Understanding Static Inter-Cell Interference Coordination Mechanisms in LTE

Ashley Mills, David Lister, and Marina De Vos

***Abstract*—This work identifies the factors which determine the behaviour of static interference avoidance schemes: SINR distribution shift, MCS mapping, and proportional MCS usage. The work goes on to challenge the common assumption that it is "best" to give resources with a high reuse factor to those at the cell-edge, by showing for a fixed rate service class, that it is best to be greedy and give these resources to those at the cell-centre. The work is performed using monte-carlo simulations, only in the downlink direction, on a London scenario with realistic path loss and network data. All work is statistically quantified using appropriate tests.**

***Index Terms*—LTE, Interference Coordination, Soft Frequency Reuse.**

I. INTRODUCTION

THE next generation wireless technology, Long Term Evolution (LTE), has been designed to deliver higher spectral efficiency and increased cell-edge throughputs relative to HSPA [1]. It is expected that LTE will be deployed in a reuse one configuration, in which all frequency resources are available to use in each cell. Although LTE can operate at SINRs as low as -6.5dB [2], concern still persists over cell-edge performance.

This has led to the proposal of numerous inter-cell interference coordination mechanisms. A large number of these are dynamic in nature and usually assume communication between basestations [3]–[15]. These schemes have tended toward taking more and more cells into account, and it would appear that the industry is converging toward multi-cell processing with a centralised RAN architecture [16], [17].

Despite this progress and innovation, interest still persists in static schemes that it is assumed can be deployed within LTE without modification of the extant standards and without significant modification of extant equipment.

Static schemes usually fall into one of three broad categories: traditional hard frequency reuse, soft frequency reuse [18], and partial frequency reuse [19]. Notwithstanding variants and other techniques that do not fit the classification, this taxonomy will serve the argument advanced here.

A. Soft Frequency Reuse

Soft Frequency Reuse was proposed by Huawei in [18]; supplemented in [20]. This proposal is effectively reiterated by Ericsson in [21] and by LG Electronics in [19] although the latter augments the description with a priority based frequency planning scheme. Alcatel propose a method very similar to soft reuse in [22], albeit with a reuse factor higher than three at the cell edge. Semi-static variants of soft reuse are proposed in [23]. Soft frequency reuse is usually portrayed as depicted in Figure 1.

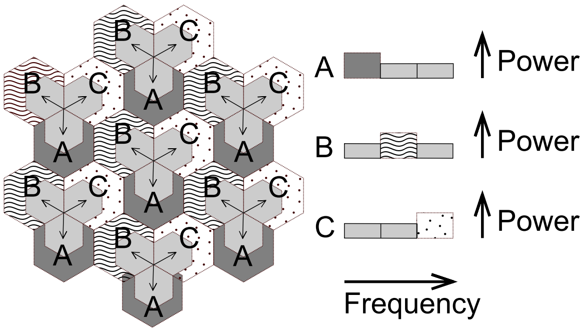

Fig. 1. Soft frequency reuse as conventionally presented

The left side of Figure 1 shows a hexagonal configuration of cells, colour coded and labelled according to a tessellating pattern to indicate which parts of the frequency band are allowed in each part of each cell. The right of the figure shows the frequency-power transmit profiles for each of the three types of cell that arise.

The general concept is that BSs transmit at reduced power over the whole transmission band, to create spatially separated cell centres that do not interfere with each other. At the cell edges, a boosted reuse three pattern is used so that received signals are orthogonal between otherwise interfering cell-edge UEs.

The mean cell throughput under soft reuse for the downlink is examined in [24]. It is claimed that 5th percentile throughput can be improved relative to reuse one in trade off for a reduction in total cell throughput by applying soft reuse. Since the work only examines the mean cell throughput, it provides no insight into the behaviour of more realistic schedulers.

Partial reuse differs from soft reuse in that the tessellated part of the spectrum is kept disjoint from the reused part of the spectrum [19].

B. Conflicting Results

Examining results on soft and partial reuse [14], [18], [22], [25]–[30] reveals some conflicting statements.

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Manuscript received April 14, 2011; revised May 1, 2011; accepted June 30, 2011

doi:10.4304/jcm.6.4.312-318

For example both [26] and [30] claim that partial reuse, relative to reuse one, gives improvements in throughput at the 5th percentile point, yet [29] concludes that “the basic partition-reuse scheme studied was not capable of improving the rate at the 5% CDF point”.

And [27] claims that soft reuse provides gains in both cell-edge *and* total throughput when compared with reuse one yet [28] concludes that “With the expected link performance no improvement can be found with static downlink reuse schemes.”. Furthermore [26] shows completely the opposite: losses in both cell-edge *and* total throughput for some scenarios.

The discussions in [29] and [28] go some way to explain, for their own results in isolation from others, why they turn out the way they do, yet no general explanation is proffered.

We contribute to this body of work in two ways: firstly we statistically quantify our results to provide confidence in them, something that none of the cited works do, and secondly: we explain clearly how different results can manifest from the application of the same or very similar schemes by identifying the principal factors involved and explaining their interactions (Section IV).

C. Challenging a common assumption

A common assumption in the works cited above, is that it is better to give the resources with a higher reuse factor to the UEs at the “cell-edge”. This is evidenced by the observation that none of the work suggests doing the opposite. And although in [31] a convincing mathematical argument is advanced as to why the cell edge may benefit *more* from interference coordination than the “cell-centre”, this says nothing of the trade-off in general.

Without strong empirical support, it is far from clear that giving the better resource to the cell-edge UEs is *always* the best scheduling strategy. And it must be observed that subbands with higher reuse factors offer improved SINR to *all* UEs, not just cell-edge UEs. So it isn’t clear apriori what the best scheduling strategy is for a given performance metric.

Against this backdrop we decided to examine scheduling strategies that favour high SINR UEs even when a soft reuse scheme has been applied, and were surprised to find, contrary to intuition, that a net gain in number of satisfied UEs could be obtained. This is explained with reference to the determinant factors identified in Section IV.

D. Document outline

The rest of this document is organised as follows. In Section II, the soft reuse terminology used here is defined. Experimental assumptions are explained in Section III. In Section IV, the factors complicit in causing static reuse results to differ are drawn out and explained through the medium of mean-rate experiments. In Section V, a feasible scenario is examined where favouring the cell-centre UEs gives a better outcome than favouring the cell-edge UEs. The implications of the presented results are discussed in Section VI and Section VII draws the work to a close with the conclusion.

1.3

TABLE I
RELATIVE TX POWER PER VRB ON THE ASB AND BSB.

Index	1	2	3	4	5	6	7	8	9	10
ASB TX	0	$\frac{1}{9}$	$\frac{2}{9}$	$\frac{3}{9}$	$\frac{4}{9}$	$\frac{5}{9}$	$\frac{6}{9}$	$\frac{7}{9}$	$\frac{8}{9}$	1
BSB TX	3	$\frac{25}{9}$	$\frac{23}{9}$	$\frac{21}{9}$	$\frac{19}{9}$	$\frac{17}{9}$	$\frac{15}{9}$	$\frac{13}{9}$	$\frac{11}{9}$	1

II. SOFT REUSE

A problem with the presentation in Figure 1 is that it confounds the physical aspects of soft frequency reuse with the virtual aspects of resource allocation by implying that the boosted resource *should* be given to the “cell edge” UEs.

Since this work looks at giving the boosted resource to the “cell-centre” UEs, soft reuse is presented neutrally as a tessellating pattern with a boosted part and an attenuated part, in the manner of Figure 2.

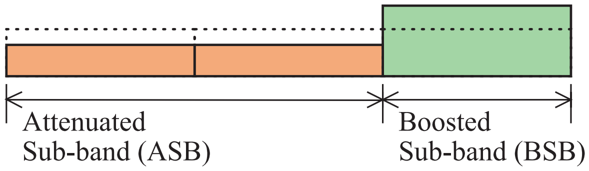

Fig. 2. Soft Frequency Reuse Configuration. The band is divided into attenuated and boosted regions. The scheduler decides which UEs are allocated to which regions.

The available bandwidth is partitioned into an Attenuated Sub Band (ASB) and a Boosted Sub Band (BSB) in the proportion of 2:1. The position of the BSB third in the overall band is changed on a per cell basis to create a tessellating pattern. The only difference from Figure-1 is that cell geography is not shown since we wish to avoid communicating apriori geographical biases on the usage of the ASB or BSB.

The relative transmit powers of the ASB and BSB determine how “soft” the overall reuse factor is. The power ratios shown in Table-I were examined in this work.

This range of soft reuse power ratios is bounded by two end points: reuse three at index 1, and reuse one at index 10. The points in between linearly interpolate across the space defined by these end points.

Observe that for Index 1, since the TX power on the ASB is 0, all UEs are assigned to the BSB. The BSB in this case uses 1/3rd of the total bandwidth at 3 times the transmit power.

In the following sections, the impact of applying each of these soft reuse power ratios is examined. Different scheduling strategies are considered to demonstrate the interaction between soft reuse power ratio and scheduling strategy. The cell performance is measured for each condition, to understand, if at all, where each soft reuse power ratio performs best.

III. EXPERIMENTAL METHODOLOGY

A. Overview

A realistic central London scenario is used to assess the gains of applying the static soft reuse power ratios shown in Table-I. The gains are measured in terms of scheduling performance for two scheduling approaches: mean rate, and fixed rate.

B. LTE System Assumptions

The left of Figure 3 illustrates the essential components of a 10MHz LTE DL frame. In time, the frame consists of 10 subframes which each last 1ms. Half of a subframe is called a slot. In frequency, each subframe is split into 50 Virtual Resource Blocks (VRBs). Each VRB is comprised of a pair of physical resource blocks (PRBs). One VRB is the smallest unit of allocation in LTE [32]. Each PRB spans 12 subcarriers in frequency and 7 symbols in time (shorter cyclic prefix was used). Each element of a PRB is called a Resource Element (RE). An RE spans one subcarrier in frequency and one symbol in time. An RE has a frequency width of 15kHz and lasts approximately 70μs.

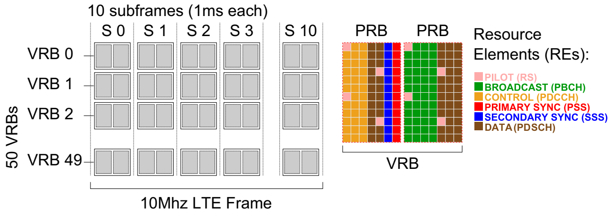

Fig. 3. The essential components of a DL LTE frame.

The right of the figure shows a VRB in detail, containing the RE types modelled here. Primary and secondary synchronisation, and broadcast channels, only occur on the three VRB either side of the central carrier. The former only occur in frames 0 and 5 and the latter only in frame 0. Their detailed action is not modelled: the channels only consume space that would otherwise be occupied by data REs. In the majority of the frame, only pilot, control, and data REs are present.

Pilot symbol positions and associated RSRP computation is modelled accurately according to [32]. Control channels are assumed to consume the first 3 symbols of every subframe, their action is not modelled, and they only consume space that would otherwise be occupied by data symbols. The average number of data REs per VRB was computed as 124.8720. This number is at the root of all throughput computations.

C. MCS Codeset

To map SINR to throughput, a lookup curve obtained from Vodafone Group [33] was used. Figure 4 shows the curve relative to the 3GPP reference curve which uses a single antenna (SISO) transmit/receiver [2]. The Vodafone curve uses 2x2 MIMO and assumes optimal switching between STBC and spatial multiplexing. The fading at the link level was based on the ITU Pedestrian B channel at 3km/h [34].

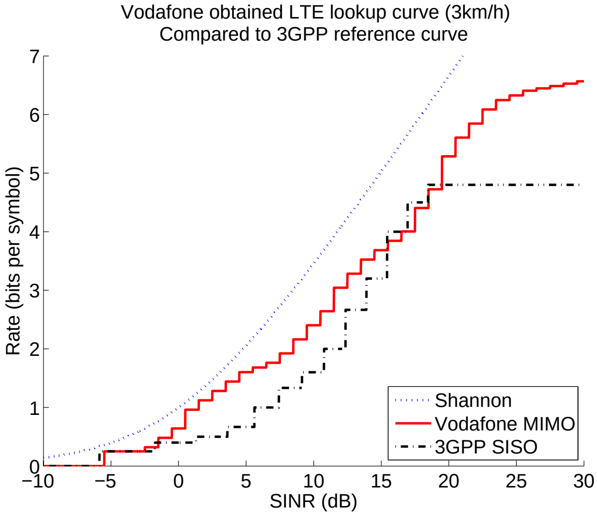

Fig. 4. SINR to MCS bitrate lookup curve used here in comparison to Shannon and a 3GPP reference curve.

Fig. 5. Atoll predictions and antenna locations for the London scenario scenario used in all simulations. Circled antennas were excluded from results collection.

D. Deployment scenario

A realistic London scenario was used for all simulations. The data represents an area of central London. Antenna settings and terrain data reflect the actual network settings used in 2004 for the Vodafone UMTS macro deployment. Figure 5 shows the London area studied along with generated pathloss predictions.

Pathloss was calculated at a resolution of $10m^2$ using the Pace3D ray tracing software module in Atoll [35]. Pace3D accurately models the effects of building penetration losses, reflection, and refraction effects and provides a realistic picture of the actual pathloss variation experienced in each cell. To mitigate border simulation affects, results were not collected for the circled cells in Figure 5.

In all experiments, each cell transmits continuously, so that the worst case interference scenario is represented.

IV. MEAN RESULTS

To generate mean cell results the following procedure was used:

```
ForEach (Soft Reuse Power Ratio) : Do
    ForEach ( Cell ) In ( Scenario ) : Do
        ForEach ( Square in Cell Area ) : Do
            A <— ASB Bitrate
            B <— BSB Bitrate
            C <— Mean: 2/3 * A + 1/3 * B
        Done
        Compute mean of A,B,C over Squares
```

```
    Done
    Compute mean of A,B,C over Cells
    Record A,B,C for Soft Reuse Power Ratio
Done
```

In the first line, the transmit power profile is applied to the network. This means every cell transmits at exactly the power specified in the profile on each VRB. A full interference model is examined which means all cells are simultaneously transmitting on all VRBs. The algorithm then iterates over all cells in the scenario, and averages the measures A, B, and C for each cell at a resolution of $10m^2$. This is the meaning of “Square” in the algorithm. The algorithm ends by averaging the results across all cells.

Figure 6 plots the mean cell throughput as a function of soft reuse power ratio.

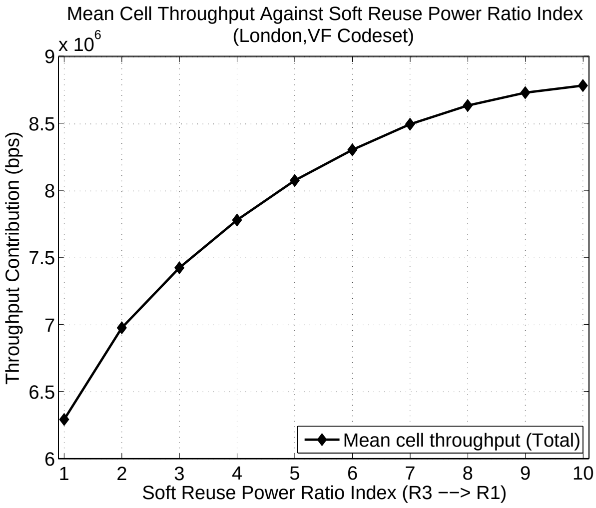

Fig. 6. Mean cell throughput

The general trend observed is a decline in throughput when moving away from reuse one toward reuse three. To compare the two extremes: mean throughput is $\approx 40\%$ greater under reuse one than it is under reuse three. This difference is significant with $p < 1 \times 10^7$ under a right tailed, unequal variance, ttest (Satterthwaites approximation was used to address the Behrens Fischer problem [36]).

It is desired to understand exactly why this result is observed. It is straightforward to examine the two end points: reuse three and reuse one. The question is why the reduction in bandwidth in the reuse three case is not “compensated”, to borrow terminology from [37], by the improved SINR conditions.

To see why, consider the SINR distributions under reuse three and reuse one, as illustrated in Figure 7.

The SINR distribution is right-shifted under reuse three compared to reuse one. For any monotonically increasing MCS lookup curve, improved SINR results in improved bitrate. Yet since bandwidth is reduced by a factor of three the effective bitrate observed will be reduced by a factor of three. For a given UE to benefit, it must thus obtain more than a factor three improvement in bitrate.

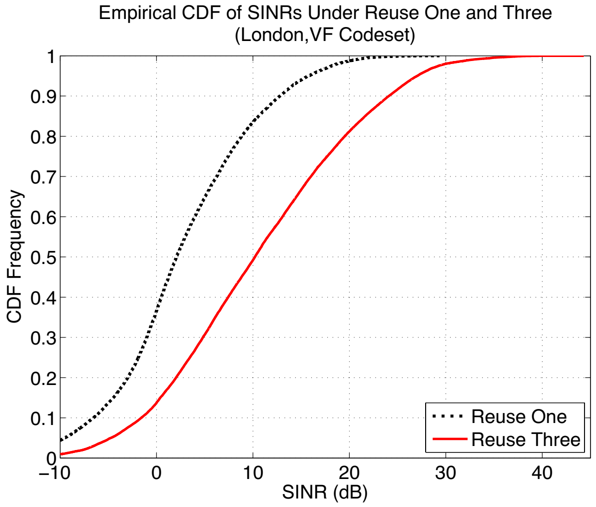

Fig. 7. Cell SINR CDFs under reuse three and reuse one.

Figure 8 illustrates which parts of the cell obtain such an improvement when switching from reuse one to reuse three and which do not. The figure plots the effective bitrate under reuse three, for sets of UEs defined by MCS index under reuse one. To make this clear, consider MCS index 10. The reuse one rate plotted is simply the rate for that MCS scheme. The reuse three rate, is the effective mean bitrate of all UEs under reuse three, that under reuse one were served by MCS index 10. A way to think of this is that each MCS serves an area of the cell under reuse one, and the plot shows how the mean bitrate changes over each MCS-area when switching to reuse three.

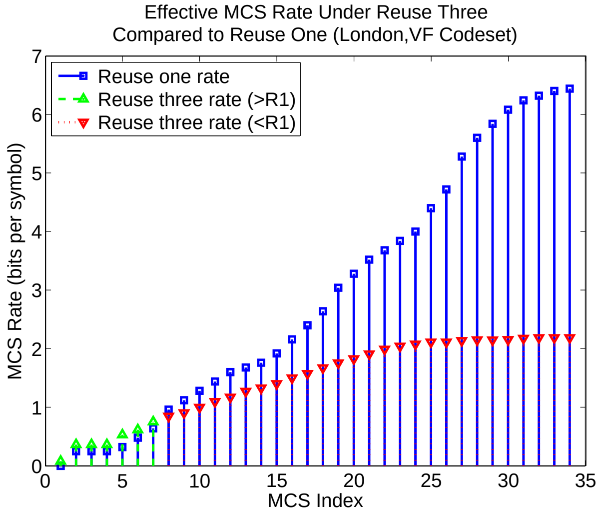

Fig. 8. Effective change in bitrate index when switching from reuse one to reuse three.

The points labelled with up arrows are those which result in an effective bitrate improvement and those labelled with down arrows an effective bitrate loss. As can be seen, some parts of the cell, namely those defined by low index MCS schemes, do benefit from switching to reuse three. It follows that the mean cell result is determined by the relative proportional use of each MCS scheme. Figure 9 plots the relative proportional use of each MCS scheme under reuse one.

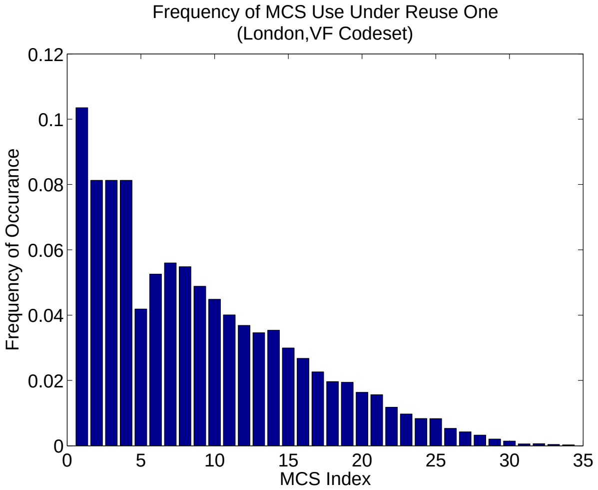

Fig. 9. Frequency of MCS use under reuse one.

When the MCS distribution shown in Figure 9 is considered against the effective bitrate changes shown in Figure 8, the outcome is that approximately 50% of the UEs gain from switching to reuse three, and approximately 50% do not gain. When reuse three wins out, a mean improvement of ≈ 0.13 bits per symbol is obtained, whereas when reuse one wins out, a mean improvement of ≈ 1.88 bits per symbol is obtained. The overall result is that reuse one wins out when the whole cell is taken into account, as was illustrated in Figure 6. It should now be clear that the mean cell result is determined by three items:

1) The change in SINR distribution bought about by the coordination of interference.
2) How this corresponds to a change in MCS schemes used due to the gradient of the MCS lookup curve.
3) The relative proportional use of each MCS scheme before coordination.

Clearly then, these items are critical, and anything that changes them can change the outcome of the competition between reuse three and reuse one, or in general reuse one and some other interference scheme such as soft reuse that improves SINR. From this it follows that scheduling policy plays a crucial role in determining whether a given interference coordination scheme brings about a benefit or not. The scheduler decides which UEs receive resources, and thus modifies the relative proportional use of MCS schemes, which is the third item above.

For schedulers which bias the resource allocation to low SINR UEs, or for cells which have a very large percentage of low SINR UEs, there is likely to be a benefit from statically applied soft reuse schemes. In other cases, there will not be. However, the exact scheduling strategy and exact UE distribution will determine the overall result and should be examined on a case by case basis.

To summarise: in the mean, no net benefit is obtained from the application of any soft reuse scheme tested. The reason for this has been clearly explained in terms of the interaction between SINR distributions, MCS lookup curve, and proportional use of MCS schemes.

In the next section soft reuse is applied to a fixed rate scheduler to get some idea how in practise, scheduling shifts the relative proportional use of MCS schemes, and whether or not this results in an overall benefit under soft reuse.

V. FIXED RATE RESULTS

In this section a semi-realistic scheduler is examined whose goal is to satisfy as many UEs as possible, where each UE has the same fixed bitrate target. The scheduler operates as described below:

```
ForEach (UE in Scheduling Order) : Do
    Allocate VRBs from the BSB Until :
        No VRBs remain
        OR UE is satisfied.
    Allocate VRBs from the ASB Until :
        No VRBs remain
        OR UE is satisfied.
    Update satisfied UE count accordingly
Done
```

The scheduler always allocates the best resource, the BSB, first. This means that the scheduling order is important. To investigate the impact of which UEs get preference for the BSB, three scheduling orders were considered:

1) Greedy - The UEs are scheduled according to wideband SINR in descending order from best to worst.
2) Random - The UEs are scheduled in random order.
3) Leftist - The UEs are scheduled according to wideband SINR in ascending order from worst to best.

Note that the third of these is the approach which is usually promoted in the literature (see for example [18], [26], [38], [39]), namely that the boosted part of the spectrum should be given to the "cell-edge" UEs.

The complete process for obtaining results, which is executed for each fixed rate target, and each scheduling strategy, is as follows:

```
ForEach (Soft Reuse Power Ratio) : Do
    ForEach ( Cell ) In ( Scenario ) : Do
        ForEach ( Random seed in 1 to 1000 ) : Do
            Drop 25 UEs at random
            Schedule the UEs
            Record number of satisfied UEs
        End
        Compute mean over all UE drops
    End
    Compute mean over all cells
End
```

Figure 10 plots the number of satisfied UEs, under the best soft reuse power ratio, for each bitrate target, and for each of the scheduling strategies.

The results are surprising and show that giving the BSB to the "cell-edge" UEs, actually results in the worst performance. It turns out that it is always best to be greedy and give the BSB to the best SINR UEs, at least for the scheduler examined. Note that the number of UEs satisfied never reaches

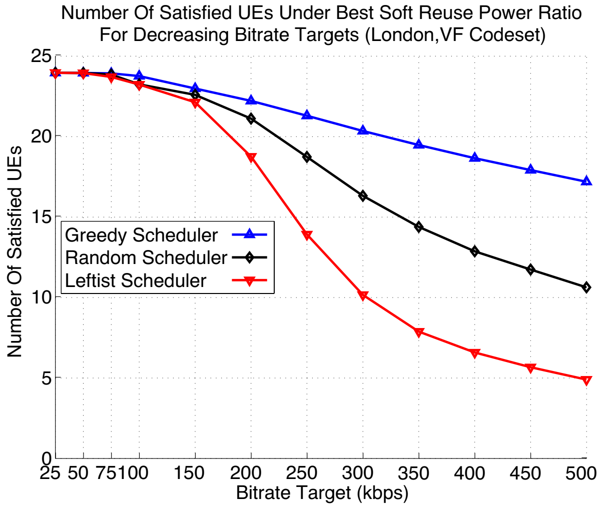

Fig. 10. Number of satisfied UEs under the best performing soft reuse power ratio, for each bitrate target.

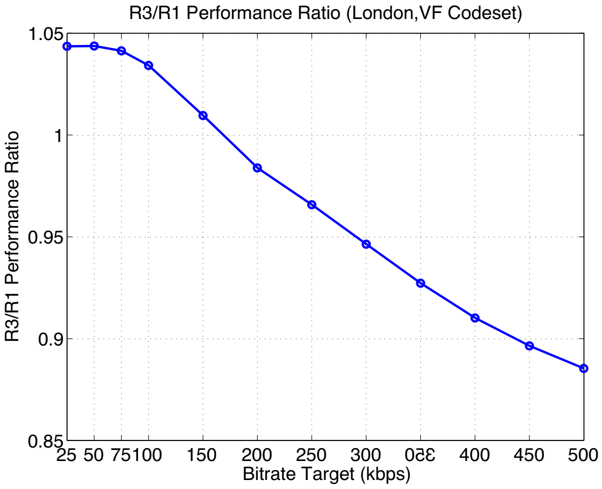

Fig. 11. Ratio of satisfied UEs under reuse three to satisfied UEs under reuse one, for each bitrate target.

the maximum 25, this is because the Monte Carlo simulation samples some areas which cannot receive any throughput under the MCS lookup curve used. In practise however, time dependent variation, and partial loading, should allow all UEs to be satisfied for reasonable bitrate targets.

Figure 10 plots the number of satisfied UEs under the best soft reuse power ratio for each fixed rate target. It does not specify which soft reuse power ratio is best for each fixed rate target. For the greedy scheduler, the only scheduler of interest given the above results, the answer is as follows: for bitrate targets 500 down to 200, reuse one satisfies the greatest number of UEs, and for bitrate targets 150 and below, reuse three satisfies the greatest number of UEs.

Thus, no intermediate soft reuse scheme ever does better than either reuse one or reuse three in this scheduling scenario. Given that either reuse one or reuse three satisfies the greatest number of UEs, Figure 11 plots the ratio of the number UEs satisfied under reuse three, to the number satisfied under reuse one.

When 25 UEs are trying to get 500kbps each, the system is overloaded, and in this case reuse one satisfies upto 10% more UEs than reuse three. For the lower load and saturation states, reuse three satisfies upto 4% more UEs than reuse one. The former gain comes about because the greedy scheduler prioritises UEs with a high MCS which benefit *most* from having the full resource available to them. The latter gain comes about because reuse three is able to serve UEs which cannot be served under reuse one due to the cut-off point in throughput caused by the lookup curve. In practise this gain is likely to be diminished because time-dependent fading will periodically bring cut-off UEs into service.

Furthermore, given the results of Section IV, it will be observed that any reuse three gain will come at the cost of reduced mean rate, and will only be apparent for low bitrate targets. Thus it is unlikely in practise that any significant gain in fixed rate satisfaction would be observed from the application of soft-reuse in the general case.

VI. DISCUSSION

A. Summary

The conditions under which soft reuse can be expected to benefit have been clearly enumerated: SINR distribution shift under ICIC, SINR to MCS mapping, and proportional usage of each MCS scheme before and after ICIC. In addition, the intuitive notion that the “cell-edge” UEs should receive the boosted part of the spectrum has been demonstrated false in the case of a fixed bitrate service class presented.

B. Scope of results

It may be argued that the results presented here are too specific, and that they “overfit” the particular London scenario examined. Given this possibility, the experiments presented were repeated for a 57 cell hexagonal environment and repeated again for the 3GPP codeset shown in Figure 4.

In the hexagonal case, there are greater benefits from coordination, but overall the mean rate still favours reuse one, and the fixed rate scheduling outcome shows the same trends described here. Using the 3GPP codeset, the only differences observed are expected lower throughputs, but no diversion from the trends. In summary, there are no qualitative differences in the results or the implications of the results. Note however that the degradation observed when switching from hexagons to the London scenario is likely to be even greater for femtocells and highly irregular networks. This is because the spatial orthogonality on which static reuse schemes depend, will be eroded.

C. Contributions of this paper

The novel contributions of this work are threefold:

- The primary factors which manifest static reuse results are illustrated through a simple example. These are: SINR distribution shift under ICIC, SINR to MCS mapping, and proportional usage of each MCS before and after ICIC due to user distribution and scheduling strategy. Different

scheduling strategies may manifest fundamentally different outcomes for a given ICIC approach.
- Simulations are performed for a realistic London deployment, and all results are quantified statistically. This is in contrast to former work cited.
- The assumption that the cell-edge UEs should be assigned the best resources, implied by former work, is challenged and demonstrated false for the traffic class examined.

VII. CONCLUSION

We propose examining results in terms of relative MCS improvement curves *given* the scheduler examined as we have done here, rather than solely in terms of CDF shifts due to the soft reuse scheme applied. The former approach captures the important interactions between UE distribution, scheduling strategy, and MCS codeset, whereas the latter only reflects the SINR change independent of these.

The notion that it is better to give "cell-edge" UEs the resources having a high reuse factor has been demonstrated false in the case examined here.

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