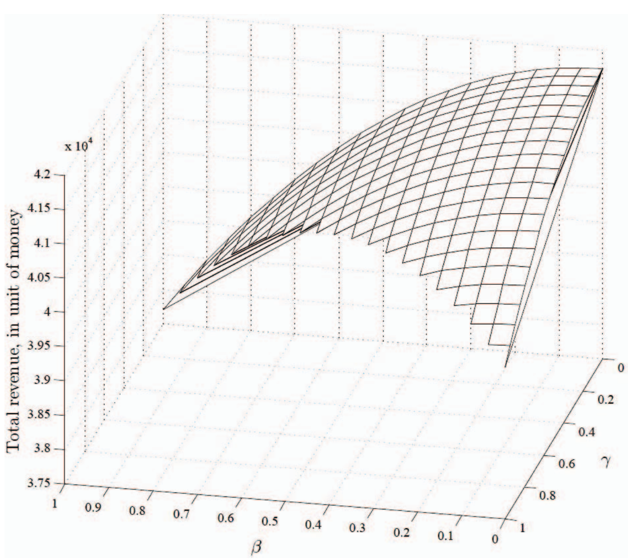

Fig. 3: Service provider revenue as a function of fine-tuning exponents in bearer downgrading index, i.e. α, β and γ ($\alpha = 1 - \beta - \gamma$).

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