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Interference Coordination Method for CSI Improvement in LTE Uplink with Carrier Aggregation

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Abstract—**Carrier Aggregation is an important feature in Long Term Evolution Advanced (LTE-A). It allows operators to provide larger operational bandwidths without the need of having a contiguous, large piece of spectrum. However, an increased bandwidth also needs a larger channel sounding to obtain channel state information (CSI), required for frequency domain scheduling and link adaptation. This constitutes a serious challenge for the uplink since wideband sounding reference signals cannot be transmitted by cell edge (power limited) users and hopped sounding requires a long time to sweep the entire transmission band, thus leading to outdated and less reliable CSI. Also, average interference and its variation in time can seriously jeopardize the CSI at the eNodeB. In this paper, we present an integration of inter cell interference coordination with CSI reporting by reducing the interference variability through controlled allocations. Results show that the entire CSI accuracy can be improved and so does the overall cell performance.**

I. INTRODUCTION

Carrier aggregation (CA) is one of the key techniques in Long Term Evolution - Advanced (LTE-A). At the current standardization level, Release 10 and onwards allow LTE-A to extend its bandwidth operation up to 100 MHz by simultaneously aggregating several pieces of spectrum. This is an interesting feature since operators do not typically own more than 15-20 MHz of contiguous bandwidth. Given this, when using CA, user equipments (UEs) are allowed to transmit simultaneously in different component carriers (CCs)

To achieve a good link adaptation (LA) and allow opportunistic frequency domain scheduling in the uplink (UL), the eNodeB (eNB) needs to evaluate the UE channel response. With this aim, the UE sends sounding reference signals (SRSs) with the objective of obtaining accurate channel quality indicators (CQIs). SRSs can occupy the entire system bandwidth (wideband SRS) or just a small piece that hops along the entire band. Wideband SRS provide poor channel information in the cell edge, where UEs are often power limited and suffer from increased interference. On the other hand, hopped SRSs provide the system with a more reliable CSI in power limited cases, but needs an increased time delay to sound the entire system bandwidth. This problem is more critical with the use of CA, where the total available bandwidth increases and the UE has to sound a larger piece of spectrum.

A second problem with UL CQI acquisition is the intrinsic rapid variations of the interference levels. This is not only due to short term fading, but also because of scheduling decisions. With every transmission time interval (TTI), allocated resources are updated and so the sources of interference in each PRB are changed. This implies fast SINR variation and reduces the sounding reliability, eventually generating errors in the LA and reducing the UE throughput. For this reason, using mechanisms for interference variability contention can yield to lower CSI errors.

Non-contiguous resource allocation in the UL is highly beneficial, since large frequency diversity gains can be obtained. Authors in [1] evaluate these gains while considering two different SRS setups, selected based on the UE SINR. Results show that, while non-contiguous allocation let the UE exploit additional gains, SINR estimation failure can potentially degrade the UL performance. To accurately measure the UL channel response, frequency resources should be sounded taking into account the UE power needs and also the interference generated. Work in [2] discusses this topic and focuses on the need for the availability of multiple bandwidth configurations for SRS transmissions. If bandwidth can be adapted, then there are lower modulation and coding scheme (MCS) selection error caused by decreased received signal power density. Results show that the adaptive control is especially effective in hyper dense scenarios with high volumes of traffic. In a CA context, work in [3] proposes the use of sounding signals only in active CCs, and if simultaneous transmission in both CCs is carried out, then SRS should be configured separately. This provides extra flexibility in interference coordination, for example in heterogeneous networks.

Regarding interference reduction, inter cell interference coordination (ICIC) techniques have been widely studied in the downlink [4]. Some interesting works have also appeared in the UL [5], [6], [7], though there is far less literature. All these references have shown that ICIC improves the UL performance by reducing the interference impact. However, none of them consider realistically the channel information obtained through sounding signals, and the misalignment that exists in the SINR measured from SRS with respect to the actual SINR, the one that the UE experiences in the subsequently allocated data channel.

This work proposes extending a classic soft frequency reuse (SFR) approach to the SRS operation to improve the CQI acquisition in the UL, and therefore enhance the spectral efficiency. By adopting SFR, each eNB has a smaller area reserved for cell edge UEs sounding; shortening their total sounding BW limits interferences in both SRS and data transmissions. This solution allows to reduce the time delay between two consecutive sounding measurements. The resulting effect is an overall improvement in the UL transmission, since more accurate and up-to-date CQI is available for scheduling and link adaptation.

The reminder of this paper is organized as follows: Section II explains the CQI acquisition in the UL. Section III describes the SRS allocation process in LTE UL with the added ICIC approach and the system model followed by section IV with the description of the simulation environment. Section V presents results and discussion. To end with this article final conclusions are drawn in section VI.

II. CQI IN THE UPLINK

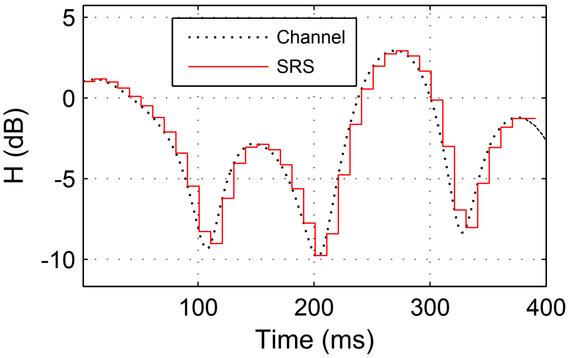
Sounding signals are sent in the UL last symbol of the sub-frame, with the main goal of achieving up-to-date and accurate CQI. SRSs supports opportunistic frequency domain scheduling, since the best spectrum areas can be detected. Eventually it also contributes in the decision of the best MCS.

Cell specific configuration parameters are ll the sounding parameters such as: sounding bandwidth, frequency and time domain resource selection, are configured by the eNB on a cell-wide basis. Specific per-UE configuration parameters are: sounding periodicity, bandwidths, and hopping patterns. With this, more efficient allocations can be done given each UE power capability. A combination of frequency and code division multiplex (FDM and CDM) is used to multiplex users in SRS transmissions. FDM is done following a transmission comb structure and CDM is done using different cyclic shifts. Currently in LTE only two transmission combs are supported. For each sounding region up to eight UEs can be multiplexed via cyclic shifts, n_{SRS}. Based on this, both FDM and CDM allows to multiplex a total of 16 UEs in the same spectrum area; such number of UEs is not feasible since there are orthogonality and interference issues, so a more realistic estimate is to multiplex 6 to 8 UEs [8].

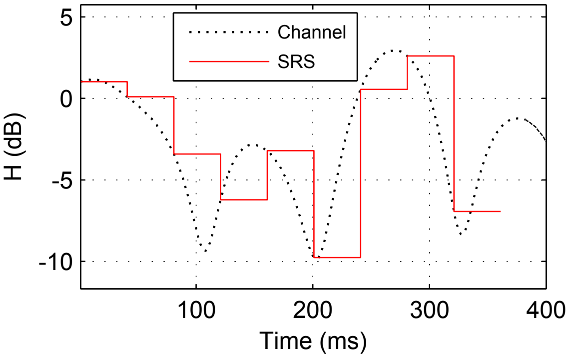
Reduced sounding bandwidths are desirable for cell edge UEs to assure the reliability of the measurement given their low power availability. But, this leads to a larger time to measure the entire system bandwidth, increasing the period between two consecutive measurements of the same piece of spectrum (T_{sound}). This is particularly problematic in CA systems making use of wider bands, and the number of aggregated carriers increases the delay. The number of users sharing the bandwidth also affects the delay in channel measurement. Table I shows the delay T_{sound} in milliseconds experienced between two consecutive soundings in one PRB. The delay varies depending on the number of users connected to the eNB and the bandwidth being sounded each TTI, B_{SRS}. Delays account for the use of two CCs (20 MHz each) which are not simultaneously sounded.

TABLE I: Time delay between two consecutive SRS measurements (T_{sound}(ms)). Two CC of 20 MHz each.

Number of UEs	UE-specific SRS bandwidth					
	4	**8**	**16**	**20**	**40**	**80**
8	40	20	10	8	4	2
24	40	20	10	8	4	4
40	40	20	10	8	8	6
72	40	20	10	16	12	8



(a) UE Channel measured by SRS with time delay of 10 ms



(b) UE Channel measured by SRS with time delay of 30 ms

Fig. 1: Channel measurement for two different T_{sound}

The main problem of having increased delays in CSI is the lack of up to date information in the scheduling decisions and link adaptation. Figure 1 shows two different examples of channel state measurement with the use of SRS. The first figure, 1(a), has a time delay between two samples of 10 ms and the second one, figure 1(b), has a time delay of 30 ms. It is obvious that a lower time delay can capture enhanced channel information in terms of short-term deep fadings.

Another limiting aspect of the UL channel measurement is its intrinsic interference variability. Due to scheduling decisions interfering UEs may change from one transmission time to another, so the total aggregate interference power also

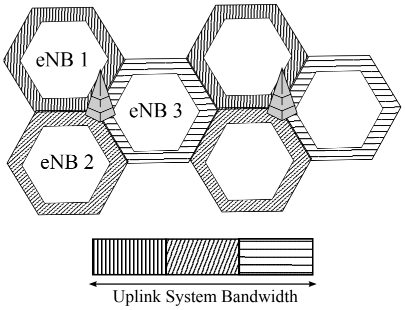


Fig. 2: Sounding procedure that all UEs in the scenario follow.

changes. The higher the number of active users in neighbouring cells, the more variable interference becomes and more important differences may occur between the sounded SINR and the SINR at the actual data transmission time interval. Assuming that schedulers generally try to preserve a certain proportional fairness, the probability of having always the same interferer sources is lower with the load.

III. SOUNDING PROCESS WITH ICIC

This section describes the solution proposed to increase the CQI accuracy based on the limitations exposed in the previous paragraphs. To improve the CQI acquisition, and hence the spectral efficiency, the time delay between two consecutive measurements, T_{sound}, must be low and the total aggregate interference plus its variability must be contained. ICIC techniques allow to control the generated interference in the network by coordinating the transmissions in the shared channel. One well known ICIC technique is SFR, where a small part of the spectrum is reserved for cell edge UEs. According to this, it is proposed to use SFR in the sounding procedure of cell edge UEs with a twofold aim: first, to reduce the delay in CSI measurement and second, to tackle the interference issue. By reducing the sounding region, the delay T_{sound} is naturally reduced; also, concentrating a group of users in one region reduces the interference variability.

The main idea of SFR is that the entire bandwidth is divided into different parts, as shown in figure 2. Each eNB reserves a part of the spectrum for its own cell edge exploitation and cell centre UEs share the rest of the band, whose channel conditions are not critical owing to the lower path-loss.

We consider an LTE-A UL system with CA, consisting of l aggregated CCs, and criteria for assessing UEs eligibility of transmitting in aggregated carriers is based on their available power [9].

The eNB first classifies the UEs as cell edge or non-cell edge, based on the path-loss to the serving cell. The threshold for the classification is determined as the percentile p of the maximum path-loss of the cell. A set $\mathcal{U}$ of users associated to the eNB, is sorted based on its path-loss as follows:

$$\mathcal{I} = \{i_1, i_2, \ldots, i_{|\mathcal{I}|} : L(i_k) \geqslant L(i_{k+1}) \forall k\}$$

Where, $|\mathcal{I}|$ is the total number of UEs associated to the eNB and $L(i_k)$ is the experienced path-loss by UE i_k.

The threshold τ is calculated as $\tau = L(i_x)$, where x:

$$x = \left\lfloor p \frac{|\mathcal{I}|}{100} \right\rfloor \tag{1}$$

Each user, regardless if it is at the cell edge or not, is assigned a user block ub and a cyclic shift n_m (where $m \in M$ and M and is the set of multiplexed UEs). All UEs with the same ub share the same frequency allocation; to avoid intra-cell interference, orthogonal cyclic shifts n_m are assigned. UEs considered to be cell edge are only eligible for transmitting in the SFR reserved area, and the remainder of the users may be allocated the rest of the band.

The signal received per resource block r at the eNB side in its lth CC one round trip time later is denoted as $S_{l,r}^{\text{UL}}(i,j)$. For the sake of simplicity subindex l has been omitted in all equations

$$S_r^{\text{UL}}(i,j) = P_{\text{SRS}} h_r(i,j)\, d(i,j)^{-\alpha_{\text{p}}}\, 10^{\frac{\chi}{10}} \tag{2}$$

Where P_{SRS} is the UE transmitted power; $h_r(i,j)$ is the Rayleigh fading; $d(i,j)$ is the distance from user i to the eNB j and α_{p} is the path loss exponent; χ is a Normal random variable with zero mean and standard deviation σ.

Open loop power control expressed in equation 3 determines the UE transmitted power. Where π_A corresponds to the maximum power reduction that is intrinsic to non-contiguous allocation to avoid non-linearities of the power amplifier [10]; P_0 and α are power control parameters [11] and L is the already defined UL path-loss.

$$P_{\text{TX}}^{\text{MC}} = \min(P_{\max} - \pi_A, P_0 + 10 \log M_{\text{Alloc}} + \alpha \cdot L) \tag{3}$$

The eNB can estimate the user's i SINR at PRB r as:

$$\gamma_r^{\text{SRS}}(i,j) = \frac{S_r^{\text{UL}}(i,j)}{I_r(i,j) + \sigma_n^2} \tag{4}$$

where σ_n^2 is the noise power of the additive white Gaussian noise and I_r is the total aggregate inter-cell interference perceived in PRB r and is modeled as:

$$I_r(i,j) = \sum_{n \in N} P_{\text{SRS},n} h_r(i,j)\, d(i,j)\, d(n,j)^{-\alpha}\, 10^{\frac{\chi}{10}} \tag{5}$$

where N is the set of interfering uplink users associated to the neighbouring cells. Only users sharing cyclic shifts and user blocks are considered to interfere each other.

Following this sounding process along the entire available bandwidth lets to obtain a single value of $\gamma_r^{\text{SRS}}(i,j)$ for every PRB. This is the information used by the scheduling entity to perform spectrally efficient decisions and also for the LA to assign the most appropriate MCS. Data allocation is done only in ICIC band, where resources have available CSI.

Resource allocation is done following [12] Release 10 specifications, where non-contiguous allocation in the UL is allowed by assigning multiple clusters of contiguous PRBs. The UE allocated bandwidth is fixed along the cell radius, M_{Alloc}. A hybrid automatic repeat request aware scheduler based on proportional fair [10].

TABLE II: Simulation scenario assumptions

Parameter	Value
Inter-Site Distance	500 m
Bandwidth	2 x 20 MHz
SRS BW	8 PRBs
Shadowing correlation distance	50 m
Shadowing deviation	6 dB
Short term fading	EPB power delay profile
UE speed	3 km/h
Number of UEs served	20
Number of UEs connected	30
Target BLER	10 %
Max Tx Power	23 dBm

ENBs have pre-allocated SFR sounding regions on each CC, so that cell edge UEs with enough power capabilities can still benefit from CA and frequency diversity gain. Users do not sound simultaneously each CC, and the sounding bandwidth M_{SRS} is the same for all UEs and all CCs.

IV. SIMULATION CONDITIONS

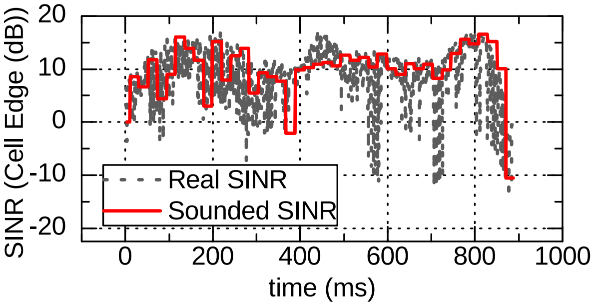
The methodology to test this strategy has been simulations. A dynamic system level simulator fully programmed in C# .NET framework has been implemented. The tool includes all the main radio resource management (RRM) functionalities identified in the UL: CSI manager, LA unit and scheduler. As specified in [13] the number of allocable clusters per CC is two, and the number of PRBs per cluster depends on the system bandwidth.

The simulated scenario has 14 tri-sectorial sites, and 42 eNBs. The wireless access network is considered to have a round trip time of 8 ms. Finite buffer communications are assumed and, as soon as the buffer is entirely transmitted, the UE is automatically reconnected in another position. Power control parameters were adjusted following the study in [11], and they are equal in all cells. The rest of simulation assumptions are summarized in Table I.

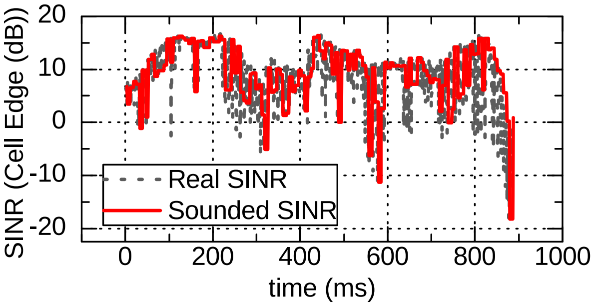
V. RESULTS

The use of ICIC over SRS is compared against a benchmark scenario in which all UEs must sound the entire system bandwidth. Unlike the ICIC solution, users in the benchmark scenario can be allocated data in all resource blocks of both CCs.

Figure 3 shows the sounded SINR obtained from the SRSs. The same cell edge user in one resource block is tested with the two approaches. The SFR mode updates much faster than the benchmark one thus allowing to capture more reliable information from the SRSs. Reducing the sounding area allows to lower T_{sound} and the actual SINR can be better followed. The CSI provided by the SRSs with the benchmark SRS allocation process differs very much from the actual SINR experienced by the cell edge UE, figure 3(a). On the contrary, by including SFR on the sounding allocation process, most of the fadings are better captured and the SINR information is far more accurate, figure 3(b).



(a) UE SINR with benchmark sounding process



(b) UE SINR with ICIC sounding process

Fig. 3: Comparison of sounding information versus actual SINR

An advantage of the SFR ICIC method is that cell edge interference is less variable because allocations are less changeable among users; and, on the other hand, a cell edge UE is never interfered by other cell edge UE in near cells. This can be noted in figure 3 quantitatively, where the real SINR in 3(a) is more variable than the real SINR in 3(b). Figure 4 quantifies this issue by representing the probability density function of the interference. The average aggregate interference generated does not differ much one from the other. This is because in both cases the RU in the sounding process is 100%, all sounding resources are being allocated. However, the variability in time of the total interference experienced does change: the deviation in the interference distribution is smaller and also the SINR trace is less noisy. Only a fraction p of UEs are allocated sounding resources in the SFR area, whereas in the benchmark scenario, all UEs are allocated sounding resources along the whole CC bandwidth.

All together, the reduced sounding period and the reduction of interference variability, leads to an improvement in the entire system performance. With a better CSI, the link adaptation is much more precise. Figure 5 pictures the probability density function of the SINR error for all UEs. This error is calculated as the difference between the SINR perceived once the data signal is received and the SINR of the associated sounded signal previously received in that physical resource block. The introduction of SFR into the sounding process allows to improve the misalignment between both and lets improve the CSI in more than 10% for the zero error case. The occurrence

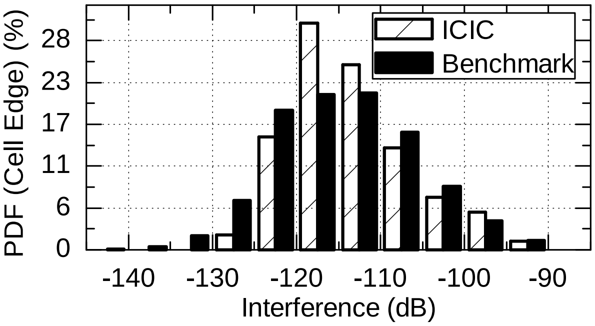


Fig. 4: PDF of the interference in cell edge

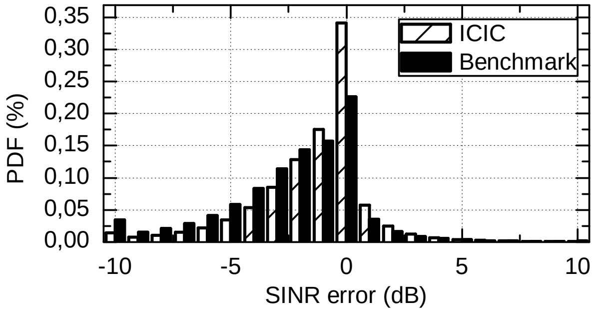


Fig. 5: SINR error of sounding with respect to data

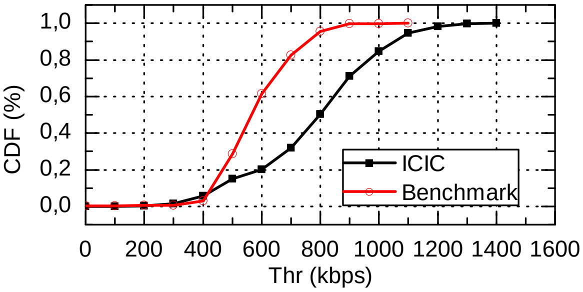


Fig. 6: UE experienced throughput CDF

of large error values is reduced as well. Being more accurate in the CSI and link adaptation decisions eventually results in a global performance increase, because less retransmissions are needed. Figure 6 depicts the CDF of the UE throughput with an evident gain, in particular the average cell throughput improves a 36%. Employing CA provides the system with an increased bandwidth, which lets UEs benefit from frequency diversity gain while restricting the sounding channels. There is no further signalling or implementation changes required to support this functionality, since the allocation of sounding resources is done at eNB level and signalled to the UE.

VI. CONCLUSIONS

In this paper we have studied the sounding procedure in the LTE-A UL using CA. We have recognised the main problems of the CSI acquisition in the UL of LTE-A systems using CA. First, sounding such an increased bandwidth implies outdated CSI and both LA and frequency division scheduling performance is far from accurate. Also, the number of UEs that share the spectrum affects the variability of the interference generated, reducing even more the CSI accuracy. In order to reduce the misalignment between the CSI and the actual SINR experienced, we have integrated the sounding process in a SFR ICIC solution with CA. Reducing the sounding bandwidth, increases the accuracy of the CSI for two main reasons: more up to date information is available since more frequent measurements can be taken, and also interference variability decreases in the cell edge. Results indicate a reduction in SINR error estimates with the corresponding BLER decrease along with a 36% improvement in the average UE throughput.

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