Enhanced Inter-Cell Interference Coordination in Co-Channel Multi-Layer LTE-Advanced Networks

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ENHANCED INTER-CELL INTERFERENCE COORDINATION IN CO-CHANNEL MULTI-LAYER LTE-ADVANCED NETWORKS

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ABSTRACT

Different technical solutions and innovations are enabling the move from macro-only scenarios towards heterogeneous networks with a mixture of different base station types. In this article we focus on multi-layer LTE-Advanced networks, and especially address aspects related to 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. The benefits of using advanced terminal device receiver architectures with interference suppression capabilities are motivated. Extensive system level performance results are presented with bursty traffic to demonstrate the eICIC concepts ability to dynamically adapt according to the traffic conditions.

INTRODUCTION

In recent years, cellular operators have experienced a significant boom in mobile data traffic growth. The traffic growth is especially coming from the introduction of mobile broadband and data oriented devices; e.g. smart phones and USB modems. 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 percent of the total traffic volume is carried on only 30 percent 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 by 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. Migration from High Speed Packet Access (HSPA) to Long Term Evolution (LTE) with a flat IP-based architecture brings additional benefits in terms of improved spectral efficiencies and reduced latency [2], but those alone are insufficient when compared to the traffic growth predictions. This essentially means that other performance boosters such as the introduction of small base station nodes are likely needed. 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 heterogeneous network topologies with a mixture of macro cells for continuous wide area coverage in combination with small base-station nodes for improved hotspot performance. Thus, 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 article we focus on 3GPP LTE-Advanced multi-layer networks with macro-cells, complemented by pico nodes and/or home base stations (HeNBs) for improved performance [3, 4]. Especially the uncoordinated deployment of HeNBs has recently attracted attention in research, where aspects such as interference avoidance, off-load effects, and architecture/access constraints have been studied [5]. LTE-Advanced is introduced with 3GPP release-10 (Rel-10), and includes a variety of new enhancements as compared to the first LTE releases [4], 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. The

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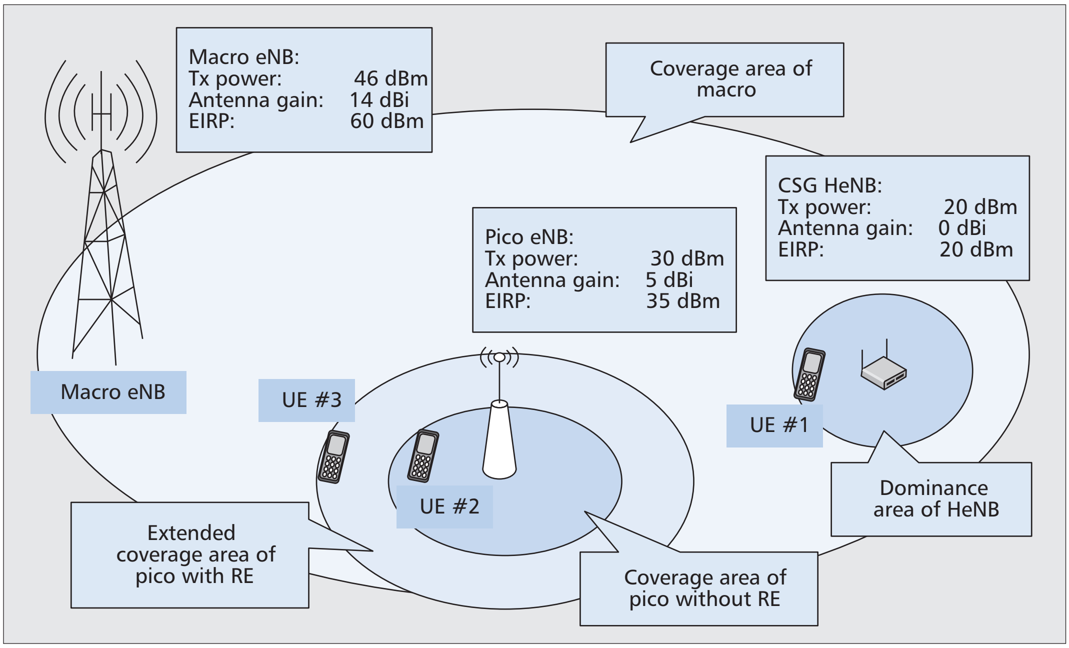

Figure 1. *Simple illustration of interference scenarios and challenges in multi-layer networks.*

The downlink is known to be the most challenging link from an interference perspective in multi-layer co-channel deployed networks, and is therefore chosen to be the focus in this article, although the uplink of course also requires attention when deploying multi-layer networks.

first LTE release (Rel-8) also included simple frequency-domain inter-cell interference coordination (ICIC) techniques, coordinated via inter-eNB signaling of relative narrowband transmit power indicator to announce generated interference per sub-band from each cell in the downlink. An overview of Rel-8 ICIC techniques is available in [6]-[7]. However, the former frequency-domain ICIC scheme were mainly designed for macro-only scenarios, and only provide 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 of macro, pico, and HeNBs. Note that as compared to Rel-8 ICIC, the Rel-10 eICIC scheme offers benefits for both physical data and control channels. Our starting point in this study is that good wide-area macro coverage and performance continues to be essential, so one of the questions we address is how to best deploy and manage those small base stations without jeopardizing the macro-layer performance, while still maximizing the overall network performance. The latter can be achieved by using different strategies in combination with autonomous network controlled interference management techniques such as the eICIC concept. The downlink (i.e. forward link) is known to be the most challenging link from an interference perspective in multi-layer co-channel deployed networks, and is therefore chosen to be the focus in this article, although the uplink (i.e. reverse link) of course also requires attention when deploying multi-layer networks. An overview of other 3GPP heterogeneous network features is available in [8].

The article is organized as follows: First the multi-layer network is outlined, using an example with co-channel deployment of macro, pico, and HeNBs. This example is used to establish a baseline and to outline the main interference challenges in such scenarios. Secondly, the new 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. Following this, examples of system level performance results for eICIC are presented. Finally, the article is closed with summary and concluding remarks.

Interference Challenges in Multi-Layer Networks

Figure 1 illustrates an example multi-layer network with macro, pico, and HeNB. Assuming an operating bandwidth of 10 MHz, a typical configuration of the macro base station (eNB) is 46 dBm transmit (Tx) power per sector, and 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. The HeNB has the smallest EIRP of only 20 dBm in the considered example. However, despite the relative low EIRP of the HeNB, each HeNB still creates a so-called dominance area as pictured in Fig. 1 where terminal devices, or user equipments (UEs) as they are called in LTE, served by the macro eNB will experience problems as they will be subject to too high interference from the HeNB. Therefore, co-channel deployed HeNBs

The higher DIR means that the experienced signal-to-interference-ratio (SIR) can be improved 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.

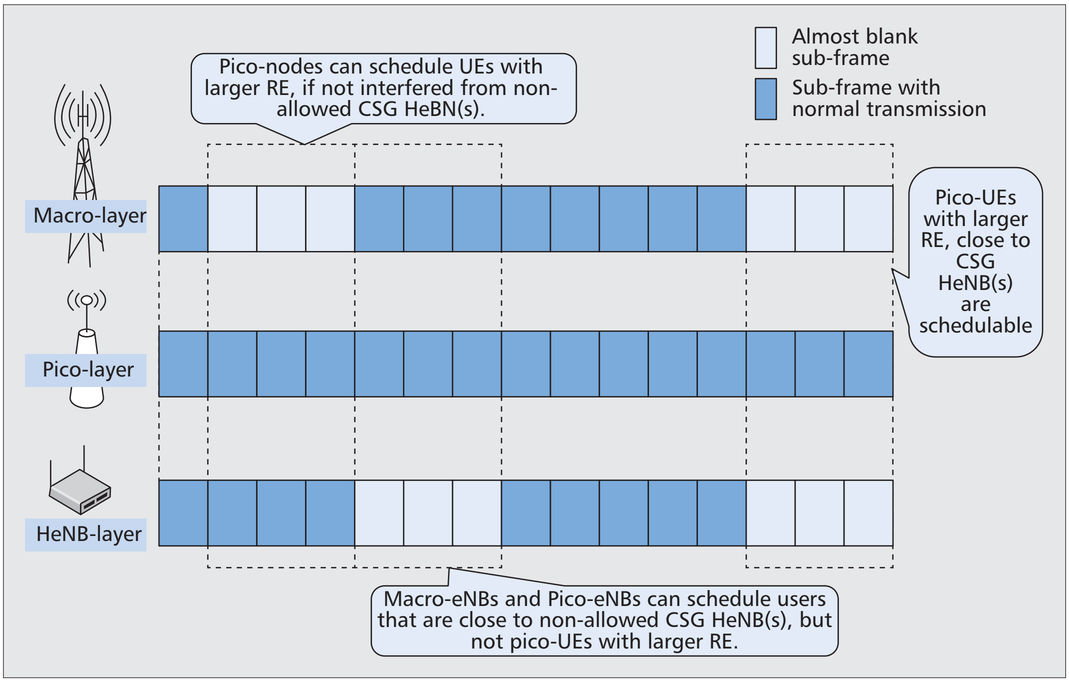

Figure 2. *Basic principle of TDM eICIC for LTE-Advanced.*

with restricted access (closed subscriber group – CSG) are often said to cause macro-layer coverage holes if no active interference management technique is applied [5]. The interference problem associated with HeNBs is further complicated by the fact that such nodes are user deployed (i.e. uncoordinated deployment), thus resulting in an inherently chaotic interference footprint. One of the problems addressed by eICIC is therefore to form resource partitioning between macro and HeNB to avoid macro-layer coverage holes so that UE #1 in Fig. 1 can still be served by the macro. Rel-10 also includes autonomous HeNB power setting schemes, where the HeNB transmit power is adjusted to minimize the interference generated for nearby macro-UEs.

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) [2], only UEs in the close vicinity will end up being served by the pico as illustrated by UE #2 in Fig. 1. 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 second problem addressed by eICIC is therefore the interference from macro to pico (i.e. referring to UE #3 in Fig. 1). 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.

As the example scenario in Fig. 1 illustrates, the interference characteristic of multi-layer networks is significantly different from traditional macro-only networks, where eNBs are carefully deployed after thorough network planning considerations to ensure good coverage and avoid unfortunate interference conditions. For the multi-layer network, the interference footprint becomes more chaotic, and thus calls for additional autonomous interference management mechanism for optimal operation as compared to macro-only deployments. 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. For multi-layer networks as the one pictured in Fig. 1 the DIR is often found to be higher than observed in macro-only networks. As examples of the latter, a macro-UE close to a HeNB experiences high DIR due to the strong interference from that node. Secondly, a pico-UE in the extended coverage area (referring to UE #3 in Fig. 1) also experiences high interference from the macro-cell. The higher DIR means that the experienced signal-to-interference-ratio (SIR) can be improved 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.

eICIC Concept Description

Basic Principle

The basic principle of eICIC is illustrated in Fig. 2 for a scenario with co-channel deployment of macro, pico, and HeNBs. The concept relies on accurate time- and phase-synchronization on

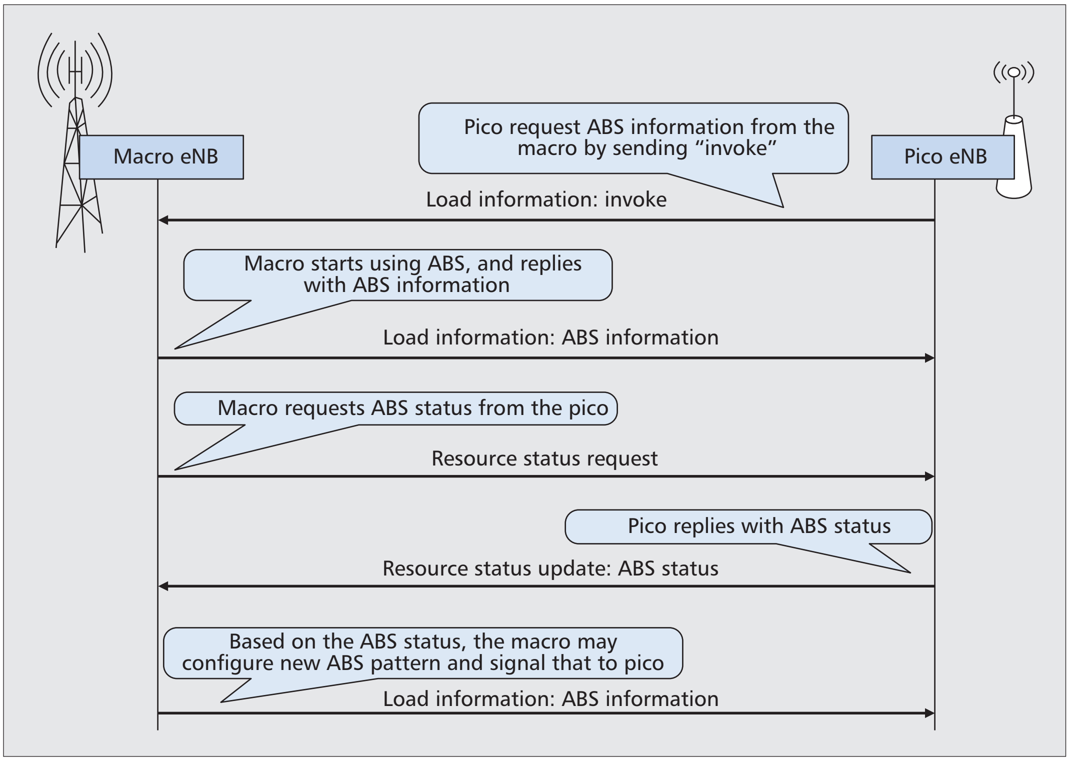

Figure 3. *Example of X2 signaling for distributed coordinated adaptation of ABS muting pattern.*

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.

subframe resolution between all base station nodes within the same geographical area. The duration of one subframe equals 1 ms. 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. Compared to a subframe with normal transmission, the average transmission power from an ABS is therefore often reduced by approximately 10 dB, assuming that base stations use two transmit antennas. However, the aforementioned 10 dB reduction of interference from ABS can in some cases still result in interference problems. 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 [8]. During subframes where CSG HeNBs use ABS, macro-UEs in the close vicinity can therefore still be served, which would otherwise experience too high interference during time-periods with normal subframe transmission from the CSG HeNBs. Similarly, during subframes where the macro-layer uses ABS, there is less interference generated for users served by pico and HeNB nodes. This implies that pico and HeNB are 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. But, as will be discussed in more details later, the number of subframes configured as ABS needs to be carefully chosen to maximize the overall system performance, as using ABS at macro also has negative consequences in terms of lost macro-layer capacity. Similar problems also exist when using ABS at HeNBs.

In order to gain from TDM 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. As an example, 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. Similarly, a macro-UE close to a non-allowed CSG HeNB[1] (i.e. located in HeNBs dominance area) shall only be scheduled during the subframes where the HeNB uses ABS. Other macro-UEs not subject to severe interference from non-allowed CSG HeNBs are schedulable in all other subframes not configured as ABS at the macro eNB.

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,

[1] A non-allowed CSG HeNB refers to a cell where the UE does not have a matching CSG identity in its white list, which means that the UE is not authorized to connect to the cell.

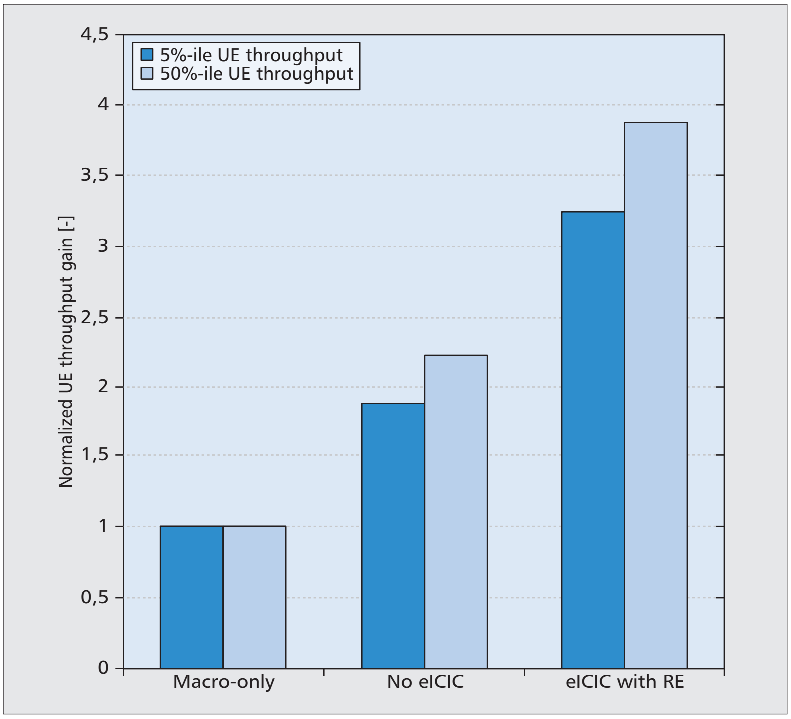

Figure 4. *Relative user-throughput performance gain of deploying pico eNBs with/without eICIC for full buffer traffic.*

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 the same ABS muting pattern. That is, clusters of HeNBs within the same geographical area are suggested to be configured with either the same or at least overlapping ABS muting patterns. Due to the architecture characteristics of HeNBs, it is assumed in Rel-10 that the ABS muting pattern for such nodes is semi-statically configured from the network management system.

For other base station types such as macro 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 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. As illustrated in Fig. 2, it is the macro eNBs that are expected to use ABS for such a scenario. The macro is assumed to act as the master, and therefore the eNB deciding which subframes it wants to configure as 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 mutting 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 can be found in the X2 application protocol specification [9].

In addition to the new Rel-10 X2 signaling for collaborative distributed configuration of ABS muting patterns, the existing X2 signaling supported in Rel-9 (and therefore also in Rel-10) can also be used for eICIC scenarios. Especially the X2 signaling for mobility load balancing (MLB) is considered beneficial for eICIC as it facilitates negotiation of mobility parameter settings such as the RE offset [2].

UE Measurements and Mobility Aspects

The use of ABS muting patterns naturally results in more severe 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[2]) feedback from UEs. It is therefore possible 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. This naturally improves the eNBs possibility of tracking the channel quality fluctuations at the UEs, and thereby conducts more accurate scheduling and link adaptation decisions. Similarly, the network can also configure restrictions for radio resource management measurements such as e.g. reference symbol received quality (RSRQ). The latter can for instance be used for macro-UEs to make more accurate handover to pico, such that the

[2] *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.*

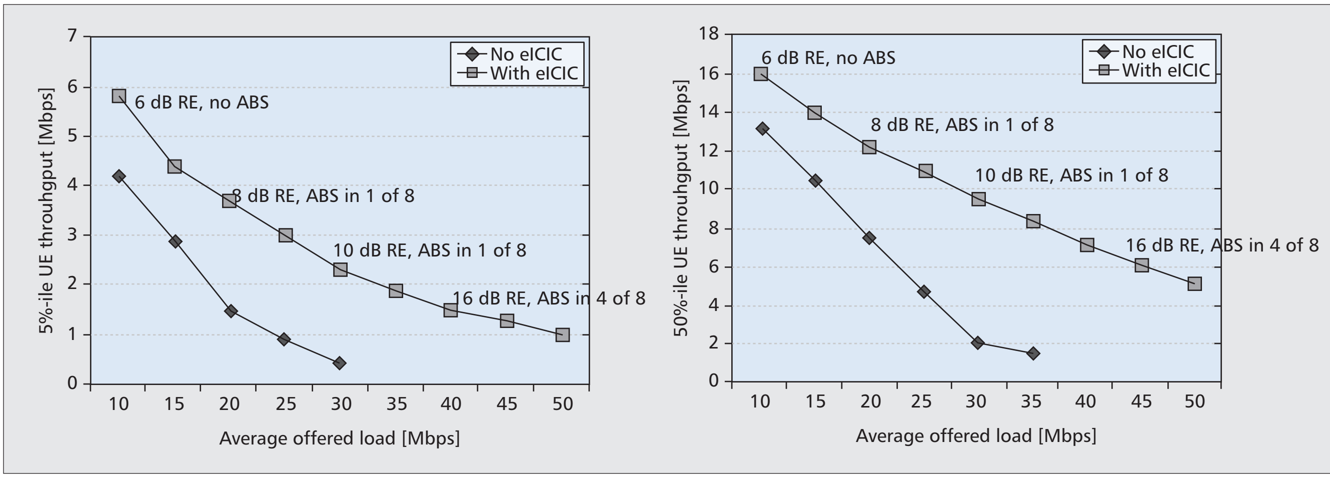

Figure 5. *User-throughput performance with/without eICIC for dynamic traffic versus the average offered load per macro-cell area. The scenario includes 4 picos per macro-cell area.*

RSRQ on the pico is measured only during subframes where the macro is using ABS. Finally, measurement restrictions can also be configured for radio link monitoring (RLM). As an example, configuration of RLM measurement restrictions is useful for macro UEs in the close vicinity of a non-allowed CSG HeNB, so RLM is only conducted when the HeNB uses ABS. Without configuration of RLM measurement restrictions, such macro UEs would risk triggering undesirable radio link failures if RLM includes full interference from HeNBs. All of the aforementioned measurement restrictions for Rel-10 UEs are configured with radio resource control (RRC) messages as specified in [10], and are therefore only applicable for connected mode terminals. Notice that configuration of such measurement restrictions is not supported for LTE legacy Rel-8 and Rel-9 UEs.

PERFORMANCE OF eICIC

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 [11] for hotzone deployment of pico eNBs in macrocells. 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 [11], 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 5th percentile and 50th perentile 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 (IC) of residual interference from ABS such as CRS interference [8]. Finally, all UEs are assumed to support configuration of measurement restrictions for efficient eICIC operation as described in the previous section. More details on UE support for eICIC can be found in [13, 14].

The normalized user-throughput performance is summarized in Fig. 4 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 percent over the pure co-channel deployment scenario. The eICIC results are obtained with 50 percent 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 offloading more UEs to the picos. Without eICIC, only 38 percent of the users are served by the picos, while with eICIC enabled it increases to 78 percent.

The results reported in Fig. 5 show the experienced 5th percentile and 50th percentile user throughput performance versus the average offered traffic per macro cell area, respectively. Those results are obtained for a dynamic traffic model with Poisson call arrival, assuming a finite payload for each call. Once the payload has been successfully delivered to the UE, the call is terminated. 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 signaling for dynamic adaption 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

eICIC benefits	Protect UEs from interference originating from non-allowed CSG cells. Increased offload to 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. The eNB ensures backwards compatibility towards UEs by transmitting necessary control channels and physical signals, as well as System Information.
Time synchronization	Requires strict time synchronization between base station nodes. No mandatory 3GPP time-synchronization requirements for FDD. Several implementation alternatives; e.g. GPS and backhaul based solutions such as IEEE 1588.
ABS muting pattern configuration	Static configuration of ABS muting pattern from management system for HeNBs. Distributed dynamic coordination of ABS muting pattern between macro and pico via standardized X2 signaling.
Network RRM	eNB RRM functions such as the packet scheduler shall ensure that UEs requiring protection from aggressor nodes are only scheduled 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 potentially with reduced performance.

Table 1. *Summary of LTE eICIC benefits, requirements, and characteristics.*

have approximately the same average transmission resource utilization (i.e. measured by average usage of physical resource blocks [9]). At high offered traffic, the gain from applying eICIC is on the order of 80–100 percent for the considered scenario and traffic model.

Although the eICIC performance results presented here are for a scenario with co-channel deployment of macro and pico eNBs, the eICIC scheme also provide benefits for scenarios with HeNBs as discussed earlier. Examples of performance results for macro and HeNBs are reported in [12], where combinations of HeNB power control and eICIC with resource partitioning are studied.

Concluding Remarks

In this article we have motivated the future needs for multi-layer LTE network, consisting of a macro-layer for continuous coverage everywhere, complemented by small cells for hotspot capacity and coverage improvements. However, such multi-layer LTE networks also present a number of challenges that need to be carefully addressed to reach the best possible overall system performance, and thereby ensure maximum value of the investment. Here interference related challenges top the list, so efficient interference management schemes are perceived to be among the key enabling mechanisms for successful co-channel multi-layer deployment. The first LTE-Advanced release (Rel-10) therefore introduces a new eICIC scheme. The eICIC mechanism is designed to solve downlink interference challenges that arise if macro, pico, and HeNB are co-channel deployed. The interference management is essentially facilitated by letting the different base station nodes use ABS in a coordinated manner. For the eNBs interconnected 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 1. Our studies have furthermore shown that the combination of network controlled multi-layer interference management and the use of mobile device architectures that support interference suppression is an attractive combination.

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Biographies

KLAUS INGEMANN PEDERSEN (klaus.pedersen@nsn.com) received his M.Sc. E.E. and Ph.D. degrees in 1996 and 2000 from Aalborg University, Denmark. He is currently with Nokia Siemens Networks in Aalborg, Denmark, where he is working as a senior wireless network specialist. His current work is related to radio resource management and 3GPP standardization of Long Term Evolution (LTE) and LTE-Advanced. The latter includes work on carrier aggregation, heterogeneous networks, mobility, interference management, and system performance assessment. He is the author/co-author of approximately hundred technical publications within wide range topics, as well as inventor on several patents. Have also contributed to books covering topics such as WCDMA, HSPA, LTE, and LTE-Advanced. He was recently appointed part-time professor at Aalborg University in the radio access technology section.

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