Intercell Interference Coordination in OFDMA Networks and in the 3GPP Long Term Evolution System

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Abstract— **Intercell interference coordination (ICIC) in orthogonal frequency division multiple access (OFDMA) networks in general and in the 3GPP Long Term Evolution system in particular has received much attention both from the academia and the standardization communities. Understanding the trade-offs associated with ICIC mechanisms is important, because it helps identify the architecture and protocol support that allows practical systems to realize potential performance gains. In this paper we review some of the recent advances in ICIC research and discuss the assumptions, advantages and limitations of some of the proposed mechanisms. We then proceed to describe the architecture and protocol support for ICIC in the 3GPP LTE system. We make the point that the 3GPP standard is formed in a flexible way such that network operators can employ the most suitable ICIC mechanism tailored to their actual deployment scenario, traffic situation and preferred performance target.**

I. INTRODUCTION

Intercell interference coordination (ICIC) techniques for multi-cell wireless systems including the Global System for Mobile Communications (GSM), Enhanced General Packet Radio Service (EGPRS), Enhanced Data Rates for GSM Evolution (EDGE), and the Universal Terrestrial Radio Access (UTRA) have been the topic of research ever since these systems started to gain popularity. Indeed, a great number of theoretical results as well as many years of practical experience exist; for a comprehensive survey see the classical paper by Katzela and Naghshineh [1]. Recently, the 3^{rd} Generation Partnership Project (3GPP) has been completing most of the technical specifications for the Long Term Evolution (LTE) of third generation cellular systems. The technical targets of LTE include peak data rates in excess of 300 Mbps, delay and latencies of less than 10 ms and manifold gains in spectrum efficiency. Unlike the previous generations, LTE uses orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) as the baseline for modulation and multiple access scheme respectively [2]. In addition to having a new radio interface, LTE is built around a flat architecture in which radio base stations operate in a distributed fashion rather than being controlled by a central entity such as a base station controller or a radio network controller (RNC).

The aggressive performance targets, the new physical layer and the novel flat (”no RNC”) architecture of LTE has triggered a new wave of studies - both within the academia and the industry - for radio resource management in general and interference coordination in particular. An important line of works formulate the ICIC problem as an *optimization task* whose objective is to maximize the multi-cell throughput subject to power constraints, intercell signaling limitations, fairness objectives or minimum bit rate requirements [3], [4], [5]. While optimization models give an insight into the upper bounds of achievable ICIC gains, actually implementing these near optimal mechanisms are typically not feasible or economical in real systems. Indeed, the ICIC mechanisms currently studied by the 3GPP build on markedly lower complexity heuristics. From a system design perspective, ICIC mechanisms without (or with slow) intercell communication - building on some pre-configured (simple) OFDM resource block allocation rule - are particularly attractive.

Along another line, several authors have developed so called *collision models* that analyze the bit/packet error rate and throughput performance of multi-cell systems typically assuming uncoordinated (random or channel dependent) allocation of subcarriers in the different cells of the multi-cell system [6]. The methodology and the numerical results of these papers are useful because they provide insight into the probability and the impact of intercell collisions, but they do not evaluate the usefulness of practical ICIC mechanisms. Therefore, during the standardization process, the 3GPP has extensively studied a range of intuitively appealing and feasible interference coordination algorithms using advanced system simulations [12]. The outcome of these academic and industry efforts are a deep understanding of the tradeoffs coupled with interference coordination techniques, a broad consensus regarding the time scale at which practical ICIC schemes should operate [10] and a flexible support in the LTE standards suite that allows network operators to configure ICIC mechanisms that best suite their specific deployment scenario, traffic load situation and performance targets.

We organize this article as follows. In the next section, we review the fundamentals of intercell interference coordination in the light of recent advances reported in the literature. These basic insights help us to identify the key tradeoffs associated with ICIC mechanisms. In Section III we describe a hybrid ICIC scheme that addresses

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these tradeoffs and manages intercell resources at two time scales and thereby balances between intra- and intercell resource allocation. Next, in Section IV, we describe the 3GPP LTE standards support for ICIC and provide examples on practical interference coordination mechanisms. Some performance results are presented in Section V. Section VI draws conclusions and provides an outlook to LTE Advanced systems.

II. FUNDAMENTALS OF INTERCELL INTERFERENCE COORDINATION IN MULTICELL OFDMA NETWORKS

A. Interplay Between ICIC, Scheduling and Power Control

In OFDMA systems, it is useful to think of intercell interference as a collision between resource blocks illustrated in Figure 1 [6]. In such collision models, the overall system performance is determined by the collision probabilities and the impact of a given collision on the signal-to-interference-and-noise (SINR) ratio associated with the colliding resource blocks. Accordingly, ICIC mechanisms target to reduce the collision probabilities and to mitigate the SINR degradation that such collisions may cause. For instance, neighboring cells may have some cell specific preferences for different subsets of resource blocks, or neighboring cells may employ reduced power for colliding resource blocks.

To understand the potential benefits of such intercell channel and/or power coordination techniques, consider Case A, Case B and Case C of the seven cell system shown in Figure 2. In this system there is a single served user per cell, each being located in the interior (Case A) or in the cell edge area (Case B). In Case C, some of the users are "interior" and some are "exterior". Here we assume that the single served user in each cell is scheduled on all resource blocks, that is all resource blocks in all cells collide with probability 1. Figure 2 illustrates the overall system throughput without/with optimum (intercell) power control in these three cases.

The total system throughput as the function of the ratio of the exterior users is shown in the upper part of the figure. When all users are interior (Case A), there is virtually no gain when employing intercell power control. In contrast, in Case B, there is substantial gain by reducing the power (here illustrating the downlink case) on each resource block. This simple example demonstrates that employing full power in all cells may be suboptimal depending on the user locations.

In more realistic cases, different users are scheduled on different resource blocks in each cell and so the set of colliding resource blocks changes dynamically both in time and frequency.

In order to assess the ICIC potential in this situation, consider the simple experiment depicted in Figure 3. Here we let multiple users to be evenly distributed over the coverage area of a seven-cell system. The scheduler operates in such a manner that at each scheduling instant only one user per cell is selected for transmission. As in the previous case, the one scheduled user transmits on every resource block so that each resource block is constantly colliding in the system. This case thus effectively switches between Case A and Case B of the previous example. In the round robin case users are scheduled independently of their instantaneous channel conditions, while the proportional fair scheduler takes into account the users' channel conditions and their past throughput. In Figure 4 we notice that with proportional fair scheduling, the gain of intercell power control is smaller (compare the 10% complementary distribution function values with "fixed power" and with "power control"). This is because the proportional fair scheduler tries to increase the throughput in each cell by scheduling interior users more frequently (see the table in Figure 4), which limits the potential of intercell power coordination as compared to the round robin scheduler. This result indicates that the ICIC gains depend on the employed scheduler: channel dependent (single cell) scheduling tends to limit the potential benefit of intercell coordination.

B. Key Trade-offs of Intercell Interference Coordination

Both from a theoretical and a standardization perspective a key issue is to determine what information over what time scale should be reported by mobile stations (MS) and what pieces of information should be made available for base stations ("allocation information") either via inter base station communication or by the operation and maintenance (O&M) subsystem such that the overall system (that is the *multi-cell*) performance is optimized (for a summary, see Table 1). This is a nontrivial issue because it needs to address the following trade-offs:

- As we have seen previously, coordination between base stations may increase the overall system throughput at the expense of (possibly too extensive) backhaul communication and intra-node processing. (This trade-off has been discussed in, for instance, [5].)
- Limiting the use of some of the OFDM resource blocks reduces or eliminates intercell collisions at the expense of under-utilizing radio resources and loosing some degree of multi-user diversity in a frequency selective environment. That is, intercell collision avoidance (see for instance [6]) may prohibit the use of subcarriers or resource blocks that are momentarily in good fading conditions.
- Throughput maximization often leads to unfair allocation of resources which in turn may lead to quality-of-service (QoS) violations.

In order to deal with the first trade-off above, it has been proposed to distinguish between two time scales [3], [9]. Resource allocation at the OFDM *frame* level is responsible for allocating resource blocks and power for the duration of the next scheduling interval (being typically at the millisecond level). Thus, the frame is the basic unit for resource handling at the base station level, appropriate for intra-cell scheduling and resource allocation. In contrast, an OFDM *superframe* that consists

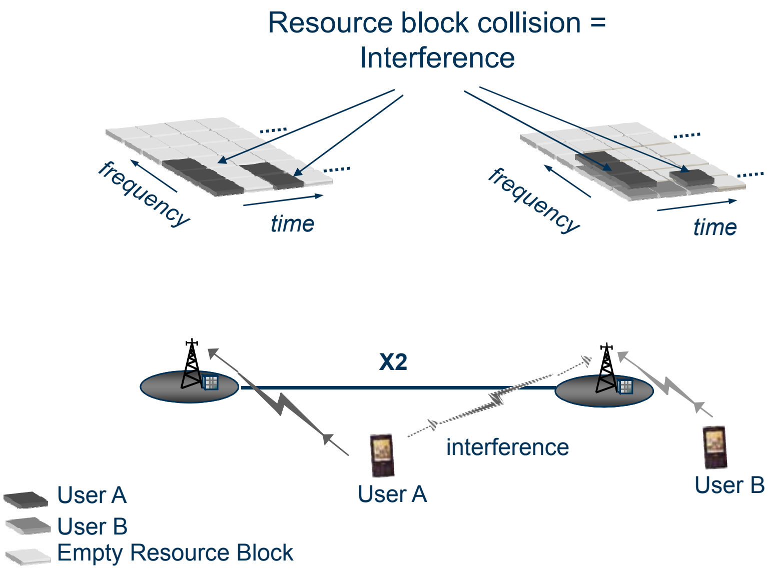


Figure 1. In OFDM, the basic unit for scheduling and resource allocation is a resource block representing a number of subcarriers allocated for a user in the time and frequency domains (upper part). Intercell interference is caused by collisions between resource blocks that are used simultaneously by several cells (lower part).

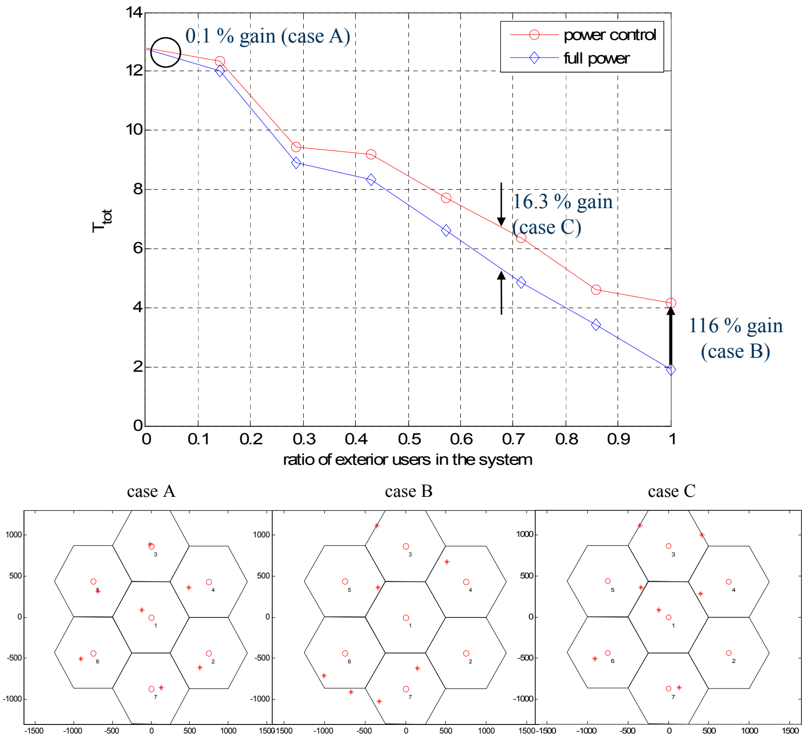
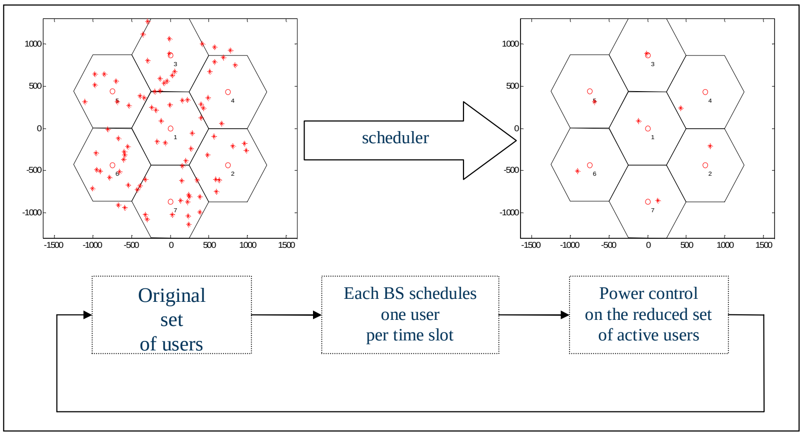


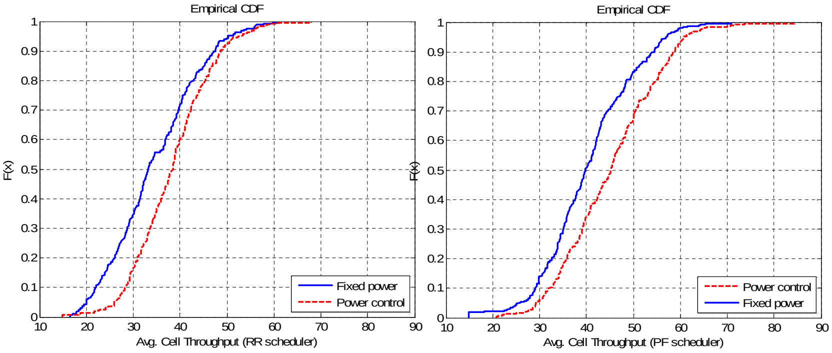
Figure 2. A seven-cell system, in which there is a single user served in every cell. In case A, this single user is close to its serving base station, whereas in Case B, all users are close to the cell edge. Case C is an intermediate situation, in which some users are in the interior of the cell and some are in the exterior area.

of a number of consecutive frames, is appropriate for intercell resource coordination including intercell collision avoidance and intercell power control [10].



Parameter	Value
System Bandwidth	20 MHz
Average number of users per cell	15
Users' mean speed	10 m/s
Handover	Hard handover
Multipath fading	3GPP SCM SuburbanMacro model
Link adaptation	ACM Modulations: BPSK, QPSK, 16QAM, 64QAM Code rates: 0.01-0.99

Figure 3. The same seven-cell system as in Figure 2 but assuming multiple users per cell. In each cell, the scheduler selects a single user for transmission at every time instant (which would be the case, for example, with a round robin or with a proportional fair scheduler). As in the previous figure, throughput optimum power control is employed for the subset of scheduled users in every time instant.



	Scheduling attempts for exteriors	Scheduling attempts for interiors
Round Robin	754	402
Proportional Fair	665	455

Figure 4. The probability distribution function of the total system throughput when employing round robin and proportional fair schedulers without and with intercell power control. Inter-cell power control has much less impact on the cell edge throughput when employing the proportional fair scheduler than with round robin.

The second trade-off can be dealt with by comparing channel state unaware resource block allocation with opportunistic allocation at the base station (frame) level without and with intercell resource block coordination. As we will see, the combination of these two aspects (intercell coordination at the superframe level and opportunistic scheduling at the frame level) gives rise to four different resource allocation strategies. All of them support Reuse-1 frequency allocation, in line with the well established view that static reuse schemes are inferior to dynamic ICIC approaches that allow for the full reuse of the allocated spectrum [3], [2], [10], [11], [15], [16].

Finally, the third aspect (fairness) may be addressed by allowing a minimum and a maximum number of resource blocks (r_{min} and r_{max} respectively) to be associated with each user and requiring that the number of resource blocks allocated to each user must be between these values. This approach leads to formulating a throughput maximization problem such that even the ”most unlucky” users are granted a certain minimum number of resource blocks and thus (assuming the lowest modulation and coding rate) a minimum (in 3GPP parlance: guaranteed) bitrate (GBR) [7].

III. A HYBRID APPROACH TO DEAL WITH SINGLE- AND MULTICELL RRM

The seminal paper by Li and Liu [3] has explicitly addressed the first two above mentioned trade-offs and triggered a number of refinements, such as [7] and most recently [8] addressing the third tradeoff. The Li-Liu scheme focuses on the downlink and operates simultaneously at two different time scales. According to this approach, there is a central algorithm (somewhat unfortunately referred to as the ”radio network controller” (RNC) algorithm explained below) operating at the superframe (tens of milliseconds) level that physically can be implemented as part of a base station utilizing the allocation and MS-reported pieces of information listed in Table 1.

The OFDMA system consists of L base stations (BS) and $M = \sum_{l=1}^{L} M_l$ users, where M_l denotes the number of users that are connected to (served by) BS-l. The BS that serves User-m is denoted by $l(m)$. The long term channel gain between User-m and BS-l is denoted by $G_{m,l}$ (typically available through pilot measurements); these gain values are organized in the matrix $\mathbf{G}$ consisting of M rows and L columns. Let the indicator variable $y_{m,n}$ take the value of 1 whenever RB-n is assigned to User-m and zero otherwise and let $P_{l,n}$ denote the transmission power employed by BS-l on RB-n. The constant noise power on a RB is denoted by σ_{RB}^2. Using these notations, the resource block and power assignments are captured by the matrices $\mathbf{Y}_{M,N} = [y_{m,n}]$ and $\mathbf{P}_{M,N} = [P_{m,n}]$ that determine the long term signal-to-interference-and-noise (SINR) values experienced by User-i on resource block RB-n as follows:

$$\vartheta_{i,n}(\mathbf{Y},\mathbf{P}) = \frac{P_{l(i),n} \cdot G_{i,l(i)}}{\sigma_{RB}^2 + \sum\limits_{l \neq l(i)} \sum\limits_{m \in \mathcal{M}_l} y_{m,n} \cdot P_{l,n} \cdot G_{i,l}},$$

where $\mathcal{M}_l$ is the set of users served by BS-l.

Since the system employs adaptive modulation and coding that is characterized by the link adaptation function f_{LA} such that the average number of bits transmitted for User-i on RB-n (during the period of a superframe) can be expressed by $T_{i,n} = f_{LA}\big(\vartheta_{i,n}(\mathbf{Y},\mathbf{P})\big)$. The f_{LA} function can be derived from an (assumed given) function that maps the SINR of a symbol to the number of bits carried by that symbol making use of the notion of the effective SNR. Thus, the total number of bits carried over RB-n in the multi-cell system is:

$$T_n(\mathbf{Y},\mathbf{P}) = \sum_{i=1}^{M} y_{i,n} \cdot T_{i,n}.$$

The resource assignment problem at the superframe level can now be formulated as finding the $\mathbf{Y}$ and $\mathbf{P}$ matrices such that the overall multi-cell throughput is maximized. The key characteristics of the superframe level throughput maximization problem is that it does not require the instantaneous channel conditions as an input variable. This is advantageous from a system design perspective, since it does not require inter base station communication at the frame level.

Once $\mathbf{Y}$ and $\mathbf{P}$ are available and assuming that the instantaneous *single cell* channel conditions are available (through *channel quality indicator* (CQI) reporting) at the frame level, it is possible to take advantage of multi-user frequency diversity. Let $h_{m,n}$ denote the instantaneous channel gain (including fast fading) between User-m and BS-$l(m)$ on RB-n. Then, when RB-n is assigned to User-i (where n is allowed by the superframe level assignment), the number of bits transmitted on that RB becomes $T'_{i,n} = f_{LA}(\gamma_{i,n})$, where

$$\gamma_{i,n} = \frac{P_{l(i),n} \cdot h_{i,n}}{\sigma_{RB}^2 + \sum\limits_{l \neq l(i)} \sum\limits_{m \in \mathcal{M}_l} y_{m,n} \cdot P_{l,n} \cdot G_{i,l}}.$$

To gain some insight into these trade-offs consider Figure 5. This figure shows the average cell throughput in a seven cell system as the function of the total bandwidth occupancy for four different intercell coordination schemes. The lower two curves correspond to the case in which the base stations do not make use of instantaneous channel conditions (”RNC” and ”Random”). For ”RNC”, the superframe level radio network controller algorithm has been employed, while for ”Random” there is no intercell coordination. The upper two curves (”RNC+BS” and ”BSunc”) are obtained when the base stations schedule users who are in favorable channel conditions (opportunistic scheduling). Again, the ”RNC+BS” curve corresponds to the case in which a superframe level ICIC is employed, while there is no coordination in the ”BSunc” case. The gap between these curves gives us an indication on the opportunistic scheduling gain as the function of the channel occupancy. The uppermost curve is obtained by coordinating resource block and power allocation between cells using the so called ”radio network controller” (RNC) algorithm proposed by [3] and [7].

IV. STANDARDS SUPPORT FOR ICIC IN 3GPP LTE

It is important to realize that virtually any type of RRM algorithm, including ICIC algorithms are out of the scope of the standards. The 3GPP LTE Release 8 standard has been developed such that it supports configuring a wide range of interference coordination approaches while it allows for virtually any type of scheduler operation, including channel state dependent (opportunistic) schedulers. In this section we briefly describe the protocol support that the LTE standards include and discuss some example that can be realized making use of the standards support.

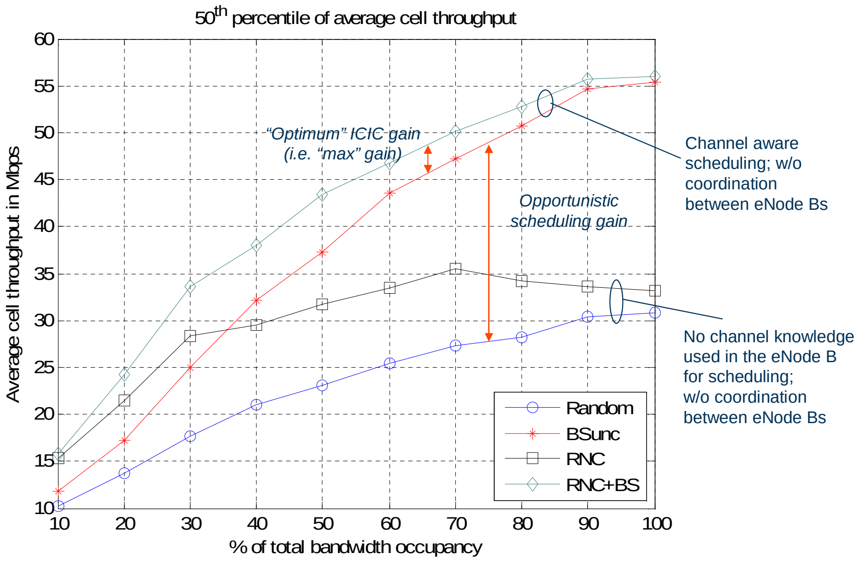


Figure 5. Average cell throughput in a seven cell system under four resource allocation strategies. Under "Random" allocation, there is no intercell interference coordination and the base stations do not make use of channel state knowledge in their scheduling decisions. "RNC" uses intercell coordination at the superframe level (still assuming channel unaware scheduling at the base station level). "BSunc" uses opportunistic scheduling, but no RNC algorithm. Finally, "RNC+BS" uses both the RNC algorithm and channel dependent scheduling.

ICIC Technique	**Allocation Information**	**Reported Information by Mobile Station**	**ICIC Time Scale**
Static Planning	P_{max}, U_{max}	None	$>$ Days
Self Configured	P_{max}, U_{max}	I_{nc}	Days
Adaptive to Cell Load	P_{max}, U_{max}	L, I_{nc}	Minutes
Adaptive to User Load	$P_{max}^{DL}, P_{max}^{UL}(\mathrm{MS}), U_{max}$	$I_{nc}(\mathrm{MS})$, $T(\mathrm{MS})$	Hundreds of Milliseconds; Seconds
Synchronized Scheduling	$P_{max}^{DL}, P_{max}^{UL}(\mathrm{MS}), U_{max}$	$I_{nc}(\mathrm{MS})$, $T(\mathrm{MS})$	Milliseconds

Figure 6. An overview of ICIC time scales including the information that base stations use for resource allocation (P_max denoting the maximum allowed power on each OFDM resource block and U_{max} denoting the maximum allowed fractional load parameter [1]) and the pieces of information that are reported by mobile stations to base stations (I_{nc} denoting the measured interference power level from neighbor base stations and $T(\mathrm{MS})$ denoting the actual traffic load per mobile station.)

A. *ICIC Time Scales*

For LTE, the critical role of the ICIC time scale has been early recognized, much in line with the tradeoffs discussed in Subsection II-B [10]. Although the LTE specifications do not explicitly prescribe the time scale at which ICIC should operate, agreeing on some basic principles helped to progress standardization in terms of enabling parameters, information elements and measurements.

Table 1 lists the so called *allocation information* and *reported information* associated with ICIC mechanisms that operate on different time scales - ranging from static coordination to fully synchronized intercell scheduling. Allocation information allows base stations to control interference and can be obtained either by inter base station communication or from the operation and maintenance (O&M) subsystem. Reported information refers to measurements either by mobile or base stations. In fact, this framework complemented by the standardized information elements exchanged between LTE base stations over the so called X2 interface (discussed in the next subsection) readily allows to implement hybrid ICIC schemes that operate simultaneously at two different time scales as the one discussed in Section III. For example, for the user load adaptive dynamic coordination operating on the superframe level, the allocation information includes the maximum downlink output power as a function of frequency and time (P_{max}^{DL}), the MS specific maximum uplink output power as a function of frequency (P_{max}^{UL}), and possibly a fractional load parameter [1] that limits the probability with which a specific resource block is taken into use ($U_{max} \leq 1$). The reported (MS specific) information for this case consists of the measured downlink interference level from neighbor cells (I^{DL}), uplink interference levels per MS (strong UL interferers) in neighbor cells (I^{UL}) and MS specific UL traffic load information (T).

B. *Inter Base Station Protocol Support for Proactive and Reactive ICIC Approaches*

In line with what has been discussed in this paper, the basic rationale for intercell interference and power control is to avoid that mobile stations served by neighboring base stations are scheduled on the same resource blocks (i.e. time and frequency resources) with a ”too high” power. Clearly, a key issue is the usage (scheduling) of the same resource blocks (”collisions”) in neighbor cells and the usage of the power level on those resource blocks, so as to avoid overload and thereby to ensure an acceptable uplink SINR level for scheduled mobile stations. Not surprisingly, within the 3GPP it has been a consensus that dynamic (event triggered) schemes are superior to static schemes that would limit the applied power level on a subset of the resource blocks a-priori irrespectively of the momentary usage of the same resource blocks in the neighbor cells.

Intuitively it seems clear that dynamic, event-triggered ICIC approaches can operate either proactively or re-actively depending on how the triggering criteria are defined. Proactive methods avoid harmful collisions by scheduling resource blocks that are either not used by the neighbor cell, or are not sensitive to interferers (e.g. used by interior UEs). In Section 3 we have seen a sophisticated proactive ICIC scheme based on the approach of Li and Liu. In contrast, reactive schemes are triggered by an ”overload” situation , i.e. when there is too much interference on a resource block that is sensitive to such neighbor cell interference (since it is used by an exterior UE).

Rather than promoting either approaches, the 3GPP has decided to provide support for both proactive and reactive schemes and allow equipment vendors and network operators to configure a wide range of (non-standardized) ICIC algorithms. According to the standard, a pro-active *High Interference Indicator (HII)* as well as a reactive *Overload Indicator (OI)* can be exchanged between base stations. The granularity of both indicators is the OFDM resource block, that is the same entity as the basic unit for scheduling [2].

C. Example of ICIC Algorithms Enabled by the Standard

The simplest example supported by the standard is one that does not use inter-BS communication, that is either the HII or the OI [12]. Instead, this simple ICIC scheme uses so called frequency domain *start indices* defined according to a reuse pattern. This cell specific start index designates the resource block in the frequency domain where the scheduler of the given cell starts the allocation. As long as the load in the cell does not exceed its equal share from the frequency band, collisions are avoided.

When the start index based allocation order is combined with the use of the HII indicator it becomes possible to dynamically adjust the start indexes of the cells according to the load variations in the cells. Such a solution has the additional benefit that it does not need to pre-configure the start indexes in a planned manner, e.g., via O&M. In 3GPP parlance, the HII indicator can be used to signal the start index and the length of the “protected band”, where neighbor cells allocate their own bands such that collisions are avoided as much as possible.

The algorithm can be further enhanced by the use of the OI indicator in cases when the collisions of neighbor cell resource allocations are inevitable, either due to the high load or due to the sub-optimality of the start index selection of the cells. Obviously, it is hard to expect from a distributed start index selection mechanism to avoid any overlaps of the protected bands. The OI can be used as a reactive complement of coordination handling the situation in which the proactive scheme has failed to select perfectly non overlapping protected bands. The OI can also be used to request neighbor cells to refrain from scheduling UEs detected causing high interference in a given band (e.g., in the overlapping region). It can be set as a rule that as long as the cell receiving the OI request uses resource blocks above its fair share, it should always obey the OI request from its neighbors.

V. PERFORMANCE RESULTS

A. Simulation Environment

For simulations we use a system level simulator, which implements detailed channel propagation models as well as higher layer link protocols and functions, such as HARQ, ARQ, link adaptation and scheduling. Network layer protocols such as TCP/IP are also implemented. The channel propagation models are according to the ones defined by the 3GPP channel models from which we use the typical urban channel [17].

The scheduler selects users according to a weight function such that the channel quality and the QoS metrics are weighed depending on the parametrization of the algorithm. This parametrization takes into account service specific QoS requirements, such as the current delay of voice packets and the past throughput for TCP/IP users. The scheduler takes into account the QoS metric and the channel quality with equal weights.

Once the scheduler has selected the UE(s) and their assigned Resource Block(s) (RB) for uplink transmission in the subsequent TTI, the link adaptation selects modulation (QPSK, 16QAM, 64QAM) and coding rate. It *estimates* the (expected) interference on the scheduled RB(s) in the subsequent TTI, based on measured interference in past TTI(s). Subsequently, it allocates power on the RBs such that a target SINR is reached. The target SINR is set such that a given Block Error Rate (BLER) is reached (0.1) assuming the highest candidate modulation and coding rate. If the target SINR cannot be reached due to lack of power, then the SINR achieved with the maximum power is used and the modulation and coding rate is scaled down accordingly.

B. Numerical Results and Discussion

In Figure 7 we show results from system simulations using the simulation environment described above. As it can be seen on the first graph (a) the measured cell edge throughput of narrowband, “circuit switched” like users shows significant gains with ICIC algorithms with gains up to 50-60%. It is also worth noting that the

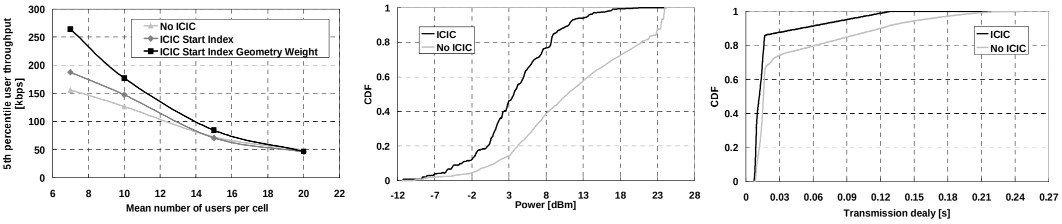


Figure 7. Cell edge throughput (a) shown for "circuit switched" like narrowband users, packet delay (b) and UE power consumption (c) shown for "packet switched", "TCP" like users. The "No-ICIC" algorithm uses no coordination at all, the "Start index" algorithm uses the pre-configured start indexes to start the allocations from, the "Start index - Geometry Weight" starts the allocation with the most exterior user first.

largest throughput gains are achieved when the path gain "geometry" of the UE, i.e., the UE path gain relation to the own cell vs. the neighbor cell is taken into account in the allocation order. In the case of the *"Start index - Geometry Weight"* algorithm each cell starts the allocation with the most exterior user and thereby ensures that the most harmful collisions (i.e., exterior-exterior collisions) are avoided as much as possible.

For packet switched, TCP like traffic it is not the throughput gains that are the most visible (not even shown in the figure), but rather the gains in delay and UE power consumption. The primary reason for the throughput gains to vanish for packet switched, "TCP" like users is the burstiness of such traffic, where the traffic flow is interleaved with random idle periods. Such idle periods create the opportunity to regain the lost bandwidth due to potential collisions by scheduling further resource blocks to users. Such retransmissions - although increase the delay of the packet and the UE power consumption - typically do not impact the carried number of useful bits, i.e., the throughput. This is opposed to "circuit switched" like traffic for which the scheduler is assumed to assign a periodically recurring set of resource blocks, matching e.g., the periodicity and the average data rate of voice traffic. In such cases the bandwidth lost due to a collision cannot be compensated by scheduling extra resources.

VI. CONCLUSIONS AND OUTLOOK

In this paper we took a look at the potential of intercell interference coordination in terms of the throughput, delay and mobile station energy consumption gains that are theoretically possible by using multi-cell power control and multi-cell scheduling in wireless cellular systems. As such high speed wireless networks are being standardized and deployed today, the standardization community has examined and discussed what ICIC mechanisms should be supported in commercial systems. While some ICIC schemes benefit from standardized light-weight intercell communication protocols, ICIC algorithms are typically not subject to standardization. Examples on feasible ICIC mechanisms include pro-active schemes that can operate without or with inter-cell communication.

As Multiple-input multiple-output (MIMO) systems are being commercially deployed, the research community started exploring the potential of ICIC for MIMO cellular systems. While a large amount of works on MIMO cellular systems focused on capacity analysis and receiver design for interference mitigation, much less work has reported results on the usefulness of multi-cell MIMO power control. This first results from [13] indicate that adaptive multi-cell power control techniques can increase the uplink throughput of multi-cell MIMO systems, but it is still an open question whether such schemes will be feasible and economical in real systems. Likewise, multi-cell scheduling and joint power control and scheduling in MIMO cellular systems is a natural candidate for the evolution of ICIC [14], but it remains to be seen whether such solutions will be commercially successful.

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