eICIC Functionality and Performance for LTE HetNet Co-Channel Deployments

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***Abstract*— Different technical solutions are enabling the move from macro-only scenarios towards heterogeneous networks with a mixture of different base station types. In this paper we focus on multi-layer LTE-Advanced networks, and especially address aspects related to co-channel interference management. The network controlled time-domain enhanced inter-cell interference coordination (eICIC) concept is outlined by explaining the benefits and characteristics of this solution. Extensive system level performance results are presented with bursty and non-bursty traffic to demonstrate the eICIC concepts ability to dynamically adapt according to the traffic conditions.**

Index terms—**Heterogeneous network, LTE-Advanced, range extension, TDM muting.**

I. INTRODUCTION

In recent years, cellular operators have experienced a significant boom in mobile data traffic growth. And still, the annual traffic growth rates are estimated to remain high, resulting in an estimated global mobile traffic increase of factor 26 from 2010 to 2015 as reported in [1]. Furthermore, cellular operators have in general reported non-uniform traffic distributions in their networks, stating that for instance 50% of the total traffic volume is carried on only 30% of the macro-sites. Exact percentages of course vary from network to network. Thus, this translates to predictions that traffic volume increase in certain geographical hotspots may far exceed the average expected traffic predictions for the entire network. The latter presents an enormous challenge on how to best evolve cellular mobile networks to be able to carry those high amounts of data. As the spectral efficiency per link is approaching theoretical limits (Shannon), our postulate is that the new performance leap in terms of improved spectral efficiency per unit area will mainly come from using HetNet (Heterogeneous Networks) topologies. In a HetNet, a mixture of macro cells for continuous wide area coverage combined with small base-station nodes for improved hotspot performance is used. Migration from macro-only to heterogeneous networks is expected to accelerate during the years to come. Small low power base-station nodes are therefore regarded as one of the key technology enablers for hotspot capacity improvements to meet the expected traffic growth. However, multi-layer deployment with a variety of base station types also presents challenges in terms of e.g. interference management and general systems performance optimization.

In this paper we focus on downlink 3GPP LTE-Advanced multi-layer networks with macro-cells, complemented by pico nodes for improved performance [2]-[3]. LTE-Advanced is introduced with 3GPP release-10 (Rel-10), and includes a variety of new enhancements as compared to the first LTE releases [3], including several innovations for attractive deployment of different base station types. Among those, autonomous interference management features play an important role to facilitate easy deployment of small base station nodes without prior manual (or semi-automatic) radio network planning. Thus, interference management techniques are one of the components facilitating easy "zero touch" deployment of small base station nodes. An overview of inter-cell interference coordination (ICIC) techniques for the first LTE release (Rel-8) can be found in [4]-[6]. However, the former frequency-domain ICIC schemes were mainly designed for macro-only scenarios, and only provides improvements for the physical data channels, while failing to offer protection for physical control channels carrying critical information for achieving good system performance. A new enhanced ICIC (eICIC) scheme for multi-layer networks has therefore been developed for LTE-Advanced (introduced in Rel-10), which offers time-domain resource partitioning between network layers for better performance. The eICIC concept is custom designed to handle the potential downlink interference problems that may arise in multi-layer networks with co-channel deployment. Note that as compared to Rel-8 ICIC, the Rel-10 eICIC scheme offers benefits for both physical data and control channels. An overview of other 3GPP heterogeneous network features is available in [7].

The article is organized as follows: First the multi-layer network is defined, using an example with co-channel deployment of macro and pico. This example is used to establish a baseline and to outline the main interference challenges in such scenarios. Secondly, the new time-domain (TDM) eICIC concept is described in detail, and it is explained how it offers a mechanism for addressing the major downlink interference problems in multi-layer co-channel scenarios. Moreover, we provide guidance on the signalling exchange and network configuration based on the mechanisms available in Rel-10 specifications. Following this, examples of system level performance results for eICIC are presented. Finally, the paper is closed with summary and concluding remarks.

II. HETNET CO-CHANNEL INTERFERENCE CHALLENGES

Fig. 1 illustrates an example of multi-layer network with macro and pico. Assuming an operating bandwidth of 10 MHz, a typical configuration of the macro base station (eNB) is 46 dBm transmit (Tx) power per sector, 14 dBi antenna gain (including feeder loss), which results in an equivalent isotropic radiated power (EIRP) of 60 dBm. The pico eNB only has an EIRP of 35 dBm in the example in Fig. 1, which naturally results in significantly smaller coverage than the macro eNB.

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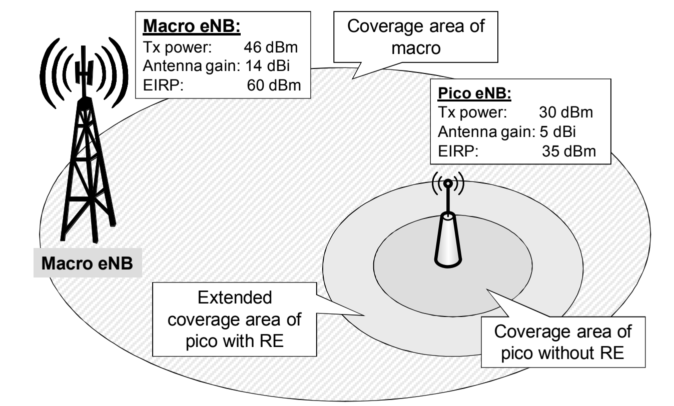


Fig. 1 Simple illustration of interference scenarios and challenges in multi-layer networks.

The coverage area of the pico eNB is not only limited by its transmit power, but also to a large extent by the interference experienced from the macro eNB. Thus, if the serving cell selection is based on downlink UE measurements such as reference symbol received power (RSRP) [8], only UEs in the close vicinity will end up being served by the pico. The service area of the pico can be increased by applying a so-called range extension (RE), where a cell specific bias to the UE measurement of X dB is applied for a pico to favour connecting to it. However, in a traditional co-channel scenario without any explicit interference management, it is typically only possible to use small values of the RE, say few dBs as pico UEs will otherwise experience too high interference from the macro layer. The problem addressed by eICIC is therefore the interference from macro to pico. Reducing the macro interference by means of resource partitioning will allow using much higher pico RE offsets to significantly increase the offload from the macro-layer.

Another characteristic of multi-layer networks worth mentioning is the higher dominant-interference-ratio (DIR). The DIR basically expresses the ratio of the dominant interferer versus the sum of the rest of the interference at the receiver. The higher DIR means that the experienced signal-to-interference-ratio (SIR) can be improved significantly if advanced receivers capable of suppressing the dominant interferer are used. The combination of advanced interference suppression terminal receivers and network centric eICIC schemes therefore offers attractive improvements for multi-layer networks.

III. The eICIC Concept

The basic principle of eICIC is illustrated in Fig. 2 for a scenario with co-channel deployment of macro and pico. The concept relies on accurate time- and phase-synchronization on subframe resolution between all base station nodes within the same geographical area. A base station reduces the interference to its surrounding neighbours by using so-called almost blank subframes (ABS). An ABS is characterized by minimum transmission, where just the most essential information required for the system also to work for legacy LTE UEs is transmitted. Thus, during ABS, the signals that are mainly transmitted are common reference signals (CRS), as well as other mandatory system information, synchronization channels, and paging channel if these collide with the ABS. It is therefore often assumed that eICIC is operated together with advanced UE receivers that are capable of further suppression of the residual interference from ABS, such that UEs virtually experience close to zero interference from base station nodes using ABS [7]. More details on UE interference cancellation for eICIC cases can be found in [9]-[10]. During subframes where the macro-layer uses ABS, there is less interference generated for users served by pico. This implies that the pico is capable of serving UEs from a larger geographical area during subframes where macro uses ABS as those UEs are no longer dominated by interference from the macro layer. This essentially means that using ABS at macro makes it possible to increase the offload of traffic to the small-cell layer.

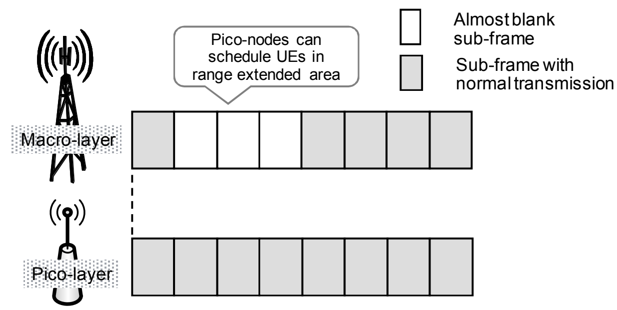


Fig. 2 Basic principle of TDM eICIC for LTE-Advanced.

In order to gain from eICIC, the base station packet scheduler and link adaption functionality in principle needs to be aware of the applied ABS muting patterns at the different base station types. Thus, pico eNBs should only schedule users subject to potentially high macro-layer interference during subframes where macro cells use ABS. Other pico-UEs are schedulable during all subframes.

Although the focus of this paper is on scenarios with macro and picos, the eICIC concept can also address problems related to co-channel deployment of macro and home eNBs, i.e. especially for avoiding macro-layer coverage holes caused by deployment of closed subscriber group home eNBs [11].

A) Network configuration of ABS muting patterns:

The ABS muting pattern is periodical with 40 subframes for FDD mode, while taking other periodicity for TDD mode depending on the uplink/downlink configuration. The periodicity of 40 subframes for FDD has been selected to maximize the protection of common channels, including uplink hybrid automatic repeat request (HARQ) performance. For maximum benefit from eICIC, base station nodes of the same type in a given local area are recommended to use overlapping and coordinated ABS muting patterns.

For base station types such as macro, micro, and pico the Rel-10 specifications support mechanisms for distributed dynamic configuration of ABS muting patterns that seek to maximize the overall system performance while taking the quality-of-service (QoS) requirements of individual users into consideration. In the following we illustrate how this is possible with an example for a scenario with macro and pico (Figure 3). The macro is assumed to act as the master, and therefore the eNB deciding which subframes it wants to configure as ABS. The macro eNB has various sources of information available for deciding if some subframes shall be ABS. Among others, the macro eNBs can estimate if it can configure more subframes as ABS while still being able to serve all its users according to their minimum QoS requirements. In addition, the Rel-10 specifications include several enhancements for the X2 application protocol (AP) to facilitate collaborative configuration of ABS muting patterns between eNBs. Referring to the example in Fig. 3, a pico eNB can send a Load Information X2 message to a macro eNB with information element (IE) Invoke. The Invoke message indicates to the macro eNB that it would like to receive ABS information from the macro, potentially with more subframes configured with ABS. The macro eNB responds to such a message by sending another X2 Load Information message to the pico with IE ABS information. The ABS information includes information of the currently used ABS muting pattern at the macro-eNB (expressed with a 40-bit word for FDD cases). The ABS information can also be exchanged between macro eNBs to align that neighbouring macro eNBs use the same, or overlapping, ABS muting patterns. Furthermore, the macro-eNB can initialise a Resource status reporting initialisation procedure, asking the pico to report usage of the allocated ABS resource. The pico provides the information with a Resource status update message with IE ABS status. The ABS status provides the macro eNB with useful information on how much of the ABS resource is blocked at the pico node; either because of scheduling of critical UEs during subframes where macro uses ABS, or because of other limitations. In this context, the term “critical UEs” refers to UEs that are only schedulable by the pico during subframes where the macro uses ABS. In the ABS Status, the pico may also indicate that part of the allocated ABS resource is not usable, e.g. due to interference experienced from other macro-eNBs. Thus, based on the ABS status, the macro eNB has additional information to determine the consequences of configuring more or less subframes as ABS, before potentially deciding on a new ABS muting pattern. Whenever the macro eNB decides to change the ABS muting pattern it informs the pico eNBs in its coverage area by sending the ABS information. The exact definition of the various X2 messages that form the light-weight inter-eNB eICIC coordination protocol can be found in the X2 application protocol specification [12].

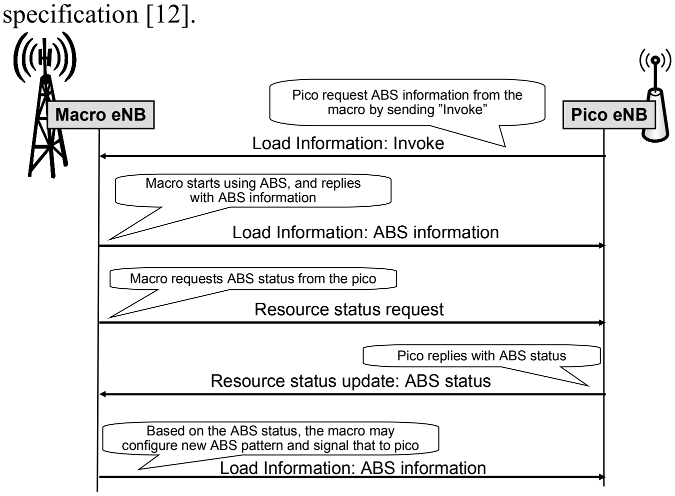


Fig. 3 Example of X2 signalling for distributed coordinated adaptation of ABS muting pattern.

B) UE measurements and mobility aspects:

The use of ABS muting patterns naturally results in more severe time-variant interference fluctuations in the network, and therefore it becomes more challenging for the eNBs to conduct accurate link adaptation (i.e., selection of modulation and coding) and air interface aware packet scheduling based on channel state information (CSI[1]) feedback from UEs. It is therefore necessary for the network to configure restricted CSI measurements for Rel-10 UEs, so that the eNB receives such reports corresponding to normal subframes and ABS, respectively. However, notice that configuration of such measurement restrictions is not supported for LTE legacy Rel-8 and Rel-9 UEs, and thus those UE categories may potentially experience lower performance in networks with eICIC enabled. Figure 4 illustrates the importance of restricted CSI measurements. In particular, the CQI reporting is depicted. Rel-10 UEs are configured to report different CQI reports during ABS and non-ABS, guaranteeing the receiver side BLER performance. On the other hand, Rel-8 and Rel-9 UEs do not support measurement restrictions and the estimated interference is averaged in time domain across a certain time window. Therefore, the interference variation due to eICIC is not directly reflected in the CQI report of the legacy UEs. Although not captured in the Figure, there is a delay before the packet scheduler at the eNB can receive the CQI information sent by the UE due to the time taken by the physical layer to process the information. With measurement restrictions, the last CQI report during ABS is applied at the eNB until the new update is available, and analogously for the non-protected subframes.

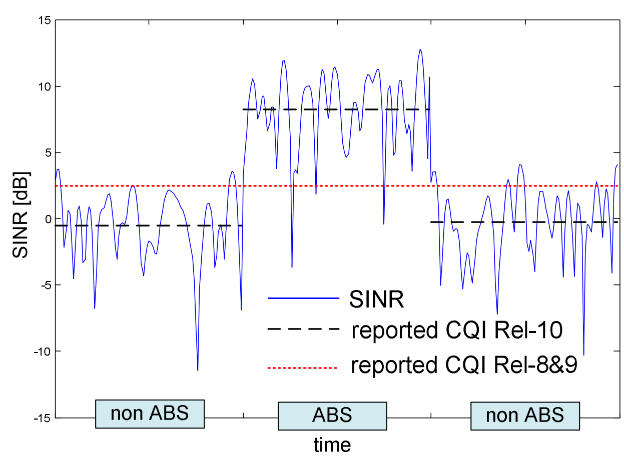


Fig. 4 UE CSI measurement restrictions.

Similarly, the network can also configure UE measurement restrictions for radio resource management measurements used for mobility purposes. Finally, measurement restrictions can also be configured for radio link monitoring (RLM). All of the aforementioned measurement restrictions for Rel-10 UEs are configured with radio resource control (RRC) messages as specified in [13], and are therefore only applicable for connected mode terminals.

[1] CSI refers to channel quality indicator (CQI), as well as rank indicator (RI) and pre-coding matrix indicator (PMI) if multiple-input-multiple-output (MIMO) is used.

IV. PERFORMANCE ASSESSMENT

In the following we present system level performance results for co-channel deployment of macro and pico eNBs. The scenario assumption is in coherence with the definition given in [14] for hotzone deployment of pico eNBs in macro-cells. The macro layer is a traditional three-sector hexagonal grid with 500 meters inter-site distance, assuming 4 pico eNBs placed randomly in each macro-cell area. Aligned with the assumptions in [14], a higher user density is assumed around each pico eNB to model traffic hotspots in a simplified manner (aka 3GPP scenario 4b). The primary performance metrics reported in the following are the 5%-tile and 50%-tile downlink experienced user throughput. UEs are assumed to have two receive antennas, using a linear minimum mean square error (MMSE) receiver. In addition, the UE receiver performs non-linear interference cancellation of residual interference from ABS such as CRS interference [9]-[10]. Finally, all UEs are assumed to be Rel-10 compliant with the possibility to configure measurement restrictions for efficient eICIC operation as described in the previous section. Default simulation parameters are summarized in Table 1.

Table 1: Summary of simulation assumptions.

Parameter	Setting
Network Layout	500m macro-layer Inter-Site Distance with 4 pico-eNBs per macro-cell
Cell layout	21 macro-cells with wrap-around
UE placement	2/3 of UEs close to pico; the remaining UEs are uniformly distributed within the macro-cell area.
Transmit power	Macro-eNB: 46 dBm; pico-eNB: 30 dBm
HARQ modeling	Ideal chase combining
Bandwidth	10 MHz at 2000 MHz carrier frequency
Antenna system	2 x 2 with rank adaptation
Antenna gain	Macro: 14 dBi; pico: 5 dBi; UE: 0 dBi
Antenna pattern	Macro: 3D [11]; Pico and UE: Omni
Traffic model	Full buffer and finite buffer (1 Mbit payload) with Poisson arrival
Path loss	Macro to UE: $128.1+37.6 \cdot \log10(R[km])$ Pico to UE: $140.7+36.7 \cdot \log10(R[km])$
Shadow fading	Lognormal. std=10 dB for pico-eNB to UE links, 8 dB for Macro-eNB to UE links
eNB packet scheduling	Proportional Fair (PF)
CQI delay	6ms

The normalized user-throughput performance is summarized in Fig. 5 for the case with simple full buffer best effort traffic. The performance is normalized with respect to the macro-only scenario without picos. It is observed that the performance improvement from adding 4 picos is in excess of factor 2 without eICIC, while it increases to nearly a factor 4 if eICIC is enabled. More precisely, the relative gain from applying eICIC and large RE is on the order of 75% over the plain co-channel deployment scenario. The eICIC results are obtained with 50% of the subframes configured as ABS and 14 dB RE, which appeared to be the best configuration for the considered scenario. The eICIC gain mainly comes from

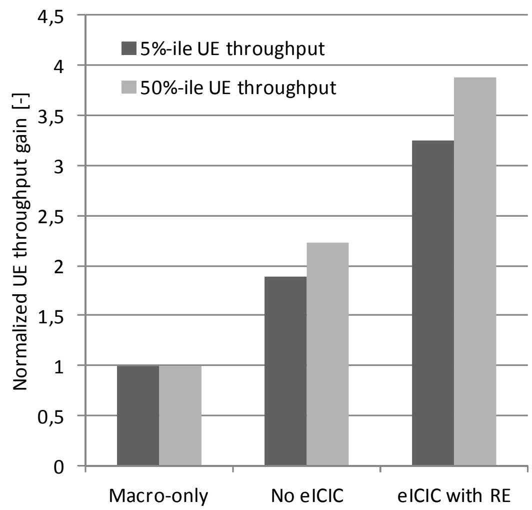


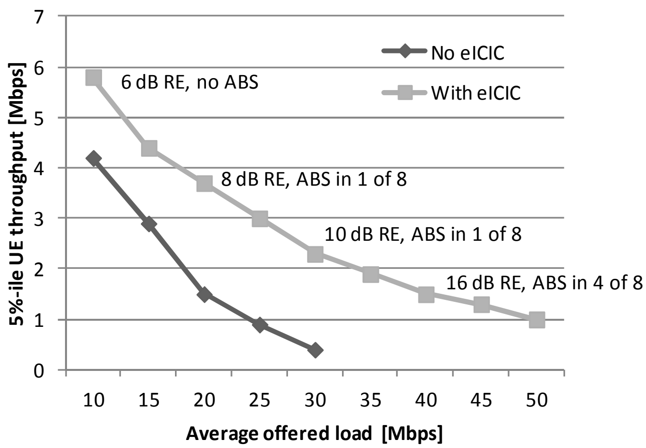
Fig. 5 Relative user-throughput performance gain of deploying pico eNBs with/without eICIC for full buffer traffic.

offloading more UEs to the picos. Without eICIC, only 38% of the users are served by the picos, while with eICIC enabled it increases to 78%.

The results reported in Fig. 6 shows the experienced 5%-ile and 50%-ile user throughput performance versus the average offered traffic per macro cell area, respectively. Those results are obtained for a dynamic traffic model with homogeneous Poisson call arrival, assuming a finite payload for each call. Once the payload has been successfully delivered to the UE, the call is terminated. As load increases, more UEs are sharing the same amount of resources and hence the UE throughput gets lower. It is illustrated how the optimal eICIC configuration varies versus the offered traffic load by displaying the best settings of ABS muting ratio and RE. The new Rel-10 X2 signalling for dynamic adaptation of ABS muting patterns (as summarized in Fig. 3) allows the system to self-adjust to use the best configuration depending on traffic load conditions. At low offered load, it is observed that there is little, or marginal, gain from applying eICIC, and thus the system converges to not using ABS at the macro-layer. This is because there is only marginal other-cell interference at low load conditions. However, as the offered load increases and both macros and picos start to have higher probability of transmitting (and thus causing interference for other cells), the system converges to using more ABS at the macros and higher RE at the picos. In fact, we have found that the optimal setting of ABS and RE corresponds to the point where macro and pico cells have approximately the same average transmission resource utilization (i.e. measured by average usage of physical resource blocks [12]). At high offered traffic, the gain from applying eICIC enables on the order of 80%-100% higher offered load while still being able to serve the users with the same data rate.

V. CONCLUSION

Interference related challenges top the list for HetNet co-channel deployments, so efficient interference management schemes are perceived to be among the key enabling



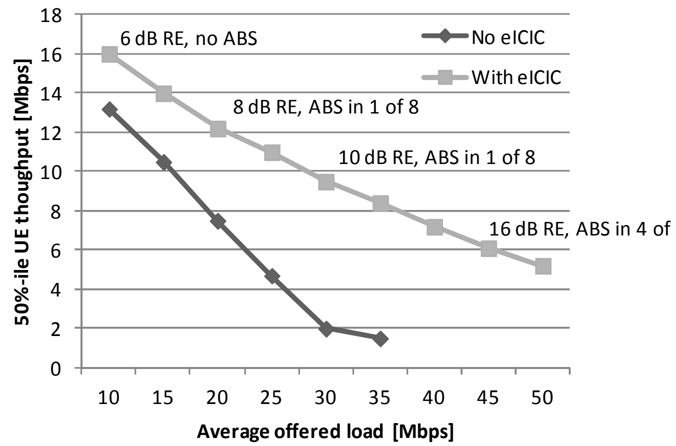


Fig. 6 User-throughput performance with/without eICIC for dynamic traffic versus the average offered load per macro-cell area. Scenario includes 4 picos per macro-cell area.

mechanisms. The eICIC mechanism is designed to solve downlink co-channel HetNet interference challenges. The interference management is essentially facilitated by letting the different base station nodes use ABS in a coordinated manner. For the eNBs inter-connected via the X2 interface, new standardized messages are introduced. These messages form a simple light-weight coordination protocol for distributed dynamic adjustment of ABS muting patterns. In order to fully benefit from eICIC, terminals supporting configuration of time-domain measurement restrictions and the capability of suppressing residual interference from ABS are required. The main benefits, characteristics, and requirements for eICIC are summarized in Table 2.

Table 2: Summary of LTE eICIC benefits, requirements, and characteristics.

eICIC benefits	Increased offload to micro and pico nodes via reduced co-channel macro interference.
ABS characteristics	ABS are subframes with reduced transmit power (including no transmission) on some physical channels and/or reduced activity. Backwards compatibility towards UEs by transmitting necessary control channels and physical signals as well as System Information.
Time synchronization	Requires time synchronization between eNBs. E.g. GPS and backhaul based solutions such as IEEE 1588.
ABS muting pattern configuration	Distributed dynamic coordination of ABS muting pattern between macro, micro, pico via standardized X2 signalling.
Network RRM	Packet scheduler shall schedule pico-UEs requiring protection from aggressor nodes when these use ABS.
UE requirements	Best performance achieved with UEs supporting configuration of restricted RLM, RRM, and CSI measurements, as well as CRS interference cancellation. Also works for Rel-8/9 legacy UEs but with reduced performance.

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