Time-Domain and Frequency-Domain Muting schemes for Interference co-ordination in LTE Heterogeneous networks

Naveen Arulselvan
Altiostar Networks
narulselvan@altiostar.com

Manjari Chhawchharia, Moushumi Sen
Nokia Siemens Networks
{manjari.chhawchharia,moushumi.sen}@nsn.com

Abstract—The need for Inter-cell Interference Coordination (ICIC) schemes in LTE heterogeneous networks, is well elucidated in literature [1]. We consider distributed scheduling mechanisms so that multiple base-station vendors can co-exist. Moreover, in legacy LTE networks, fast timescale coordination across base-stations may not be possible due to the inherent backhaul latency. In such a framework, we study the relative performance of frequency-domain and time-domain interference coordination schemes. We also compare the performance of legacy users who are agnostic to the ICIC scheme employed by the network, with users who can intelligently report channel measurements, depending on the parameters used in the ICIC scheme. Surprisingly, we find that network can efficiently compensate for the legacy user’s inadequacy in reporting. Overall, these studies can help the cellular operator to prioritize the strategy for network evolution and decide the timelines to offer advanced user equipment.

I. INTRODUCTION

In traditional cellular networks base stations are deployed in a planned layout. Such base stations have similar transmit power levels, antenna patterns and backhaul capabilities. User Equipments (UEs) are typically connected to the base-station which provides the strongest coverage \(^1\). In turn the transmission parameters of the base-station are fine-tuned to maximize the coverage as well as mitigate interference between base stations. In these homogenous networks capacity enhancement is achieved via Cell splitting or Carrier Aggregation. But the site acquisition costs are constantly increasing in dense urban areas, and new carriers become available only in the higher end of the spectrum, where coverage tends to be poorer. Needless to say, such processes are costly and iterative. Capacity-building solutions have to be re-designed for the next-generation cellular networks because data traffic, driven by the proliferation of smart phone devices and tablets, is growing exponentially. As a result operators need a scalable model for network evolution which improves the user experience in a cost-effective manner. Several picocells underlaid in a conventional macro base-station offer a robust solution towards that end [2],[3]. In such Heterogeneous networks (or Het-nets) the umbrella macro base-station provides wide area coverage. The picocells have substantially low transmit powers as compared to a macro base-station and caters to traffic hotspots. The placement of pico base stations may be based on the estimation of dead zone areas or the traffic density in the network. Due to their compact form factor, pico base stations offer flexible possibilities in terms of site acquisitions [4].

Macro and pico cells are deployed on the same downlink carrier to maximize spectral efficiency. But a simple deployment of pico nodes can lead to under-utilization of air interface resources due to the relatively small footprint of the pico cells. To increase the number of UEs attached to the pico cell, Cell Biasing or Cell Range Extension is used. Such biasing enables heavily-loaded macro cells to transfer users to lightly-loaded pico cells. However, downlink interference experienced by such users become worse as they are no longer connected to the strongest cell. As a result the pico users are subjected to harsh interference from the macro cells in the absence of any interference co-ordination scheme. Third Generation Partnership Programme (3GPP) Release 10 has adopted Enhanced Inter-Cell Interference Co-ordination (eICIC) scheme to achieve optimal system performance. eICIC is essentially a time-domain muting mechanism to mitigate interference, which needs synchronization across base-stations. In this work we compare muting schemes in both time and frequency domains. In particular, we study the performance of legacy UEs which are not capable of subframe-specific channel measurements and agnostic to the interference co-ordination efforts made by the network.

The disparity between the transmit power levels of macro and pico base stations, which can be as high as 20 dB, implies that the downlink coverage of a

\(^1\)UEs may be temporarily connected to a weaker base-station to avoid ping-pongs during handover.
pico base station is smaller than that of a macro base station. But the uplink coverage of all the base stations is similar as it is based only on the UE’s transmission power. This creates a mismatch between downlink and uplink handover boundaries. The provision for independent cell selection in uplink and downlink is being discussed in 3GPP. Here we still consider selection of base-station based only on downlink signal strength.

There have been several prior work in this area. Analytical models have been derived for generalized heterogeneous networks in [5]. TDM-ICIC has been studied in [6]. Muting scheme for closed-subscriber groups have been investigated in [7]. Specifically ICIC schemes with muting have been studied in [8],[9],[10],[11]. But these schemes have limitations such as modeling only full-buffer traffic. Moreover they all assume the need for a centralized scheduler which would need co-ordination at sub-millisecond granularity. In this work we study bursty traffic with distributed scheduling that requires limited co-ordination between interfering base-stations. This would enable co-existence of multiple base-station vendors in the operator ecosystem.

II. SYSTEM MODEL

Consider a heterogeneous network with \( K \) macro cells in a regular hexagonal grid. In each macro cell we assume there are \( K' \) pico cells randomly placed. Out of \( N \) users in a given macro area, \( N'(<N) \) users are deployed in a hotspot surrounding each pico-cell while the remaining \( N - K'N' \) users are uniformly deployed. The transmit powers in the downlink are \( P_m \) and \( P_p \) for the macro and pico cell respectively. User association is based on the strongest downlink signal strength. In Figure 1(a) the cell-edge boundary of the pico cell is given by

\[
\frac{G_p P_p}{R^\alpha} = \frac{G_m P_m}{D'^\alpha},
\]

where \( R \) is the coverage radius of the pico cell, \( D' \) is the corresponding distance from the macro cell and \( \alpha \) is the path-loss exponent. For the sake of convenience we take the pico-cell location to be origin. Then the locus of the pico-cell’s coverage area is given by

\[
\left(X + \frac{D}{C - 1}\right)^2 + y^2 = \frac{C D^2}{(C - 1)^2},
\]

where \( C \) equal \( \frac{G_m P_m}{G_p P_p} \) and \( D \) is the distance between the macro and pico base-stations of interest. We can then observe that:

- Coverage area of the pico cell is a circle whose center is located away from the macro, and
- Coverage area of the pico cell increases with \( D \)

For the parameter settings listed in Table 1, the coverage area of a given pico cell turns out to be less than ten per cent of the macro area. This limits the benefit of deploying picocells as most UEs will attached to the macro base stations if cell selection is solely based on downlink signal strength. The difference between the loadings of different base stations can lead to an unfair distribution of data rates and uneven user experiences among the UEs network-wide. The performance of heterogeneous networks will be sub-optimal. In order to balance the load between macro and pico base stations by expanding the coverage of pico base stations and subsequently increase cell splitting gains, we can introduce a Bias factor (\( B \)) to force the UE to choose the pico-cell even if the downlink signal strength is lower than the macro-cell by a factor of \( B \). This is equivalent to boosting the pico transmit power by \( B \) in (1). As a result, \( C \) decreases and the coverage area of the pico-cell increases in (2). The factor \( B \) is referred to as Cell Range Extension. Figure 1(b) illustrates the increase in coverage area for \( B \) greater than 0.

A. Need for Interference co-ordination in Hetnets

Range Extension performs load-balancing and increases resource utilization. But the interference in the system increases. Range-extended users will now face harsh interference from the macrocell due to concurrent transmission in time-frequency resources. As a result, the picocell needs to perform interference coordination with the dominant macro interferers.

A basic ICIC technique involves resource coordination amongst the co-operating base stations, where an interfering base station gives up use of some resources.
in order to enable control and data transmissions to the victim user. Resource partitioning can be performed in time, frequency or spatial domains [12]. In this paper we restrict our focus to time-domain and frequency-domain based resource partitioning schemes. We assume ideal control channel and compare the performance of the two co-ordination schemes. Before we detail the two schemes studied, we outline how such co-ordination schemes can work in a distributed fashion and also provide an overview of the modification needed to the link adaptation mechanism when these schemes are used.

B. Distributed interference co-ordination

The motivation for interference co-ordination is evident from the arguments in the previous section. In practice, while implementing interference co-ordination schemes, the system engineer is confronted with the choice of either centralized or distributed implementation. Centralized scheduling is attractive from the performance standpoint but such a scheme will need a costly new network entity and fast interconnects between the co-operating base-stations. Distributed interference co-ordination does not require new devices and makes it easier for multiple base-station vendors to co-exist. Here we focus on a class of distributed schemes. Figure 2 illustrates a cluster of three co-operating base-stations. The base-stations make unilateral decisions to mute a subset of time-frequency resources. The muting patterns are exchanged between the constituent base-stations of the given cluster, based on which scheduling decisions will be impacted.

C. Link Adaptation with interference co-ordination

From the UE feedback the base-station can estimate the received SINR of the given UE on the allocated resource blocks. In addition, the base-station will determine the spectrally most efficient modulation for which a given target error rate is not exceeded. The selected link parameters is signaled as part of the scheduling grant to the corresponding UE, whereas the actual data transmission starts a few subframes later, taking into account processing and propagation delays. Moreover, the UE feedback is not solicited every sub-frame because of ensuing control channel overhead. In reality, the interference is fluctuating as traffic is dynamic in the neighboring cells. Consequently, the actual Signal-to-Interference Ratio (SINR) value during the data transmission may be quite different from the SINR values that have been used as input for the scheduling and link adaptation algorithms. Without any appropriate countermeasures, as proposed in [13],[14], the performance would be often degraded.

In such a outer-loop link adaptation scheme, we add an UE-specific $\Delta$ to the predicted SINR values before performing the actual link adaptation. This offset is adjusted based on the outcome of previous transmission attempts of the corresponding UE. In particular, if the transmission attempt was successful, the offset is increased by $\delta_{up}$ whereas in case that the transmission was not successful, it is decreased by $\delta_{down}$. By relating $\delta_{up}$ and $\delta_{down}$ as follows

$$\delta_{down} = \left(\frac{1}{\epsilon} - 1\right) \delta_{up}$$

it is possible to achieve an average error target $\epsilon$. One of the main tasks of the link adaptation scheme is to adjust the UE-specific offset such that it accounts for the average interference level generated by UEs in the non-cooperating cells. With time-varying co-operation it will be necessary to use a separate link-adaptation loop. In other words the base-station will maintain two separate offsets, to be applied when co-operation is turned on and off, respectively. We assume such a modification to the link adaptation in the time and frequency domain co-ordination schemes below.

III. TIME-DOMAIN INTERFERENCE CO-ORDINATION

Time-Domain Muting (TDM) ICIC was a feature extensively studied and adopted in 3GPP Release 10. TDM-ICIC is considered to adapt well to user distribution and traffic load changes. In TDM-ICIC a macro base station reserves a fraction of the subframes, $\eta$, for use by pico stations. This maybe based on the number of UEs served by pico and macro base stations and/or based on the data rate requirements of the UEs.
Figure 3 shows an example of time-domain muting in the macro cells. In this example, two out of the eight time-domain resources are not used by the macro base-station. These empty time-slots are referred to as Almost Blank subframes (ABS). In such sub-frames the macro cell still needs to transmit legacy common control channels to enable backward compatibility with Release-8 UEs. The pico cell can exclusively schedule data transmissions to users attached to them. Data suppression in macro-cells greatly reduces interference experienced by pico UEs. In addition, the pico UEs may even cancel the interference caused by the mandatory transmission of reference or synchronization signals on the ABS subframes using advanced interference-cancellation receivers [15]. This alleviates the need for cell planning of heterogeneous deployment. But such UE receivers are expected only from 3GPP Release 11 onwards. As a result we study static setting of $\eta$ based only on range extension.

In practice we may dynamically adapt $\eta$ based on instantaneous or long-term cell-load. Such dynamic ABS adaptations would need more frequent information exchanges between the coordinating macro cell and corresponding pico-cells. We do not study such a possibility as we focus on distributed scheduling with limited co-ordination.

We note that the TDM-ICIC scheme is transparent to the UE attached to the pico-cell. So legacy UEs can be range-extended and served during ABS sub-frames. However the channel measurements which is fed back to the pico cell will be averaged over ABS and non-ABS subframes. On the other hand 3GPP Release-10 UEs are able to report dual channel measurements. In particular, for ABS subframes, such UEs can notify superior signal-to-interference ratios, thereby allowing the pico-cell to allocate higher data rates. In this study we study the impact of TDM-ICIC on both Release-9 and Release-10 UEs.

IV. FREQUENCY-DOMAIN INTERFERENCE CO-ORDINATION

The concept of Frequency-Domain Muting (FDM) ICIC is illustrated in Figure 4. Consider UE $i$ attached to the pico cell for which the macro cell is the strongest interferer. Let $G_{p,i}(t)$ be the UE’s downlink channel gain on the frequency resource $t$ in the pico cell and $G_{m,i}(t)$ be the signal strength of the macro cell. $G_{other,i}(t)$ denotes the interference from all other cells. When UE $i$ is scheduled on the given resource $t$ the received SINR is given by

$$\nu_i(t) = \frac{G_{p,i}(t)}{G_{m,i}(t) + G_{other,i}(t)}. \quad (4)$$

If the strongest interferer can be muted, the received SINR increases to

$$\nu_i^{\text{mute}}(t) = \frac{G_{p,i}(t)}{G_{other,i}(t)}. \quad (5)$$

The gain in spectral efficiency $S_i(t)$ with muting frequency resource $t$ is given by

$$S_i(t) = \frac{1 + \nu_i^{\text{mute}}(t)}{\nu_i(t)}. \quad (6)$$

This suggests that suppressing the dominant interferer for a cell-edge user can lead to huge gains in spectral efficiency.

For the FDM-ICIC scheme, we construct the cooperating set $C_i(N)$ which consists of the $N$ strongest interferers of each cell-edge UE $i$. After scheduling is complete, say UE $i$ has been allocated $M_i$ Resource Blocks (RBs). If the gain in spectral efficiency by muting $S_i(M_i)$ is greater than $\rho$ the base-station will request all cells in $C_i(N)$ to mute on the chosen $M_i$ RBs. For optimal system performance $\rho$ greater than $N + 1$ offsets the resource loss in the muting cells. Since the muting decisions are made unilaterally, there can be several overlapping muting requests. Ties are
TABLE I

SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-site distance</td>
<td>500m</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>2GHz</td>
</tr>
<tr>
<td>UE speed</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Macro transmit power</td>
<td>20W</td>
</tr>
<tr>
<td>Pico transmit power</td>
<td>1W</td>
</tr>
<tr>
<td>Rx Antenna gain</td>
<td>0dB</td>
</tr>
<tr>
<td>Tx Antenna gain</td>
<td>17dB</td>
</tr>
<tr>
<td>Antenna downtilt</td>
<td>15 deg</td>
</tr>
<tr>
<td>Users per macro area</td>
<td>30</td>
</tr>
<tr>
<td>Picos per macro area</td>
<td>2</td>
</tr>
<tr>
<td>Traffic</td>
<td>FTP model</td>
</tr>
<tr>
<td>Offered load</td>
<td>5.1, 10 Mbps per cell</td>
</tr>
</tbody>
</table>

arbitrarily broken based on a priority order. For the numerical studies we restrict ourselves to muting only the top interferer.

V. SIMULATION STUDY

In this section, we study the system performance for the two muting schemes. A 57-sector hexagonal macro cell-layout with users randomly dropped within each sector is used for this evaluation. Table I gives other relevant simulation parameters. We vary $\eta$ between $\{0.125, 0.25, 0.5\}$ in the TDM scheme and, vary $\rho$ between 1 and 8 in the FDM scheme, to obtain different operating points of cell-edge and average throughputs. The trade-offs between cell-edge and average throughputs for all users in the system as well as for pico and macro users separately, are shown in Figures 5 through 7 for the lower offered load and in Figures 8 through 10 for the higher offered load. Baseline operating point, indicated as a circle, denotes no muting. We can then make two observations

- There are regimes where Frequency-domain muting performs better than Time-domain muting but there is a greater range of operating points that TDM can offer.
- There is marginal gain in performance between Release-9 and Release-10 UEs. This indicates that Release-9 UE capability may be limited in terms of reporting differential CQI under muting and non-muting hypotheses. But the outer-loop power control at the network will appropriately boost the spectral efficiency. So the degradation in performance of legacy users is minimal.

VI. CONCLUSIONS

We studied legacy LTE networks where fast coordination among base-stations may not be possible.
While FDM-ICIC can perform better than TDM-ICIC in certain regimes TDM schemes could achieve higher cell-edge performance. Modeling inaccuracies in interference estimates in the real networks, may tilt the balance towards TDM-ICIC. Surprisingly, the performance of legacy UEs is similar to Release-10 UEs who are able to report channel reporting under multiple muting hypotheses. Clearly, the power control mechanism in the base-station is able to compensate for the inadequacy in UE’s reporting.

Acknowledgments: The authors would like to thank members of the Advanced Technology group in Nokia Siemens Networks, for several useful discussions.

References