Improving the Interplay between Periodic Channel State Information Feedback and Static Intercell Interference Coordination in LTE.

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Abstract— **In the context of OFDMA-based cellular networks, Intercell Interference Coordination has been recognized as a key concept to achieve seamless levels of Quality of Service. This is especially true in scenarios where dense reuse of spectrum is pursued. In practice, *static* intercell interference coordination techniques (soft- and fractional-frequency reuse) enjoy acceptance among mobile operators due to their natural compatibility with current standards (LTE, LTE-A). In this article, an improved *periodic channel state information feedback* scheme suitable to work in conjunction with static ICIC techniques is presented. In the proposed solution, mobile terminals report sequentially and periodically the quality of bandwidth portions over which they are allowed to be transmitted according to the selected ICIC strategy policies. By doing this, not only the signaling overhead is limited but also a better view of users' channel is provided to the scheduler. Thus, the proposed strategy is simple, feasible and easy-to-implement. Simulations results show that gains in terms of system capacity are achieved with respect to existing LTE-based mechanisms without additional complexity.**

Index Terms— **Long Term Evolution, LTE, Intercell Interference Coordination, ICIC, Channel State Information, CSI, Joint System Capacity.**

I. Introduction

The demand for new and attractive services in wireless environments is currently growing faster than ever. Especially in the wireless communications arena, services and applications are increasingly requiring rigid Quality of Service (QoS) levels. Today, there is consensus that Long Term Evolution (LTE) [1], and WiMAX [2] are the technologies expected to establish a worldwide dominance in a short term. On the other hand, LTE-Advanced (LTE-A) (the evolution of LTE) is the 3rd Generation Partnership Project (3GPP) proposal for the International Telecommunications Union (ITU) International Mobile Telecommunications-Advanced (IMT-A) systems [3], [4], i.e. 4G systems.

LTE, LTE-A and WiMAX employ Orthogonal Frequency Division Multiple Access (OFDMA) as access technology for the downlink [5] mainly due to its flexibility for resource allocation and because OFDMA provides intrinsic orthogonality to user equipments (UEs), which translates into an almost null level of *intracell* interference. However, with a low frequency reuse factor (ideally 1), cell edge users are especially susceptible to the effects of *intercell* interference and therefore, their radio channel quality in terms of Signal to Interference plus Noise Ratio (SINR) are much worst than the ones experienced by users close to base stations. Thus, unless more resources are assigned to them, the QoS remarkably depends on users position which yields to the well known tradeoff between *fairness* and *efficiency* [6].

To the light of this situation, Intercell Interference Coordination (ICIC) techniques have been recognized as key enablers of current cellular technologies [7]–[10]. Broadly speaking, the main target of any ICIC strategy is to determine what resources (bandwidth and power) are available at each cell at any time in order to improve fairness among users. Several descriptions of ICIC techniques can be found in [11]–[13] along with different performance assessments [6], [14]. According to the temporality in which resource allocation is performed, ICIC strategies can be group into *static* and *dynamic* schemes. Although dynamic proposals [15]–[18] feature the advantage of adaptability to changing network conditions, they typically assume detailed channel knowledge (both in time and frequency) which limits their value from a practical perspective. In addition to this, both complexity and signaling overhead are usually restrictive. Therefore, nowadays mobile operators prefer static ICIC strategies (Soft Frequency Reuse (SFR) [19] and Fractional Frequency Reuse (FFR) [20]) to deal with intercell interference due to their inherent ease of implementation and that require none or little intercell communication.

In this work, both the feasibility of static ICIC strategies and limitations of LTE's Channel State Information (CSI) feedback mechanisms [21], [22] are jointly considered. In LTE, CSI feedback is the process by which mobile terminals inform to their serving base stations the radio channel quality of either any particular subband or the whole system bandwidth. Therefore, the novel CSI feedback strategy proposed in this paper aims at improving the Block Error Rate (BLER) and hence system performance. The proposed mechanism takes advantage

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of the typical *per-class* bandwidth allocation pattern used in SFR and FFR. The term *per-class* refers to the fact that static ICIC strategies rely on classifying users into different classes according to the average radio channel quality.

To be precise, in the proposed solution UEs only feed back to their serving base stations the quality of specific subbands over which they are allowed to be transmitted (according to the policies of the selected ICIC scheme). However, and in order to limit the signaling overhead, the quality of each of these subbands is reported sequentially i.e. one by one periodically at each reporting interval. Thus, the proposed solution falls into the category of **periodic CSI feedback schemes**. No additional capability is required at UEs and only a very small amount of information needs to be transmitted (occasionally) in the downlink. A detailed explanation of the proposed mechanism is presented in Subsection IV-B. Since there are not contributions explicitly designed to operate in conjunction with static ICIC strategies in an efficient manner, the performance comparison presented herein considers the proposed scheme and existing LTE ones in order to highlight the validity and usefulness of this proposal.

The rest of the article is organized as follows: Section II introduces some practical elements of intercell interference mitigation together with a review of related contributions. Section III provides a detailed description of the system model and methodology followed in this work. A description of both static ICIC schemes and CSI feedback mechanisms is presented in Section IV. Once reached at this point, the mathematical formulation is introduced in Section V. Finally, Sections VI and VII close the article with performance evaluations and conclusions respectively.

II. Background and Related Work

In this section, some practical elements related to the problem of interference mitigation in OFDMA networks are discussed. In addition, the need for efficient/feasible CSI feedback schemes is also remarked to the light of related contributions presented here.

A. Background

As it was commented earlier, the downlink of LTE and LTE-A is based on OFDMA, being the capacity of these systems mainly *interference limited*. To be precise, the capacity in terms of throughput depends strongly on the amount of interference coming from neighboring cells. Thus, the channel quality is expressed in terms of the SINR which in its general form can be written as follows:

$$\gamma = \frac{S}{\eta + I} \tag{1}$$

where S represents the useful signal power and η and I correspond to the background noise and interference power respectively. In general, η can be considered constant and in case of interference-limited systems, could be even considered negligible.

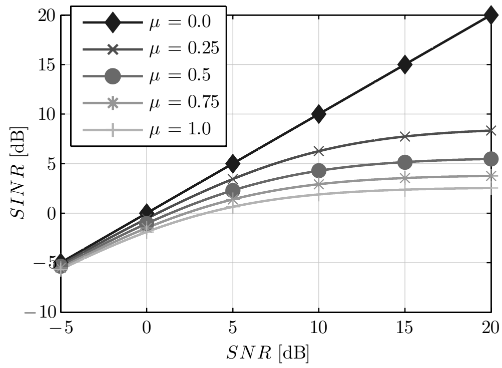


Figure 1. γ versus SNR (SIR_{min}=2.62dB)

The first fundamental problem appears because I is highly *non-predictable* due to time-varying transmission properties at neighbor cells as **traffic patterns are very bursty** in multiservice contexts. Similarly, tracking CSI in wideband channels is also difficult due to the effect of frequency selective fading and hence, obtaining accurate/updated channel quality estimations is quite challenging (even for moderate mobility scenarios). For this reason, the performance of the proposed CSI feedback scheme is evaluated considering real traffic patterns. To put this into perspective, consider the relationship between the SINR and the amount of interference I coming from M interferer cells as follows:

$$I = \sum_{m=0}^{M-1} \mu_m I_m^{\text{max}} \tag{2}$$

where I_m^{max} is the maximum interference coming from cell m (fixed and maximum power is assumed at neighbor cells) and μ_m is the activity factor of the m^{th} cell. The activity factor is defined as the fraction of time the cell is active (transmitting), i.e. $\mu \in [0, 1]$. Then, assuming that (a) $I_{\text{max}} = \sum_{m=0}^{M-1} I_m^{\text{max}}$ and (b) $\mu_m = \mu \;\; \forall q$, Equation 1 can be expressed in the following manner:

$$\gamma = \frac{S}{\eta + I} = \frac{S}{\eta + \mu I_{\text{max}}} = \frac{1}{\frac{\mu}{SIR_{\text{min}}} + \frac{1}{SNR}} \tag{3}$$

It is important to notice that all quantities are average values (over small-scale fading of S and I) and that SIR_{min} depends on network geometry and is (in practice) determined from system level simulations or *in-field* measurements. Figure 1 shows the relationship between γ and the Signal-to-Noise Ratio (SNR) for different values of μ. Clearly, $\gamma < \mu^{-1} SIR_{\text{min}}$ and $\gamma < SNR$ always hold. Thus, without ICIC, throughput is limited by intercell interference. It can be seen that even for small values of activity factor, the SINR (and hence the cell edge throughput) will be saturated into $\mu^{-1} SIR_{\text{min}}$. The second issue is related to the fact that SINR levels (and hence QoS) **are not uniformly distributed over network coverage area**. While large and small scale fading affect users in the same manner (in average),

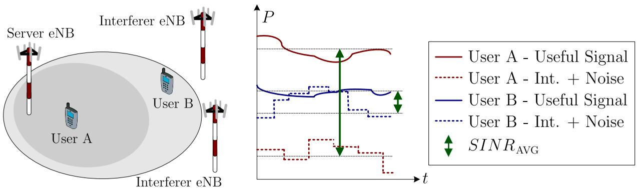


Figure 2. Main issues associated to interference control.

propagation losses are exponentially proportional to the distance to transmitters. This clearly results in a **cell edge performance degradation** (from system's perspective) and its corresponding fairness penalty (from users' point of view). Figure 2 illustrates these ideas.

Finally, a third important issue comes from a practical limitation existing in real networks. In LTE, CSI is expressed in terms of Channel Quality Indicators (CQIs) that are indexes[1] providing estimates of channel quality. Ideally, in order to account with intercell interference, the SINR at subcarrier level should be known at the evolved NodeB[2] (eNB), this can be written as follows:

$$\gamma_m^{n,sc} = \frac{P_{\hat{l},n} \cdot g_{m,\hat{l}}^{n,sc}}{(B_{\text{PRB}} \cdot N_0) + \sum\limits_{\substack{l=0 \\ l \neq \hat{l}}}^{L-1} P_{l,n} \cdot g_{m,l}^{n,sc}} \tag{4}$$

where the terms $P_{l,n}$ and $g_{m,l}^{n,sc}$ represent the power transmitted by eNB l in Physical Resource Block (PRB) n and channel gain of user m (for subcarrier sc within PRB n) with respect to eNB of cell l respectively. In LTE, a PRB is the most basic unit of transmission in frequency domain and it is composed by 12 subcarriers [23]. $\hat{l}$ corresponds to the serving cell index of user m and B_{PRB} is the bandwidth of a PRB. N_0 and L are the power spectral density of the background noise and the total number of cells in the system respectively. Equation 4 is a more detailed form of Equation 1 expressing SINR at subcarrier level[3]. Obviously, transmitting this information through the air interface is prohibitive both for the amount of signaling overhead and complexity. Thus, in LTE, CQIs are important means by which CSI is reported to eNBs. Nevertheless, there two main issues around CQIs and practical CSI feedback schemes: (1) the granularity in frequency domain and (2) the validity in time domain. Therefore, LTE has to deal with the fact that very often, CQIs reflect *rough and outdated estimates* of the actual quality at PRB level. Because of this, a deeper insight about the impact of CSI feedback schemes on system capacity is provided in this work.

[1]A CQI is a number ranging from 0 to 15 that refers to specific modulation and code rate combinations; see Section 7.2.3 in [21] for details.

[2]The Evolved-UMTS Terrestrial Radio Access Network (E-UTRAN) architecture is composed of only one logical node: the evolved NodeB. The term has been introduced in LTE to indicate that additional functionalities have been placed in the eNB compared to the functionality of the NodeB in WCDMA/HSPA.

[3]LTE physical layer details can be found in [23] and references therein.

B. Related work

In this section, a survey of relevant contributions addressing the issue of limited CSI feedback (coming from both academia and industry) is presented.

There are two different mechanisms to perform CSI feedback in LTE: *Periodic* and *Aperiodic* schemes [21].

1) Periodic CSI feedback: The UE reports channel quality *periodically* every certain interval that is configured by the higher layer on the Physical Uplink Control Channel (PUCCH).
2) Aperiodic CSI feedback: The feedback is performed *on-demand* by means of the Physical Uplink Shared Channel (PUSCH).

On the one hand, periodic CSI feedback is recommended for traffic patterns having constant or near constant bit rate such as conversational or streaming services. On the other hand, aperiodic CSI feedback is more appropriate for bursty traffic patterns in which a more detailed reporting is needed (from time to time). It is worth noting that both types of reporting can be used together. In such cases, the UE will only transmit the aperiodic report and ignore the periodic one corresponding to that instant. **This paper focuses on periodic reporting**. However, some aperiodic proposals are included and briefly commented in this survey given the interest of some common features with periodic schemes. The authors have considered that by doing this, a better view of potential research opportunities can be identified and exploited in the solution proposed herein.

Aspects related to limited CSI feedback has been matter of discussion and debate within 3GPP meetings in the last few years. Interesting ideas/mechanisms have been proposed. For instance, in [24], a mechanism for scheduling request based on CQI was proposed taking advantage of the CQI reporting periodicity. The notion of *frequency localized scheduling* was initially proposed in [25]. The proposed incremental CQI feedback scheme was suitable for situations where constant bit rate of the channel feedback and adjustable granularity were required. Right after the previous contribution, a more complete analysis of the tradeoff between CQI reports per PRB versus groups of PRBs was submitted by Nokia in [26]. Nevertheless, the potential impact on realistic traffic patterns was not considered in any case. Finally, practical LTE aspects related to CQI reporting mode, differential CQI definition and CQI measurement methodology can be found in [27], [28] and [29] respectively.

The impact of CSI feedback mechanisms on performance of OFDMA networks has been also addressed by the research community. One of the first works devoted to study this topic was introduced by Su *et al.* in [30]. In this contribution, the authors proposed a scheme in which only CQIs for subbands with good channel quality are selected to be reported. A good analysis of the signaling overhead is also presented. However, this scheme does not take into account a possible bandwidth classification typically used in ICIC strategies. In addition, reporting only the best subband could not always be the best option since

TABLE I.
SUMMARY OF RELATED WORK

Ref.	ICIC scheme	Partial CSI CQI feedback	Overhead analysis	LTE aspects	Research methodology	Context	Contribution
[24]	×	✓	✓	✓	Simulations	3GPP	CQI-based scheduling
[25]	×	✓	×	✓	Simulations	3GPP	Frequency localized scheduling
[26]	×	✓	×	✓	Simulations	3GPP	Time-Frequency reporting granularity
[27]	×	✓	×	✓	n/a	3GPP	LTE: CQI reporting procedures
[28]	×	✓	×	✓	Simulations	3GPP	LTE: Differential CQI definition
[29]	×	✓	×	✓	Simulations	3GPP	CQI measurement methods
[30]	×	✓	✓	✓	Simulations	PIC	A subband-based CQI reporting scheme
[31]	✓	Partially	×	✓	Simulations	PIC	ICIC for fractional load scenarios in LTE
[32]	Partially	✓	Partially	✓	Both	PIC	RRA in OFDMA with limited CSI
[33]	×	✓	×	✓	Both	PIC	Limited CSI + Traffic prioritization
[34]	×	✓	n/a	✓	Analytical	PIC	Subband level CQI reporting analysis
[35]	✓	✓	×	×	Simulations	PIC	Limited CSI in a FFR-based scheme
[36]	×	✓	×	✓	Simulations	PIC	Study of CSI reporting rate/delay

PIC: In Proceedings of an International Conference.
RRA: Radio Resource Allocation.

provides no information about the rest of the band to the scheduler for potentially long periods of time.

Another interesting work is the one presented by Kumar *et al.* in [31] where a set of heuristic strategies are suggested to achieve low complexity interference management taking into account many LTE aspects such *as averaged CQI* (per user) and effective SINR. Time and frequency domain scheduling interplay is also discussed. Four different algorithms were compared and the trade-off between cell throughput and coverage was studied. Besides numerical results, the main contribution of this work is that provides efficient mechanisms for intercell interference avoidance under fractional load conditions without need for dedicated signaling. Moreover, this is one of the first contributions considering realistic CSI feedback mechanisms in the context of ICIC. Nevertheless, overhead analysis and LTE implementation issues are just partially discussed.

In [32], authors presented a reduced feedback strategy based on the idea that only a small part of users would report complete channel state information. Nevertheless, the format in which such information should be sent was not addressed. To limit signaling overhead, a reduced feedback scheme was investigated. In the opportunistic base station selection algorithm, only one base station is allowed to be active on each tone (or resource block), and therefore, only one channel quality measurement per tone has to be fed back by each user. The scheme reduces significantly the signaling overhead at a expense of very small performance degradation.

Also interesting is the proposal presented by Xue *et al.* in [33]. The authors presented a *modified top M* mechanism for limited CSI feedback based on CQIs as specified in [37] that assigns different priorities based on traffic classes. Although the work presented by Xue *et al.* is very interesting from a practical point of view, additional elements could be improved. For instance, the system model is quite small, in fact, the mechanism is tested in a single cell scenario (one hexagonal cell and six surrounding ones) which can be arguable from the ICIC standpoint. At least two tiers of surrounding cells are recommended in any case. It is important to stress that *top M*-based schemes are indicated by LTE specifications to operate in aperiodic mode and hence the evaluation of this kind of mechanisms is out of the scope herein.

Recently, Donthi *et al.* [34] showed that the coarse frequency granularity of a subband incurs a significant loss in system throughput. By means of an analytical treatment, the authors obtained a closed form expressions for the downlink throughput. Thus, this work also represents an important contribution from the theoretical point of view.

An interesting work was presented by Chen and Yuan to address the problematic of bandwidth allocation for cell edges [35]. In this case, a planning-like algorithm designed to compute optimal FFR allocations was introduced. In this work, limited CSI feedback is considered partially.

Finally, a recent work in which the impact of CSI feedback rate (for aperiodic schemes) on the scheduling of video streaming can be found in [36]. Aperiodic CQI reporting schemes provide more precise description of the users' channel, nevertheless, this is at expense of additional signaling overhead and complexity [1]. The work presented in this article differs from [36] in that Basukala *et al.* assume no error in CQI estimation.

Bearing the previous in mind, Table I shows a summary of these contributions. As it can be seen, only few works address (partially) the interplay between CSI feedback and static ICIC techniques **but none of them consider it explicitly** and hence the performance comparison in Section VI focuses on the proposal presented here (which is unique in this sense) and existing LTE-defined mechanisms. In summary, the work presented in this paper differs from previous ones mainly in that:

1) The periodic CSI feedback mechanism presented here has been specifically designed to operate in conjunction with static ICIC strategies and its feasibility is also demonstrated by showing that: (a) the required signaling overhead is quite similar to practical mechanisms already available in LTE and,

(b) only a small functionality needs to be added. Details about the implementability and feasibility of the proposed solution can be found in Subsection IV-B.

2) In this paper, the analysis of several elements that **have not been considered all together** before is also presented. In particular, the impact of CSI feedback mechanisms on the ratio of satisfied users has been studied. In this sense, numerical evaluations have considered different types of traffic flows (controlled by a QoS oriented scheduler) subject to different static ICIC strategies.

III. System Model and Methodology

In this work, the downlink of an OFDMA-based cellular network that largely follows the LTE specifications is considered. References to specific 3GPP documents are indicated in the following subsections together with a detailed description of the overall setting.

A. Simulation scenario

The cellular layout corresponds to an urban and macrocellular scenario composed by 19 sites (57 tri-sectorial cells) featuring hexagonal/regular geometry. Statistics are collected from the 3 central cells (having two interference tiers) to avoid border effect.

In this work, channel model and users mobility deserve especial attention because the choice of these parameters has an important influence on the performance of CSI feedback mechanisms and hence on results and conclusions.

The mobility model is vehicular for urban scenarios as defined in [38]. However, a pedestrian speed of 3 km/h was selected at this point of the investigation. The channel model is the Extended ITU Pedestrian B defined in [39] which features a 32.55 ns sampling grid that matches the LTE sampling rate of 30.72 MHz. The implementation was done according to [40] considering a temporal resolution of 1 ms equal to the Transmission Time Interval (TTI) in LTE. Additional implementation details are shown in Table II.

TABLE II.
Simulation scenario parameters.

Parameter	Value	
Layout	Hexagonal/Tri.sectorial	
Sites/Cells	19/57	
Sites height	15 m	
Cells power	43 dBm	
UE noise figure	7 dB	
Propagation model	3GPP's Urban macrocellular [42]	
Carrier frequency (f_c)	2.14 GHz	
Shadowing	Based on multiple correlated layers [43]	
	Mean:	0 dB
	Standard deviation:	8 dB
	Sites correlation:	0.5
	Decorrelation distance:	20 m
Channel model	Extended ITU Pedestrian B [39]	
	Temporal resolution:	1 ms
	Frequency resolution:	15 kHz
	Doppler frequency (f_d):	5.94 Hz
	(f_c = 2.14 GHz and v = 3km/h)	
	50% Coherence time:	70 ms
	($T_C^{50\%} = 0.42 \cdot f_d^{-1}$)	
Mobility model	Urban vehicular [38]	
	Users speed:	3 km/h
	Correlation distance:	20 m
	Main angle:	90º
	Change dir. probability:	20%
Antennas	Kathrein 800 10271 Xpol TriSec	
	Gain:	19.33 dBi
	3 dB beam:	65º
	Front-to-back ratio:	$>$ 25 dB

B. Network setting: LTE parameters

For this study, a wideband configuration of LTE has been selected [23], [41]. To be precise, the system has 1200 allocable subcarriers spaced 15 kHz (system bandwidth is 18 MHz). These subcarriers are grouped in N_{PRB} PRBs each of them containing N_{sc} subcarriers. The minimum assignment the scheduler can grant to a user is one single PRB during 1 TTI. The total available power per cell is distributed among the PRBs according to static ICIC strategies. Note that the sum power condition is always kept. Within each TTI, 14 OFDM symbols are transmitted from which $N_{\text{OFDM}}^{\text{Sym}}$ are devoted to data transmission. In this work, N_{PRB} = 100, N_{sc} = 12 and $N_{\text{OFDM}}^{\text{Sym}}$ = 11. Asynchronous Hybrid-Automatic Repeat reQuest (HARQ) with Incremental Redundancy (IR) and a maximum number of 3 re-transmissions is implemented. When Incremental redundancy is applied, each transmission is different than previous ones. This is accomplished by generating different sets of coded bits representing the same set of information bits. Therefore, receiver can obtain certaing gain with every transmission [21]. The minimum retransmission delay is 8 TTIs and a maximum number of 8 parallel HARQ processes per user is assumed. BLER prediction is based on look-up tables obtained from link level simulations following the guidelines in [44]. In this case, BLER performance for each redundancy version (RV) takes into account not only the selected Modulation and Coding Scheme (MCS) but also the transport block size (TBS) [23], [45].

The payload Γ_τ associated to a given HARQ transmission τ, is computed according to the following expression:

$$\Gamma_\tau = f_{\text{p}}(TBS, MCS) = TBS \cdot \eta_i \cdot N_{\text{RE}} \qquad (5)$$

where η_i is the product of the modulation order and code rate of the selected MCS index i [21], [46]. N_{RE} is the number of useful Resource Elements (RE) per PRB. In this work, $N_{\text{RE}} = (N_{\text{sc}} \cdot N_{\text{OFDM}}^{\text{Sym}}) - N_{\text{RS}}$. N_{RS} is the number of Reference Signals (RS) within the $N_{\text{OFDM}}^{\text{Sym}}$ symbols and its value is equal to 6[4].

Finally, *Single-antenna port* transmission mode has been considered in this work. In this mode, one Transport Block (TB) is transmitted on the Physical Downlink

[4]There are 8 RS per PRB, nevertheless the two first are placed in the first OFDM symbol which is devoted to control signaling [23].

TABLE III.
TRAFFIC MODELS PARAMETERS.

Traffic	Parameters/Distributions
HTTP	Main object size: Truncated Lognormal (m: 10710 bytes, σ: 25032 bytes) Embedded object size: Truncated Lognormal (m: 7758 bytes, σ: 126168 bytes) Number of embedded objects: Truncated Pareto (m: 5.64) Reading time: Exponential (m: 30 s) Parsing time: Exponential (m: 0.13 s)
FTP	File size: Truncated Lognormal (m: 2 Mbytes, σ: 0.722 Mbytes) Reading time: Exponential (m: 180 s)
VoIP	AMR voice code rate: 12.2 kbps Activity factor: 50 % Voice packets: 40 bytes every 20 ms Silence packets: 15 bytes every 160 ms

m: mean, σ: standard deviation.

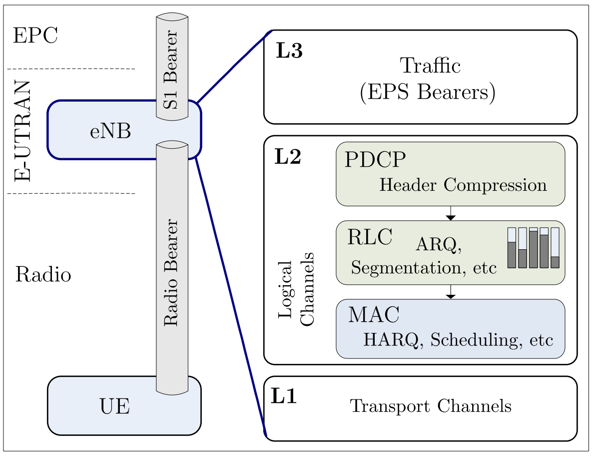


Figure 3. LTE structure/protocols for downlink traffic.

TABLE IV.
CRA SCHEDULER CONFIGURATION.

Parameter	Value
Scheduled users per TTI	$\leq$ 10
VoIP maximum delay	$\leq$ 50 ms
CRA satisfaction period (λ)	1 ms
NRT services target rate (Q_{NRT})	$\geq$ 300 kbps
RT services target ($Q_{\mathrm{RT}} = 1 - BLER$)	$\geq$ 99%

Shared Channel (PDSCH) from a single physical antenna corresponding to antenna port 0 [21], [45].

C. Traffic Models

In this work, three different traffic models are considered: Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP) and Voice over Internet Protocol (VoIP). Traffic models for HTTP (web browsing sessions) and FTP (file transfers) are defined in [41]. The traffic model for VoIP was taken from [3].

Web browsing sessions are divided into ON/OFF periods representing web-page downloads and intermediate reading times, where the web-page downloads are referred to as packet calls. These ON and OFF periods are a result of human interaction. In FTP applications, a session consists of a sequence of file transfers, separated by reading times.

Although a complete description of the traffic models is beyond of the scope of this article, Table III summarizes the main parameters of each of them.

Once traffic traces are generated, segmentation and header addition is applied according to the following protocols: Transmission Control Protocol (TCP), IP, User Datagram Protocol (UDP) and Real-time Transport Protocol (RTP). In particular, Real Time (RT) services (VoIP) and Non-Real Time (NRT) services (HTTP, FTP) are encapsulated using RTP/UDP/IP and TCP/IP respectively [47]. Finally, before traffic is delivered to the Radio Link Control (RLC) layer [48], header compression is performed by the Packet Data Convergence Protocol (PDCP) [49]. Finally, scheduling and priority handling occur at Medium Access Control (MAC) level [50]. These processes are illustrated in Figure 3.

D. Scheduling

The MAC scheduler determines how downlink (and uplink) channels in the LTE air interface are used. The scheduler allocates radio resources in such a way as to satisfy QoS requirements [51] and optimize system performance. MAC scheduler design is not specified by the LTE standard. Different scheduler may result in significantly different levels of users satisfaction and system performance, and hence mobile operators implement *vendor-specific* solutions according to their needs. Therefore, scheduling is a fundamental piece within the overall Radio Resource Management (RRM) framework in which ICIC techniques are also framed. As reference, the important interplay between ICIC and RRM has been formally recognized in [52]–[54]. As it can be seen in Figure 4, within the complex dynamics of an LTE network, none of the elements mentioned above are completely foreign to others. However, the previous depends to a large degree on CSI accuracy. That is why in this work, the focus is on the joint impact of the CSI feedback schemes and static ICIC techniques on the overall system performance from the *joint system capacity* perspective [55], [56].

The scheduler implementation largely corresponds to the *Capacity-driven Resource Allocation* (CRA) scheduler proposed in [57]. The CRA scheduler, dynamically controls the resource sharing among flows of different services such as delay-sensitive and rate demanding ones. Authors in [57] claim that CRA scheduler improves the *joint system capacity*. The joint system capacity is defined as the maximum total offered load in which all provided services fulfill the user satisfaction ratio threshold. Thus, the joint system capacity concept fits perfectly to the research objectives in this work since captures all relevant aspects of multiservice environments such as *per-service* QoS requirements. In addition, it is worth saying that

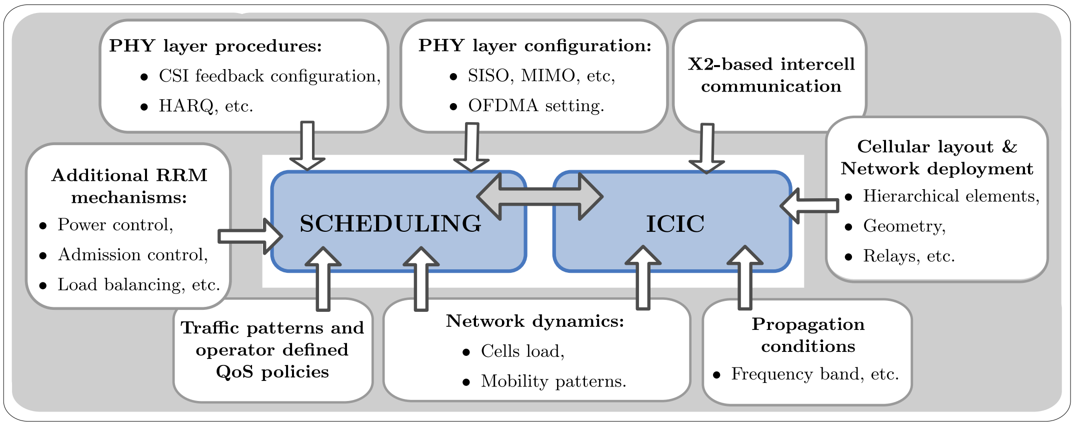


Figure 4. ICIC-Scheduling interdependencies.

the fairness concept is implicitly considered given the clear QoS orientation of this scheduler. Indeed, the CRA scheduler by itself does not apply any restriction to users based on classes (interiors or exteriors) i.e. from the scheduler perspective; all users are required to reach their QoS target. The only constraint comes from the static ICIC strategy which determines how much resources are assigned to each class of users. The operational configuration applied to the CRA scheduler is shown in Table IV.

E. Methodology

As commented previously, the whole setting has been embedded in an LTE system level simulator which is fed by a link level one, both programmed in C++. The evaluation study has been done by means of Monte Carlo simulations. Results were obtained from 500 independent experiments, each one being run for 60 seconds to account with traffic dynamics. Users were always uniform randomly spread.

IV. Static ICIC and CSI Feedback Schemes

In this section, a description of the two central elements of this study (static ICIC techniques and CSI feedback mechanisms) is provided.

A. Static ICIC

Fractional- and Soft- Frequency Reuse schemes were considered. A generic representation of these strategies is depicted in Figure 5. In SFR, intercell interference is also *interclass* because of the assignment of bands among different cells. In order to control the amount of interference received by cell edge users, low power is used in the bands to be used in the central area of the cell. This power is controlled by the parameter α. On the other hand, FFR removes completely the *interclass* interference, i.e. each class has exclusive use of its bandwidth. This is important because the performance in terms of throughput and fairness becomes independent of α since the SINR does not depend on the transmitted power as long as

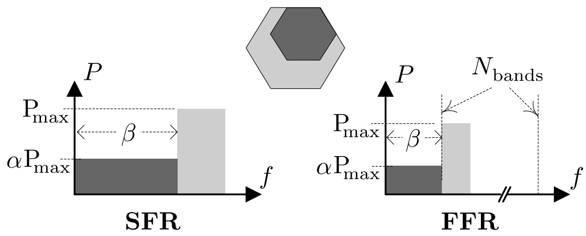


Figure 5. Static ICIC schemes.

the intercell interference level is sufficiently above of the noise floor. The bandwidth allocation is controlled by the parameter β.

These strategies rely on users classification often based on the average SINR. For a user u, $\bar{\gamma}_u$ represents its average SINR. Two possible approaches can be taken into account:

1) *Class Proportionality (CP)*: SINR thresholds (S_{TH}) are selected so that each class has the same average number of users.
2) *Bandwidth Proportionality (BWP)*: The threshold guarantees that the number of users per class is proportional to its allocated bandwidth[5].

Static ICIC techniques have been extensively studied and the associated tradeoffs are well known [6], [14], [58]. To be precise, the adjustment of the different parameters (α, β and S_{TH}) in each case allows fine tunning the efficiency vs. fairness tradeoff. Moreover, while SFR tends to favor the spectral efficiency as employs full frequency reuse, FFR is an advisable solution when fairness is an important issue and/or higher order modulations and advanced techniques requiring higher levels of SINR are expected to be used.

In this study, selected values for α, β and S_{TH} were selected considering conclusions obtained in previous studies and taking into account the regular hexagonal

[5]The proportionality that is implied by using BP refers to the fact that the number of users that is going to be classified as *Interiors* or *Exteriors* is proportional to the bandwidth available for each class (according to the selected ICIC scheme). This is done by setting the classification threshold conveniently (see parameter S_{TH} in Table V).

TABLE V.
STATIC ICIC CONFIGURATION.

	SFR	FFR
α	0.40	0.40
β	0.66	0.33
Users classification	BWP	BWP
S_{TH}	0.24 dB	1.11 dB
N_{bands}	–	3
Class index (c) and definition:		
	1: Exteriors ($\bar{\gamma} < S_{\text{TH}}$)	
	2: Interiors ($\bar{\gamma} \geq S_{\text{TH}}$)	

geometry of the cellular layout in such a way that an attractive tradeoff between efficiency and fairness can be achieved. Table V shows the particular configuration of both SFR and FFR.

B. CSI feedback schemes

As it was commented previously, *periodic* CSI reporting mode was considered because:

1) Periodic schemes can be employed with a wide range of services such as the ones considered in this study while aperiodic mechanisms are recommended just in cases where the traffic is very bursty, otherwise significant amount of uplink signaling resources would be wasted.
2) Since in the proposed scheme UEs report the perceived quality in different portions of the system bandwidth both sequentially and periodically, the proposed mechanism is therefore suitable to operate in a periodic fashion by nature.

Before describing the different CSI schemes considered here, it is important to provide some details about CQI estimation which is the main format in which LTE manages the CSI[6].

CQI Estimation.

CQI is a 4-bit integer calculated from the observed SINR. Reported CQI values are used together with additional UE capabilities[7] to select the optimum MCS index for transmission (scheduling and link adaptation). In order to allow SINR estimations, *cell-specific* RS are embedded into the overall signal bandwidth at certain REs. The RS pattern is a pseudo-random sequence, whose generation depends on the cell's identity and used cyclic prefix (details can be found in [21]).

Given a vector $\vec{\gamma}$ where its elements γ_i (i=1,2,...,N_{RS}^{Ω}) correspond to the SINR values of the different RSs in an arbitrary set of PRBs Ω computed according to Equation 4, the *effective* SINR [59] is obtained from the following expression:

$$\gamma_{\text{eff}} = f_{\text{eff}}(\vec{\gamma}) = \alpha_1 I^{-1}\left(\frac{1}{N_{\text{RS}}^{\Omega}}\sum_{i=1}^{N_{\text{RS}}^{\Omega}} I\left(\frac{\gamma_i}{\alpha_2}\right)\right) \qquad (6)$$

Parameters α_1 and α_2 adapt to different MCS. $I(\cdot)$ is a generic function that maps each SINR value γ_i to a performance metric that is averaged over all the samples. In this work, the Mutual Information Equivalent SINR Mapping (MIESM) or modulation constrained capacity [60] is employed. Therefore:

$$I(\gamma_i) = \log_2(M) + \frac{1}{2\pi M}\sum_{m=0}^{M-1} g(\gamma_i, m) \qquad (7)$$

$$g(\gamma_i, m) = \int e^{-\gamma_i(y-x_m)^2}\log_2\left(\frac{e^{-\gamma_i(y-x_m)^2}}{\sum_{k=0}^{M-1} e^{-\gamma_i(y-x_k)^2}}\right) dy$$

where M is the size of the modulation alphabet, y is the channel output and x_m are the modulation symbols. Each element $\omega_n \in \Omega$, represents the PRB with index n with respect to the whole system bandwidth and hence $n \in \{0\,1\,...\,N_{\text{PRB}}\}$.

Thus, the equivalent CQI index $\Theta \in \{0\,1\,2\,...\,15\}$ corresponding to Ω that can be supported with a nominal BLER of 10% is obtained according to:

$$\Theta_{\Omega} = f_{\text{eff}}\left(\vec{\gamma}\right) \qquad (8)$$

CSI feedback mechanisms.

In this study, 4 different CSI feedback schemes were considered. The first scheme is the ideal CQI-based CSI feedback mechanism (IDEAL) devoted to establish an upper bound from performance's point of view. Next, two periodic LTE schemes are considered: *Wideband CQI* (LTE-WB) and *UE-Selected Subband CQI* (LTE-UESEL). Finally, a fourth scheme, *ICIC Sequential* (ICIC-SEQ), also based on CQIs and suitable to operate in conjunction with static ICIC mechanisms is proposed. For all these schemes, a set of common parameters is shown in Table VI. In order to understand the CSI feedback schemes, some concepts must be introduced.

- **Active Band (AB)**: Corresponds to the portion of the system bandwidth in which a cell is allowed to transmit. In the following, Ω_{AB}^{l} represents the set of PRBs belonging to the AB in the l^{th} cell, where $N_{\text{AB}}^{l} = |\Omega_{\text{AB}}^{l}|$. $N_{\text{AB}}^{l} \leq N_{\text{PRB}}, \forall l$.
- **Reserved band (RB)**: $\Omega^{l,c}$ corresponds to the set of PRBs assigned to the class $c \in \{1, 2\}$ (See Table V) in the l^{th} cell. $\sum_c \Omega^{l,c} = \Omega_{\text{AB}}^{l}$, $\forall l$.
- **Subband (SB)**: The system bandwidth, given by N_{PRB} PRBs, is divided into N_{SB} subbands, where $\lfloor N_{\text{PRB}}/k\rfloor$ SBs are of size k and one is of size $N_{\text{PRB}} - k \cdot \lfloor N_{\text{PRB}}/k\rfloor$. Ω_b represents the set of PRBs within the b^{th} SB, $b \in \{1, 2, ..., N_{\text{SB}}\}$.
- **Bandwidth Part (BP)**: Is a set of N_{J} consecutive SBs, and a total of J BPs span the system

[6] Precoding Matrix Indicator (PMI) and Rank Indicator (RI) are required for additional transmission modes including transmit diversity, Open- and Closed- loop spatial multiplexing and Multiuser MIMO [21].

[7] The number of antennas and the type of receiver used for detection are usually considered.

TABLE VI.
COMMON PARAMETERS FOR CSI FEEDBACK SCHEMES.

Parameter	Value
Reporting period (N_p)	2 ms
CQI processing time (T_p)	3 ms
RS per PRB	4
RS power boost	0 dB

Values taken from [21], [61]

bandwidth. For $J > 1$, $N_\mathrm{J} = \lceil N_\mathrm{PRB}/k/J \rceil$ or $N_\mathrm{J} = \lceil N_\mathrm{PRB}/k/J \rceil - 1$ depending on the values of N_PRB, k and J [8]. Thus, $\Omega_{b,j}$ represents the b^{th} SB within BP j, $j \in \{1, 2, ..., \mathrm{J}\}$.

The different CSI feedback schemes are explained in the following points. Note that Δ and δ are the *CQI-based* CSI report and uplink signaling overhead associated to each scheme respectively. Also consider $t = n \cdot N_\mathrm{p}$ where $n \in \mathbb{N}^+$ and N_p is the reporting period. For the sake of simplicity, cell indexes are omitted.

1) IDEAL: In this case, one CQI value is estimated and reported to eNBs for each PRB within the active band every reporting period.

$$\Delta_{\text{IDEAL}}(t) = \vec{\mathbf{\Theta}} \in \mathbb{R}^{N_{\text{AB}}} \quad (9)$$
$$\delta_{\text{IDEAL}} = 4 \cdot N_{\text{AB}} \cdot N_\mathrm{p}^{-1} \text{ [bps]} \quad (10)$$

2) LTE-WB: One single CQI value is reported every reporting period describing the channel quality over the whole AB.

$$\Delta_{\text{LTE-WB}} = \Theta_{\Omega_{\text{AB}}} \quad (11)$$
$$\delta_{\text{LTE-WB}} = 4 \cdot N_\mathrm{p}^{-1} \text{ [bps]} \quad (12)$$

3) LTE-UESEL: The UE selects the single subband with the best CQI out of N_J subbands of the j^{th} BP and feeds back the corresponding CQI together with a label of N_L bits to identify the best SB within the current BP. The index j of the BP does not need to be fed back since the eNB can compute it directly by means of an internal counter N_SF as follows: $j = \mathrm{mod}(N_\mathrm{SF}, J)$. The size of the label is given by $N_\mathrm{L} = \lceil \log_2(\lceil N_\mathrm{PRB}/k/J \rceil \rceil)$, so in this case $N_\mathrm{L} = 2$. It is worth saying that with this approach, there is the risk of having outdated subbands for significant periods of time. Moreover, CQI is encoded differentially (3 bits) with respect to the wideband CQI that is measured by the UE every $H \cdot N_\mathrm{p}$ ms[9]. In order to avoid outdated CQI values, a *lifetime* of 16 ms $\approx 0.25 \cdot T_\mathrm{C}^{50\%}$ is considered for expired CQI values, after which, the last wideband CQI value ($\Theta_{\Omega_{\text{AB}}}$) is applied.

$$\Delta_{\text{LTE-UESEL}}(t) = \Theta_{\Omega^*} \quad (13)$$
$$j = t \bmod (J+1)$$
$$\Omega^* = \begin{cases} \underset{\Omega_{i,j}}{\operatorname{argmax}}\ f_e \ \ \forall i & j \neq 0 \\ \Omega_{\text{AB}} & j = 0 \end{cases}$$
$$\delta_{\text{LTE-UESEL}} = \frac{4 + J \cdot (3 + N_\mathrm{L})}{J+1} \left(N_\mathrm{p}^{-1}\right) \text{ [bps]} \quad (14)$$

[8]For N_PRB = 100 (the case of study), the LTE standard specifies k = 8 and J = 4.

[9]According to LTE downlink configuration followed in this work (K=1), thus $H = J \cdot K + 1 = 5$. [21]

4) ICIC-SEQ: The proposed scheme relies on the fact that previous mechanisms are not very efficient when static ICIC strategies are used. In such cases, UEs will be measuring the quality in portions of the system bandwidth over which they will be never allocated by virtue of (1) the current user classification or (2) the bandwidth allocation pattern corresponding to the ICIC scheme. In addition, reporting a CQI for the best subband of every BP is not necessarily the good strategy because it limits the scheduler's ability to exploit the frequency selectiveness of the channel. In general, and especially in multiservice scenarios, it is advisable to provide the scheduler with *a picture* as wide as possible which is one of the design targets in ICIC-SEQ. On the other hand, the proposed scheme only requires transmitting a very small amount of information (a vector $\vec{\mathbf{m}}$ of $\lceil N_\mathrm{PRB}/k \rceil$ bits) only in cases when the UE changes its current classification. Given $\vec{\mathbf{m}}$, a vector $\vec{\mathbf{s}}$ containing the indexes of non-zero positions in $\vec{\mathbf{m}}$ can be easily obtained. For instance, given $\vec{\mathbf{m}} = [1101001]$, $\vec{\mathbf{s}} = [1247]$. The operation is as follows: the eNB signals to the UE a bit stream, one bit for each SB, indicating which one is active for that UE (according to UE's classification and the bandwidth allocation in the serving eNB). This information **does not need to be updated** unless the UE changes its class. Then, the UE estimates/transmits one single CQI value corresponding to one SB sequentially every reporting period. With this approach, UEs focus exclusively on the relevant part of the system bandwidth achieving not only a more detailed description of the their channels but also without any additional complexity.

$$\Delta_{\text{ICIC-SEQ}}(t) = \Theta_{\Omega_z} \quad (15)$$
$$i = t \bmod (|\vec{\mathbf{s}}|)$$
$$z = s_i, \quad s_i \in \vec{\mathbf{s}}$$
$$\delta_{\text{ICIC-SEQ}} = 4 \cdot N_\mathrm{p}^{-1} \text{ [bps]} \quad (16)$$

Finally, regarding the feasibility of this proposal. This new scheme propose an enhancement to the current state of the standard and hence an improvement to the users' perceived QoS. Required modifications are minimal and actually compatible with existing options in LTE. To be precise, at UE's level, only a small functionality is required (but any additional capability: UEs will keep measuring SINR levels as usual; indeed they have to perform less measures than in other current options such as LTE-WB). In any case, terminals including this functionality can co-exists with existing ones, the only difference is that they will inform the network about their channel quality more clever and efficiently than the ones in *classic* modes. Finally, as it has been seen, since the amount of signaling in downlink is very small and need to be transmitted (probably from time to time) it can be easily included in any of the System Information Blocks (SIBs) available in LTE [21], [22].

V. PROBLEM FORMULATION

Table VII introduces some additional notation required to model the overall system interworking. Figure 6 depicts the overall system interworking and shows how several information structures flow from one entity to another. In order to go through the formulation, consider the different

TABLE VII.
ADDITIONAL NOTATION.

Symbol	Description
N_u	Number of users in the system.
l_u	Serving cell of user u.
L	Number of cells in the system.
τ_u	An operator containing HARQ features (MCS, TBS and RV) for a transmission to user u.
$\mathbf{T} \in \mathbb{R}^{N_u}$	HARQ information. $\tau_u \in \mathbf{T}$
$\mathbf{P} \in \mathbb{R}^{L \times N_{PRB}}$	Power allocation matrix.
$\mathbf{X} \in \mathbb{R}^{L \times N_{PRB}}$	Transmission map. $x_{l,n} \in \{01\}$. If $x_{l,n} = 1 \Rightarrow p_{l,n} > 0$, otherwise $p_{l,n} = 0$
$\mathbf{Y} \in \mathbb{R}^{N_u \times N_{PRB}}$	Resource allocation matrix. $y_{u,n} \in \{01\}$. If $y_{u,n} = 1 \Rightarrow \omega_n$ is assigned to user u.
$\mathbf{C} \in \mathbb{R}^{N_u \times N_{PRB}}$	CQI map. $c_{u,n} = \Theta_{\Omega_n}$ where $\Omega_n = \{\omega_n\}$.
$\mathbf{B} \in \mathbb{R}^{N_u}$	Buffer status of each flow: - oldest packet delay, - amount of information, etc.
$\mathbf{\Psi} \in \mathbb{R}^3$	Service set. $\mathbf{\Psi} = \{\text{HTTP FTP VoIP}\}$
$\mathbf{Q} \in \mathbb{R}^2$	Quality of service. $\mathbf{Q} = \{Q_{\text{NRT}}\ Q_{\text{RT}}\}$ (See Table IV)

steps involved in the transmission of one single TB to a user u. Focus initially on matrix $\mathbf{C}$. CQI estimation (see Subsection IV-B) is performed at UE according to some CSI feedback scheme (CFS), say CFS$_X$, thus, in general, it is possible to write:

$$\mathbf{C}(t) = f_{\text{CFS}_X} \tag{17}$$

where $\mathbf{C}$ corresponds to the CQI-based *channel descriptor* of users in the system. Therefore $\mathbf{C}$ is made based on one of the following Equations: 9, 11, 13 or 15. Given $\mathbf{C}$, the scheduling process also takes into account:

- buffers' status $\mathbf{B}$,
- QoS parameters $\mathbf{Q}$ assigned to each service $s \in \mathbf{\Psi}$,
- *per-class* power/bandwidth allocation $\mathbf{P}$, Ω^l_{AB} and $\Omega^{l,c}$ given by the ICIC strategy.
- HARQ feedback information of previous transmissions $\mathbf{T}$.

Then, as a result, CRA scheduler allocates radio resources and shape HARQ transmissions to different users every TTI. Assume that f^l_{CRA} represents the operation of the CRA scheduler at cell l and that $\mathcal{D}$ is a generic data structure. Thus, in general:

$$\mathcal{D}_{\text{Out}}(t) = \sum\nolimits_{\forall l} f^l_{\text{CRA}}\,(\,\mathcal{D}_{\text{In}}(t-1, l)\,) \tag{18}$$

$$\begin{aligned}\mathcal{D}_{\text{In}}(t,l) &= [\,\mathbf{B}(t)\ \mathbf{Q}(t)\ \mathbf{\Psi}(t)\ \mathbf{C}(t)\ \mathbf{P}(t)\ \mathbf{T}(t)\ \Omega^l_{\text{AB}}\ \Omega^{l,\forall c}\,]\\ \mathcal{D}_{\text{Out}}(t) &= [\,\mathbf{Y}(t)\ \mathbf{X}(t)\ \mathbf{T}(t)\,]\end{aligned}$$

On the other hand, consider (without loss of generality) that each user has only one active flow at a time and that the number of connected and satisfied flows from service s are μ_s and $\hat{\mu_s}$ respectively. Then, the total system load Υ, system traffic mix $\vec{\boldsymbol{\rho}}$, and the user satisfaction ratio θ_s for service s can be expressed as:

$$\Upsilon = \sum_{\forall s \in \mathbf{\Psi}} \mu_s \tag{19}$$

$$\vec{\boldsymbol{\rho}} \in \mathbb{R}^{|\mathbf{\Psi}|} \quad | \quad \rho_s = \mu_s / \Upsilon \tag{20}$$

$$\theta_s = \hat{\mu_s} / \mu_s \tag{21}$$

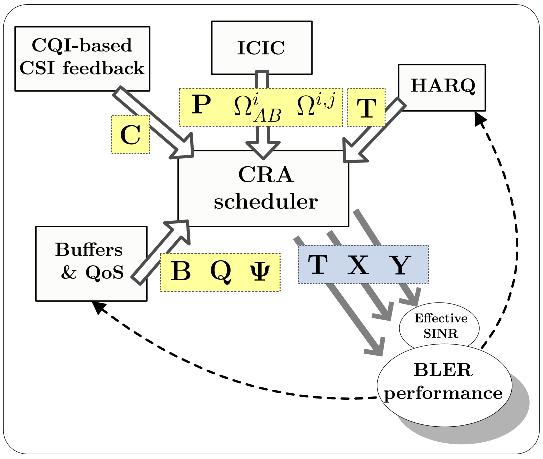


Figure 6. Overall system interworking.

In general, θ_s is a non increasing function of Υ and also depends on the traffic mix $\vec{\boldsymbol{\rho}}$. In this article, we consider that the individual capacity for a service s, ϕ_s, is the maximum system load for which $\theta_s \geq Q^{\text{TH}}_s$. Q^{TH}_s is the target users satisfaction ratio for service s. In this work, $Q^{\text{TH}}_s = Q^{\text{TH}} = 0.95\ \forall s$.

$$\phi_s(\Upsilon, \vec{\boldsymbol{\rho}}) = \max\left(\Upsilon \mid \theta_s(\Upsilon, \vec{\boldsymbol{\rho}}) \geq Q^{\text{TH}}\right) \tag{22}$$

In the same way, the capacity that can be achieved by a generic scheduler SCH, is given by:

$$\phi^{SCH}(\Upsilon, \vec{\boldsymbol{\rho}}) = \min\left(\phi_s(\Upsilon, \vec{\boldsymbol{\rho}})\right)\ \forall s \in \mathbf{\Psi} \tag{23}$$

Therefore, the impact of any given CSI feedback schemes f_{CFS_X} (Equation 17) on the overall system performance (considering the operation of the CRA scheduler) can be formulated as:

$$\text{CFS}^*_X = \underset{f_{\text{CFS}_X}}{\text{argmax}}\left(\phi^{\text{CRA}}(\Upsilon, \vec{\boldsymbol{\rho}}) \mid \mathcal{D}_{\text{In}}\right) \tag{24}$$

Equation 24 represents a convenient approach to investigate the impact of CSI feedback schemes on system performance from a QoS perspective as captures all relevant effects and interactions depicted by Figure 6. Actually, this framework is strongly recommended for multiservice cellular networks where the focus is on *QoS provisioning* [62].

Finally, the selection of the MCS index (σ^*) to be used in any given HARQ transmission τ, is done according to:

$$\begin{aligned}\sigma^* &= \underset{\text{MCS}_i}{\text{argmax}}\ \Gamma_\tau \\ \text{s.t.}\\ f_{\text{eff}}(\vec{\mathbf{q}}) &\geq \gamma^{\text{Target},10\%}_{\text{eff}}(TBS_\tau, RV_\tau, \sigma)\end{aligned} \tag{25}$$

where $\vec{\mathbf{q}}$ is obtained from the CQIs currently stored in $\mathbf{C}$ corresponding to the PRBs where τ is going to be allocated and $\gamma^{\text{Target},10\%}_{\text{eff}}$ is the minimum effective SINR required to transmit τ with a BLER $\leq 10\%$ given TBS_τ, RV_τ and MCS index σ.

TABLE VIII.
SERVICE SCENARIOS.

Name	Service(s)	Traffic mix
Only VoIP	[VoIP]	[100%]
Only FTP	[FTP]	[100%]
Multi-Service	[HTTP FTP VoIP]	[30% 30% 40%]

VI. Results and Performance Analysis

In this section, numerical results corresponding to the performance evaluation of the schemes just described in Subsection IV-B are presented. Table VIII shows the selected traffic scenarios in order to determine the impact of CSI feedback schemes on the joint system capacity, i.e. the number of satisfied flows per service, when CRA scheduler is considered.

Firstly, signaling overheads associated to the different CSI feedback schemes according to Equations 10, 12, 14 and 16 are shown in Figure 7. As it can be seen from Figure 7, the gap between practical schemes (LTE-WB, LTE-UESEL and ICIC-SEQ) and the ideal one (IDEAL) is of about two orders of magnitude since the latter implies the need to provide the eNB with CQI characterization at PRB level. It is worth to notice this fact from the very beginning as it justifies the significant performance gap obtained later on.

On the other hand, as it can be seen from Figure 7, ICIC-SEQ requires the same amount of signaling overhead than LTE-WB which is at the same time the best performance in this sense. Nevertheless, ICIC-SEQ clearly outperforms LTE-WB in terms of complexity since the latter requires the estimation of the average quality for the whole bandwidth while the former only needs to estimate the quality for a bandwidth portion corresponding to one single subband. For the case of 100 MHz system bandwidth this can be translated into savings of more than 90% in terms of the number of measurements.

A. Impact on users satisfaction ratio

Figures 8a and 8b show the users satisfaction ratio in the VoIP scenario for different cell loads. The evaluation was conducted both for SFR and FFR as function of the CSI feedback scheme. First, looking at the performance both in SFR and FFR, it can be seen that the amount of satisfied users (having BLER $< 1\%$) when different CSI feedback schemes are employed is quite similar from one ICIC strategy to another. Actually, for low load conditions, FFR tends to improve the system capacity (especially for LTE-WB and LTE-UESEL) due to higher levels of SINR achieved by FFR. In terms of individual VoIP capacity, ICIC-SEQ outperforms the users satisfaction ratio achieved by LTE-WB and LTE-UESEL in a range of about 3-12%, obtaining in both cases a individual VoIP capacity of about 150 users per cell (the maximum load achieving $Q^{\mathrm{TH}} \geq 0.95$), which is around of 50 more users (in average) with respect to the next competitors. Clearly, when IDEAL feedback is employed, capacity is then boosted up to 250 users per cell.

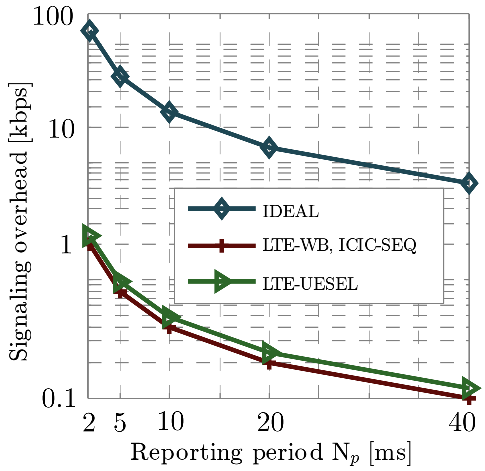


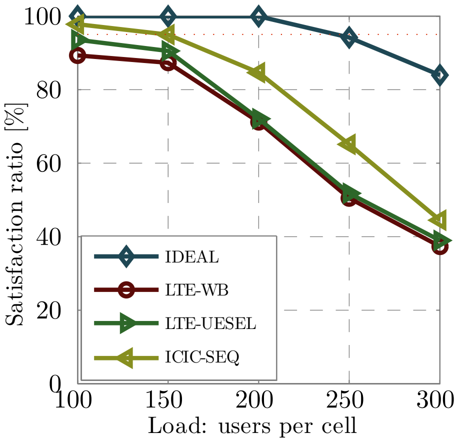
Figure 7. Signaling overhead ($J = 4$, $N_{\mathrm{AB}} = 66$, $L = 2$).

In the same way, Figures 8c and 8d show the users satisfaction ratio in the FTP scenario for different cell loads. It is worth mentioning that this scenario, largely matches the behavior of the so-called *full buffers* model from scheduler's point of view. Focusing on the ICIC strategy, it can be seen that for IDEAL, LTE-WB and LTE-UESEL, the performance is slightly better (2-8%) when SFR is employed. As expected, the greater frequency reuse favors the overall spectral efficiency, nevertheless the gap is not as significant as reported in previous studies [6], [14]. This is due to the fact that CRA scheduler tries to strictly satisfy the NRT QoS target. In addition, a small spectral efficiency loss results from the Physical Downlink Control Channel (PDCCH) capacity constraint; in this work a maximum number of 8 scheduled users per TTI has been considered (static modeling)[10]. However, this effect is clearly reduced when ICIC-SEQ is employed due to the improvement in BLER performance.

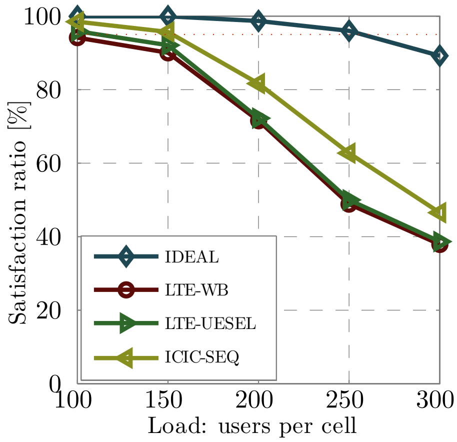
Now focusing on CSI feedback schemes, ICIC-SEQ clearly outperforms LTE-WB and LTE-UESEL in about 5-8% and 8-12% both in SFR and FFR respectively, while IDEAL is obviously superior to the next competitor (ICIC-SEQ) in about 22-35%. This performance gap is at expense of about 100X increment in signaling overhead as it was shown before. Finally, ICIC-SEQ achieves capacity gains of about 25 and 13% (10 and 5% in terms of users satisfaction) with respect to LTE-UESEL both in FFR and SFR respectively. Clearly, the performance improvement is greater in FFR as reserved bands per-class $\Omega^{l,c}$, $\forall l, c$ are smaller. This makes the operation of ICIC-SEQ even more effective while the unequal power allocation in SFR and FFR contributes to degrade the BLER performance of LTE-WB and LTE-UESEL. These results suggest that **an ICIC-SEQ like scheme can be also designed for dynamic ICIC mechanisms**.

Figure 9 shows the results corresponding to the multiservice scenario in which different services coexist in

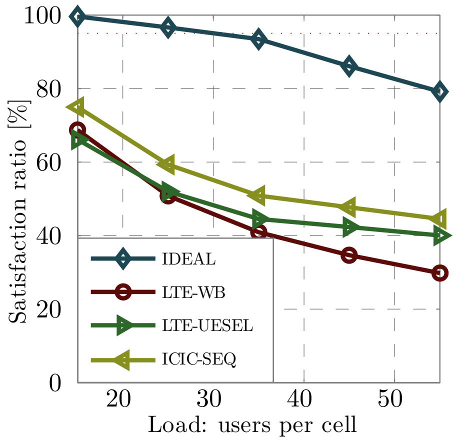
[10] The impact and optimization of the number of scheduling grants per TTI is beyond the scope herein but is left open as future work.



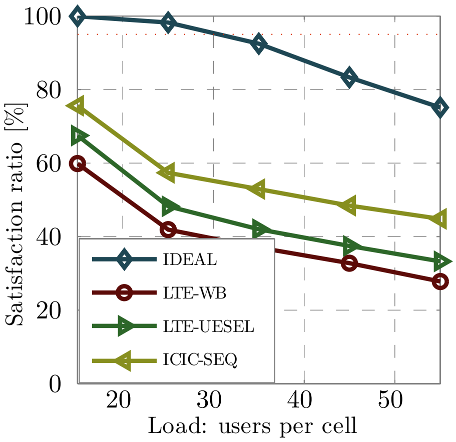
(a) Only VoIP @ SFR



(b) Only VoIP @ FFR



(c) Only FTP @ SFR



(d) Only FTP @ FFR

Figure 8. Results for only VoIP and only FTP scenarios.

the system. Since CRA scheduler does not differentiate between different NRT services, HTTP and FTP are grouped into one single class: NRT, while VoIP flows represents the class RT. As indicated in Table VIII, the traffic mix is composed by 30% of HTTP flows, 30% of FTP flows and 40% of VoIP flows. Results can be understood, to a large degree, as an intermediate point between FTP and VoIP scenarios. In this case, users' satisfaction ratio for VoIP flows is greater than the QoS threshold for this service as the system is operating quite below its capacity from the VoIP perspective and hence the impact of the CSI feedback schemes is less noticeable. It is very important to keep in mind, on the one hand that the highest individual capacity for a given service $\phi_{X,\max}$ is obtained in case where only flows of that type of traffic are present in the system as **the joint system capacity is a non-increasing function of the load**. On the other hand, looking at NRT flows, it can be notice that the system is operating above its capacity (from NRT services' point of view) and under these circumstances, the gain achieved by ICIC-SEQ with respect to LTE-WB and LTE-UESEL is more evident and in fact, more important. Again, ICIC-SEQ also reports a capacity improvement of about 5% with respect to LTE-based schemes. These results suggest that ICIC-SEQ can be used in multiservice scenarios achieving significant gains under high load conditions.

B. Additional results

In order to provide additional insight into the whole interworking, Figures 10 and 11 help to look at the problem from another perspective. One single *case of study* has been selected to illustrate these ideas because it is not possible to show the entire set of results given the large amount of experiments. However similar results were found for the rest of experiments so the analysis herein is valid and generic. The representative *case of study* corresponds to the FTP scenario with FFR (55 users per cell).

The cumulative distribution function (CDF) of the users' rate is shown in Figure 10. As it can be seen from the figure, ICIC-SEQ provides not only a higher number of satisfied users but also helps to improve data rates at cell edge with respect to LTE-WB and LTE-UESEL. Enhancing cell edge performance is precisely the main target of ICIC techniques, thus ICIC-SEQ **proves to be an excellent companion for ICIC schemes**.

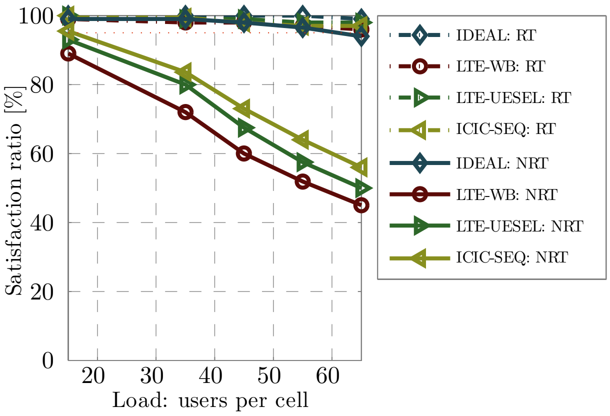


Figure 9. Multi-Service scenario @ FFR

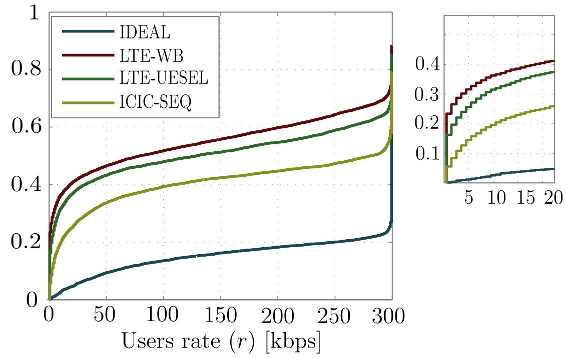


Figure 10. Users rate CDF: *Case of study*

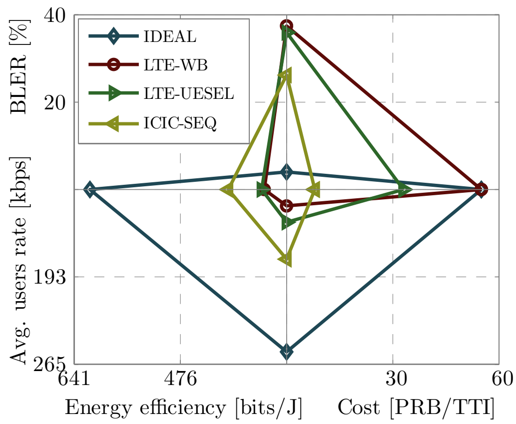


Figure 11. Additional performance metrics: *Case of study*

Additional performance metrics are shown in Figure 11. The overall energy efficiency achieved by the system and computational load at UE side[11] appear in the x-axis. The average users' rate and BLER are represented in the y-axis.

Although lower BLER does not imply *necessarily* greater capacity, what it is always true is that the BLER is always correlated to energy efficiency since less transmissions need to be done to transmit the same amount of information. This fact is clearly appreciated in Figure 11 where lower BLER implies greater energy efficiency. Thus **CSI feedback techniques minimizing the BLER are also good allies of *green* systems**.

Another aspect in which ICIC-SEQ clearly outperforms LTE-WB and LTE-UESEL is the associated computational load at UE side. In LTE-UESEL, UEs need to estimate the wideband CQI every $J+1$ reporting intervals which requires more processing. In ICIC-SEQ, UEs do not need to estimate the wideband quality and hence the computational effort and battery life are lower and longer respectively.

To conclude this section, it is worth recognizing that in order to fully exploit the frequency selectivity of the channel, reporting granularity both in time and frequency should be as small as possible. In practice, a short reporting period such as the one employed in this study (2 ms) provides good accuracy (in time domain) for low mobility scenarios, nevertheless the subband size is the minimum granularity in frequency domain. This, together with the fact that in some operation modes of LTE, PRBs allocated to one single transmission do not need to be contiguous, deteriorate the BLER performance unless additional coordination with the scheduler is done, but this is at expense of a penalty in terms of spectral efficiency.

VII. Conclusions and Future Work

QoS refers to the ability of the network to provide a desired level of service for selected traffic on the network. Typically, service levels are described in terms of throughput, latency, jitter and packet error rate and are specified for different types or streams of traffic. Designing QoS policies for evolving packet-based applications is a fundamental requirement in modern multiservice cellular systems as QoS impacts directly the Quality of Experience (QoE) of the users in the network.

In this article, a periodic CSI feedback scheme, ICIC-SEQ, suitable to work (but not only) with static ICIC techniques has been presented. The impact of the novel scheme (compared with existing LTE-based and the ideal one) on the performance of a QoS-oriented scheduler has been evaluated and analyzed in the context of a multiservice environment and from the QoS perspective. The feasibility of the presented scheme was demonstrated not only due to its effectiveness (gains were achieved in all cases) but also because ICIC-SEQ is simple and features low signaling overhead and computational cost.

It has been shown that there is a close interaction among different components of the system such as scheduler, HARQ, CSI feedback and so forth. Performance gains can be achieved by considering particular features of each entity in the design of others as it was corroborated by the results herein where **by modifying the CSI feedback scheme behavior in terms of the ICIC strategy, the whole interplay was improved**.

Moreover, the deployment of the LTE technology is an opportunity to look for *energy-efficient* radio resource management techniques. CSI feedback schemes

[11]This is measured as the average number of PRBs that need to be processed every reporting interval to perform CSI feedback according to each scheme.

minimizing the overall system BLER are clearly within this roadmap as this aspect is not only correlated to power savings but also to intercell interference mitigation. Clearly, **transmit less means interfere less**.

Finally, some items were identified as future work:

- Optimization of CSI feedback mechanisms towards dynamic ICIC strategies.
- Improving the interplay between CSI feedback schemes and QoS-oriented schedulers is actually of utmost importance since additional gains can be achieved with smart/low cost coordination. Moreover, investigating the joint impact of additional operational parameters such the PDCCH capacity and reporting periodicity on the joint system capacity will provide additional insight useful from the design point of view.
- Finally, authors consider that investigating aperiodic *service-sensitive* CSI feedback schemes, possibly operating in conjunction with periodic ones, is another topic in which additional efforts must be placed.

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